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Value chain analysis of mangrove forests in central Mozambique: Uses, stakeholders and income

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Abstract
This study aims at documenting the value chain derived from mangrove forests in selected sites in central Mozambique (Zambezi Delta, Nhangau and Chiveve River), through the identification of the services delivered by mangrove forests and assessment of stakeholder's engagement within the value chain. Furthermore, this work evaluates the income pathways as well as the current and potential benefits of different stakeholders and the socio-economic sustainability of mangroves in the three regions. Zambezi Delta is one of largest mangrove swamps in Africa and Chiveve is located in Beira City, impacted by Cyclone Idai in 2019. The main benefits obtained by the communities both in the Zambezi Delta and Nhangau were derived from commercially important wood extraction and honey production for domestic use. Within the Zambezi Delta, profit for small mangrove poles accrued at the wholesale level (82.6%), while that for large poles accrued to harvesters (125.0%), after a small initial direct investment. At Nhangau, small poles fetched profits of 17%, medium poles 11.5%, and large poles 24%; for charcoal, the greatest portion of profits went to retailers at 50%. Men were mostly involved in mangrove wood harvesting for commercial purposes, while women collected firewood mainly for domestic use. At the Chiveve, the community benefited predominantly from non-extractable services such as flooding control, water purification, nursery grounds for fisheries and aesthetic beauty. It is suggested that Mozambique mangrove forests are valued at USD 2 400 per hectare per year. This monetary accounting can be used to inform decision making on mangrove management and to improve the performance of the value chain and the wellbeing of local communities.

Keywords: mangrove products marketing, extractable goods, regulatory services, gender, Eastern Africa

Introduction
Ecological economic valuation is an effort to allocate quantitative values to the goods and services provided by natural ecosystems (Tuan, 2013) to illustrate the benefits of the extractable products that can be commercialized (Rosales *et al.,* 2017; Brander *et al.,* 2010). A value chain is the range of activities required to bring a product or service from production to final consumption (Lowitt *et al.,* 2015; Kaplinsky, 2000) and it is useful for understanding the relationships among actors in a chain and considering the potential implications for development (Graef, 2014; USAID, 2012; Borinelli and Rocha, 2006; Kaplinsky and Morris, 2001).

Value chain analysis (VCA) includes a range of activities conduced from the material production, across actors or companies involved in the negotiation, processing, stocking, transportation and commercialization,

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to the final consumer (Rosales *et al.,* 2017; Tuan, 2013, Brander *et al.,* 2010). VCA systematically maps the economic agents involved in the production, distribution, and sales of a particular product, assessing the characteristics of economic agents, profits and costs, goods flows throughout the chain, the destination and sales volumes (Rosales *et al.,* 2017; Njie, 2011).

For mangroves, the VCA is usually concentrated on extractable products (wood, firewood, charcoal and fisheries) (Tuan, 2013, Vegh *et al.,* 2014). This can include different actors, from harvesters (wood cutters, fisherman, firewood, clam and crab collectors), transporters, sellers and final consumers (Rosales *et al.,* 2017; Njie, 2011) and can be linked by a range of micro or small companies that involve wholesalers, middlemen, retailers, traders, input traders, suppliers and service providers (Zafar and Ahsan, 2006).

Studies on mangroves in Mozambique have focused on ecological parameters such as forest structure (Nicolau *et al.,* 2017; Paula *et al.,* 2014), changes in forest area (Shapiro *et al.,* 2015) and aspects of human impacts on mangrove forests (Stringer *et al.,* 2015; Bosire *et al.,* 2012; de Boer 2002). To date, studies on mangrove VCA in Mozambique are scarce or unknown, except for a recent preliminary valuation of marginal mangroves in the Maputo city area (Inácio, 2017).

This study documents the value chains derived from mangrove forests in central Mozambique with particular focus on the identification and characterization of services derived from mangrove forests in the Zambezi Delta, Nhangau and Chiveve River, as well as stakeholder engagement and their current and potential benefits within the value chain. Furthermore, this work documents the income of different stakeholders at various sites, and the socio-economic sustainability of mangroves utilization. The results can be used to inform the community, governance and management institutions, and policy makers for decision making on mangrove management.

Research Objectives

General objective

The overall objectives of this study were to: document the value chains associated with mangrove wood products in three locations in central Mozambique (Zambezi Delta, Nhangau and Chiveve River) by highlighting the extensive list of goods and services and patterns of use of products derived from mangrove ecosystems; analyse stakeholder involvement in the mangrove value chain; evaluate economic pathways and profits gained from mangrove-associated businesses; and assess the socio-economic sustainability of mangrove exploitation in central Mozambique.

Specific Objectives

The specific objectives of the study were to: identify and compare extractible, regulating or climate-related services derived from mangrove forests in the Zambezi Delta, Nhangau and Chiveve River; describe and compare mangrove value chains and the stakeholders involved in mangrove exploitation in the Zambezi Delta and Nhangau; value economic pathways and the current and potential benefits and profits that local communities obtain from mangrove wood products in the Zambezi Delta and Nhangau; and conduct an analysis of the socio-economic sustainability of mangroves utilisation in central Mozambique.

Material and Methods

Study Area

This study was conducted in the Zambezi Delta, Nhangau and the Chiveve River in central Mozambique (Fig. 1). The climate in the area is tropical with a wet warmer season from October to March (peak in January and February), and a dry cooler season during the rest of the year. Annual precipitation varies from 600 to 1 500 mm (Macamo *et al.,* 2016a).

The central Mozambique region is characterised by a swampy coast, with approximately 24 rivers discharging into the Indian Ocean (Barbosa *et al.,* 2001), and most these have their sources in neighbouring countries to the west. The shallow inshore areas have beaches mostly made up of fine sediments or muds rich in organic matter (Macamo *et al.,* 2016a). Tidal range varies between 3.46 and 6.44 m. The most important mangrove formations in this section of the Mozambican coast are concentrated in the Púnguè and Búzi estuaries, and the Zambezi Delta (Macamo *et al.,* 2016b).

The Zambezi Delta forms the largest mangrove formation in Mozambique (Barbosa *et al.,* 2001). Recent studies conducted in the inner Zambezi Delta concluded that mangroves are increasing in coverage with a net gain of 3,723 ha (10%) over a 19 years period, from 33 311 to 37 034 ha (Shapiro *et al.* 2015).

The Chiveve River is a water course with special features that flows through Beira City downstream of the confluence of the Púnguè and Búzi rivers. The Chiveve River divides the city almost in the middle, flanked by mangrove trees. This feature has both an ecological and aesthetic function. The river is dominated by salty or brackish water, getting most of its freshwater from upstream of Beira City (Uacane and Ombe, 2016). Beira, with a population of 533 825 habitants (INE, 2017), is the second largest city in Mozambique's lowland. It is located below sea level and prone to inundation from either high spring tides or storm waters (INGC, 2012). A small is central section of the Chiveve River was dredged in 2015 by the local authorities to control storm water surges and avoid flooding of Beira City at high tides.

The Nhangau village is located approximately 30 km from Beira. Although being part of this municipality, Nhangau has strong rural characteristics. Nhangau villagers have experienced the impacts of mangrove loss after years of unsustainable extraction of wood, and have been engaged in replantation and community-based management for the last 20 years.

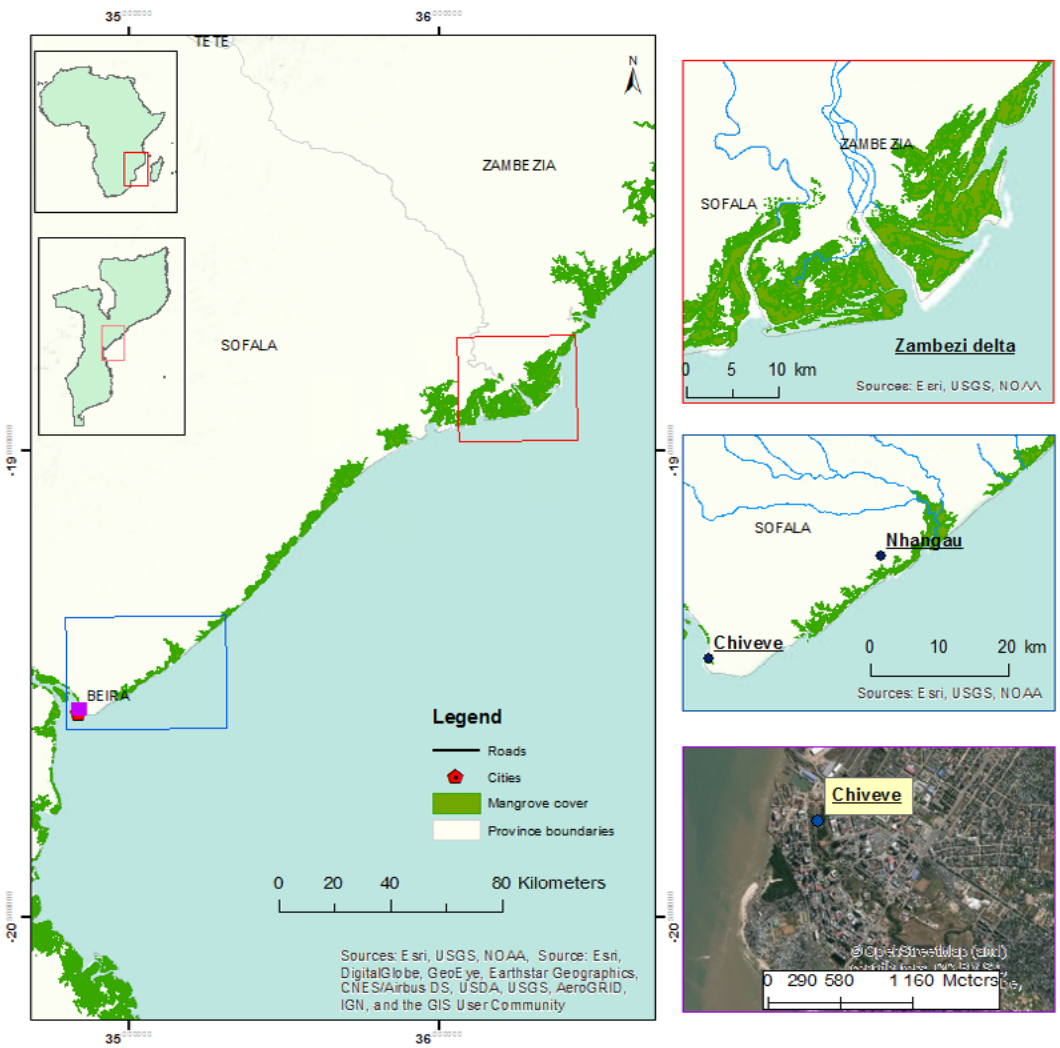

Figure 1. Study area showing the Zambezi Delta, Nhangau and Chiveve.

Methodology

In order to understand the economic benefits derived from mangrove products, semi-structured interviews where developed and tested (Schaafsma *et al.,* 2017; ter Mors *et al.,* 2013). The questionnaires contained open-ended questions to allow the participants to give more detailed information and stimulate discussion on specific issues. The intentional sampling technique (Greenbaum, 1998; Finch and Lewis, 2003) was used for identification and selection of stakeholders for the interviews. The market price assessment technique (Schaafsma *et al.*, 2017; Mojiol *et al.* 2016; Adeyemi *et al.*, 2012) was also used to support the information given by the respondents, as this technique helped to understand business practices and prices realised for mangrove wood products in the market.

Intentional sampling technique for selection of respondents

The intentional sampling technique (Greenbaum, 1998; Finch and Lewis, 2003) was used for the selection of stakeholders for the interview. The selection was based on nominations made by key informants that were interviewed at all sites (Zambezi Delta, Nhangau and Chiveve), and included local government personnel in the District Service of Economic Activities (SDAE), Provincial Directorate for Land, Environment and Rural Development (DPTADER), and local leaders.

Ecosystem services identification

Focus group discussions (FGDs) (ter Mors *et al.,* 2013) were conducted in the Zambezi Delta and Nhangau. In the Zambezi Delta a total of eight (8) communities were visited and 13 FGD were conducted, composed of 4 to 12 people per group and separated by gender (ter Mors *et al.,* 2013; Finch and Lewis, 2003; Greenbaum, 1998). A total of 91 participants were interviewed (20.9% women and 79.1% men). Individual interviews were conducted at Quelimane Town (northern arm of the Zambezi Delta and final destination for most wood products from the Delta), targeting mangrove product sellers in two different markets (Icídua and Janero markets), with the same approach being taken at the Chiveve River.

Two FGDs were conducted at Nhangau, one with 5 men and the other with 3 women, and 20 individual interviews were carried out with charcoal producers and wood cutters. Commercial mangrove cutting and charcoal production is prohibited in Mozambique, and law enforcement is greater at Nhangau. Bearing this in mind, the approach adopted facilitated the inclusion of these groups which otherwise were not willing to talk. Such apportioning of role players for the VCA follow related studies as observed in the literature (Rosales *et al.,* 2017; Tuan, 2013, Brander *et al.,* 2010; Zafar and Ahsan, 2006).

The people interviewed described the different services they extract from the mangrove forest. The three study sites were described and characterised based on site accessibility in order to help understand the willingness of the community to engage in mangrove marketing, assuming that location and means of access would be some of the main reasons considered by potential users before becoming involved in mangrove-related businesses. Such analysis has been reported elsewhere (Vishwanathan *et al.,* 2011; Brander *et al.,* 2010; Sathirathai, 1998) and is highly relevant considering the remoteness of localities such as the Zambezi Delta which has virtually no road infrastructure and low population densities (Bandeira *et al.,* 2016b).

Mangrove value chains and stakeholders in the Zambezi Delta and Nhangau

In other to understand the role and different aspects involved in mangrove-related businesses the FGDs were separated by occupation (ter Mors *et al.,* 2013; Finch and Lewis, 2003; Greenbaum, 1998); for example, people who cut mangrove poles were grouped together. The other groups were composed of transporters, sellers, and those involved in all stages from harvesting to final selling. Each FGD focused on the aspects related to the activity that they were engaged in (USAID, 2012; Borinelli and Rocha, 2006; Kaplinsky and Morris, 2001). For example, for harvesters, questions such as how they choose the species, were they go to cut, how much money they spend and for how much they sell, were asked. Based on the responses given by the respondents a value chain map was designed (Rosales *et al.,* 2017; Tuan, 2013, Brander *et al.,* 2010; Zafar and Ahsan, 2006).

Economic benefits from mangrove forests in the Zambezi Delta and Nhangau

The market price method (Adeyemi *et al.,* 2012; Brander *et al.,* 2010; Spaninks and Beukering, 1997) was used to assess the value of each product, which was established through the exchange of goods and services in the market (Carson, 2012; Splash, 2007), and the interaction between the production value (supply) and the consuming value (demand) (Adeyemi *et al.,* 2012; Spaninks and van Beukering, 1997). The market price method estimates the economic value of ecosystem products or services that are bought and sold in commercial markets (Mojiol *et al.*, 2016; Carson, 2012; Splash, 2007) and can be used to assess value changes in quantity or quality of a good or service (Adeyemi *et al.,* 2012; Borinelli and Rocha, 2006). Through the market price and data from the interviews (Rosales *et al.,* 2017; Tuan, 2013) it was possible to calculate the income generated from mangrove wood products (Bandeira *et al.,* 2016a; Bandeira *et al.,* 2016b; Macamo *et al.,* 2016b) in central Mozambique.

The income generated from mangroves was deducted from the profit that is obtained in the marketing process, which was calculated using the following formula:

Profit = Net income/Total cost

where Net income is the difference between the production value (received price * quantity) and the Total cost (includes all the necessary expenses), and includes the taxes that are paid.

Other formulas used in the process of income calculation are described below:

Production value = Received price*Quantity
Net income = Production value - Total cost
Cost/Benefit Ratio = Total cost/Production value

Quantity of poles and small poles are measured in units; fishing products in kg, and charcoal in bags.

Results

Services delivered by mangrove forests

Based on the respondents the services provided by mangrove forests in central Mozambique were divided into:

•*Direct uses (extractable wood products)* – firewood and charcoal, used for domestic consumption and poles (for house and boat construction, production of various domestic utensils, fishing traps and gear, and beehives), for either domestic or business; non-woody forest products included tree leaves used as animal fodder, honey extraction, and *Xylocarpus grannatum* is used for medicine, especially at Nhangau.

•*Indirect uses (non-extractable products)* – such as ecological services provided by mangroves as coastal protection against erosion and buffering of climatic events such as floods, as nursery areas for fauna, feeding grounds and habitat for many vertebrate and invertebrate species, biofiltering and water quality control, and carbon sequestration.

In the Zambezi Delta and Nhangau the community mentioned benefitting from both extractable wood products and non-extractable products. At the Chiveve, the communities primarily benefit from non-extractable services such their regulatory value and climate change buffering; marketing of mangrove products was negligible. Therefore, open interviews were conducted with key informants with questions being related to how the community benefit from the mangroves along the creek.

Mangrove benefits varied across the three sites as shown in Table 1.

Extractable use of mangrove products was found only in the Zambezi Delta and Nhangau. Non-extractable

Table 1. Services derived from mangrove forests in the Zambezi Delta, Nhangau and Chiveve.

Services	Uses	Location		
		Zambezi Delta	Nhangau	Chiveve
Non-extractable	Coastal protection	√	√	√
	Tide flooding control			√
	Flood control		√	√
	Water purification	√	√	√
	Landscape beauty		√	√
	Cultural and recreation assets		√	√
	Nursery ground for fisheries	√	√	√
	Fishery ground	√	√	√
Extractable	Fuelwood	√	√	
	Charcoal production	√	√	
	Wood harvesting	√	√	
	Furniture	√		
	Manufacture of canoes	√		
	Honey	√	√	
	Medicinal use		√	

uses were found in all the three sites, especially Chiveve, where these uses were the most important benefit that the community obtain from mangroves. As the mangroves in Chiveve are in the centre of Beira City (which is below sea level), they have an important role in mitigation of climate-related events, storm surges and flooding control. The Chiveve area was recently identified as a centre for development of cultural and recreation assets, environmental education and ecotourism. Due to the vulnerable nature of Beira City, alternatives to mitigate the impacts of extreme events such Cyclone Idai in 2019, the largest to hit the southern hemisphere in living memory, have again become a priority.

The three selected areas were categorized according to their characteristics (see Table 2). Willingness of community members to embark on mangrove commercialization was related to accessibility/inaccessibility to the sites. The Zambezi Delta and Nhangau are both rural areas, although with some differences. The Zambezi Delta is very remote and difficult to access, whereas Nhangau is rural but near and influenced by Beira City. Chiveve River is an urban area located within Beira.

Accessibility is roughly ranked according to six categories: proximity to a regional capital, population centre, existence of transport, road infrastructure, and access to water and electricity for each of the sites. Accessibility (or access) refers to the ease of reaching goods, services, activities and destinations, which together are called opportunities. It can be defined as the potential for interaction and exchange (Litman, 2018).

The areas were categorized into rural or urban based on the location or proximity to larger towns or municipalities. Accessibility is therefore a measure of how easy is for the community members to access the forest, which is dependent on, for example, how far it is from the community households, what transportation means they use etc. (see Table 3 below).

Species mostly harvested for wood extraction in the Zambezi Delta and Nhangau

According to key informants as well as the FGD participants, a large part of the population was engaged in mangrove harvesting, agriculture and fishing as their main activities for income generation. Although nine species of mangroves occur in Mozambique, *Avicennia marina, Bruguiera gymnorhiza, Ceriops tagal, Heritriera littoralis, Lumnitzera racemosa, Rhizophora mucronata, Sonneratia alba, Xylocarpus grannatum and Xylocarpus mullocensis,* the species chosen for harvesting varies according to the locality (see Fig. 2 below).

According to the interviewees only five mangrove species are commonly used in the Zambezi Delta with *A. marina* and *C. tagal* being most used due to their availability, followed by *X. grannatum*, *S. alba* and *R. mucronata* (see Fig. 2).

Six of the nine mangrove species that occur in the country are found at Nhangau (*A. marina, C. tagal,*

Table 2. Characteristics of the mangrove forests in the selected areas.

Location	Zambezi Delta	Nhangau	Chiveve River
	Rural	Rural	Urban
Accessibility to the community	Very remote area, difficult to access	Accessible	Accessible
Species composition	All the WIO nine species present	*A. marina, C. tagal, B. gymnorhiza, R. mucronata, S. alba and X. grannatum*	*A. marina, C. tagal and R. mucronata*
Forest trends	Increasing (see Shapiro *et al.*, 2015)	Degraded in the past. With replantation program	1/3rd of the forest degraded. Replantation program
Main Impacts	Localized erosion, also sand accretion	Human impact – deforestation for timber extraction and charcoal production	Dredged for flood control and urban planning

Table 3. Categorization of accessibility to the study areas.

Local	Proximity to a region capital city	Proximity a to population centres	Transport	Roads	Water roads	Electricity
Zambezi Delta	1	2	1	1	2	2
Nhangau	3	4	3	3	3	4
Chiveve	5	5	5	5	3	5

[1] worst | [2] below average | [3] average | [4] good | [5] very good

B. gymnorhiza, R. mucronata, S. alba and *X. grannatum*), but only four are commonly harvested in the area. *C. tagal* and *R. mucronata* are the species most commonly used followed by *A. marina* and *B. gymnorhiza* (see Fig. 2).

Use of the mangrove species by gender in the Zambezi Delta and Nhangau

In general, both men and women are involved in mangrove product use in the Zambezi Delta (Table 4), however the main products harvested vary according to gender. Because women are responsible for feeding the family, they are mostly involved in the collection of subsistence products such as firewood and small crustaceans. Men are more involved in the collection of products that will provide some cash income such as wood, poles with a larger diameter, poles with a smaller diameter commonly referred to as *laca-laca*, fish, prawns and honey. Charcoal production is mostly carried out by men, however charcoal selling involved both men and woman; nearly 50% each amongst the interviewed groups.

At Nhangau the community benefit from direct and indirect uses of mangrove products, from different types of poles from various wood sources, charcoal, to different fisheries products as well as from coastal protection, tidal flood control, nurseries for various fauna, and fishing grounds. The FGD participants reported the following main impacts of mangrove loss: drastic reduction of fisheries resources; reduction in the availability of woody resources, such as poles for house construction and charcoal production; coastal erosion; strong winds that destroyed houses, given the absence of sheltering mangroves; and heat weaves.

The different uses reported by men and women in the Zambezi Delta and Nhangau are outlined in Table 4.

In the Zambezi Delta the FGD participants mentioned that all species are used for building houses and *X. granatum* is the only multipurpose species, used for all categories mentioned. At Nhangau the key uses mentioned were fuelwood (only by women), charcoal production, construction and furniture production (by men).

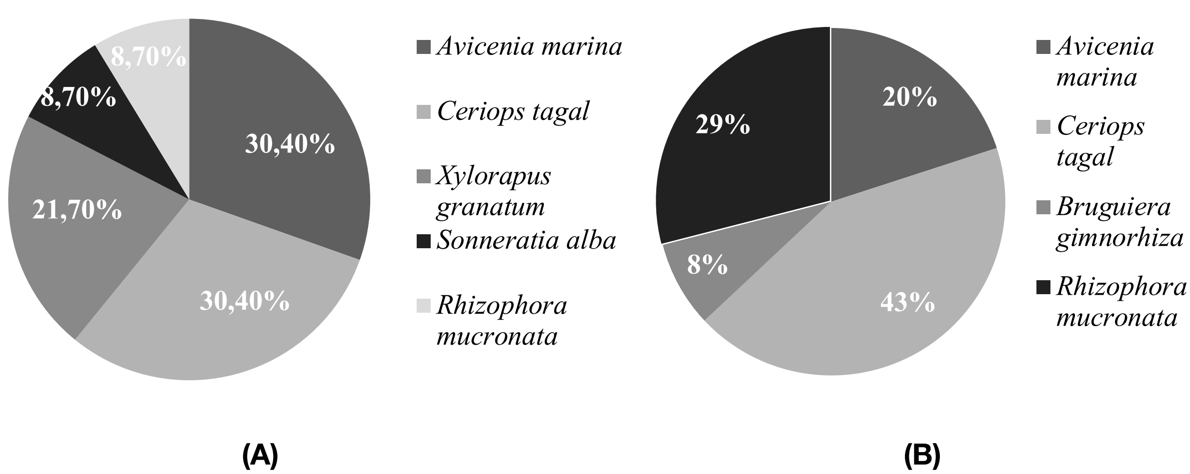

Figure 2. Mangrove species harvested in the Zambezi Delta (A) and Nhangau (B).

Table 4. Main uses of the mangrove species by gender in the Zambezi Delta and Nhangau.

Species	Zambezi Delta										Nhangau					
	Local Names	End Uses									Local Names	End uses				
		Fuelwood	Charcoal Production		Construction		Furniture		Manufacture of canoes			Fuelwood	Charcoal Production	Construction	Furniture	Medicine
		W	W	M	W	M	W	M	W	M		W	M	M	M	M/W
Avicennia marina	Muvede	√	√	√	√	√	-	-	-	-	Mpedge	√	√	√	-	-
Bruguiera gymnorhiza											Mutalatala	-	√	√	√	-
Ceriops tagal	Mucandara	√	-	-	√	√	-	-	-	-	Mucandala	-	√	√	-	-
Rhizophora mucronata	Murubulo	-	-	√	-	√	-	-	-	-	Mugorongo	-	√	√	√	-
Soneratia alba	Mpia	√	-	-	-	√	√	-	-	-						
Xylocarpus granatum	Nhantazira	√	√	√	-	√	√	√	-	√	Nhantazira	-	-	-	√	√

Use of mangroves in the Chiveve River

The mangroves at the Chiveve River (Beira City) provided a number of important non-extractable benefits to Beira City such as storm water surge flood control, tidal flooding control, water purification, aesthetic beauty, cultural and recreation assets, nursery grounds for fisheries and urban planning.

Parts of Beira City are located below sea level and are prone to inundation from either high spring tides or storm water. The Chiveve River had recently silted up reducing it to a narrow mangrove creek passage. The river was dredged in 2015 by the local authorities to make a central channel to control storm water surges and to avoid flooding at high tides. This project was welcomed by local communities given the very positive impact expected to the town. After the dredging process, mangrove seedlings where cultivated and replanted along the river. Natural regeneration was also observed to be very successful and extensive. The respondents rated the three most important benefits to their wellbeing as flood control, tidal flooding control, and water purification.

The fact that Chiveve River was dredged and restored proved to be crucial for rainwater runoff after Cyclone Idai in 2019, and is a good example of how Nature based Solutions (NbS) can be used to mitigate the impacts of extreme events and climate change, and contribute to The United Nations Sustainable Development Goals 11, 13 and 14.

Mangrove value chains and stakeholders of the Zambezi Delta and Nhangau

Based on nominations made by key informants, four groups of actors were identified within the Zambezi Delta value chain: harvesters, transporters, sellers and general users (those involved in all stages of the mangrove products value chain). Three groups of actors were identified at Nhangau, namely: harvesters, charcoal producers, and sellers.

The mangrove value chain was analysed for the Zambezi Delta and Nhangau, were different routes were followed by the mangrove wood products.

In the Zambezi Delta mangrove business activities are focused in Quelimane Town, located at the northernmost arm of the Delta, where the products that come from remote areas like Chinde (inner Delta arm) and are taken to be sold.

Quelimane Town is the last stop in the chain for mangrove products, and people travel long distances to buy and sell these products here. *A. marina and C. tagal* dominate the mangrove markets, and those interviewed rated *C. tagal* as the most preferred species due to the quality and strength of the wood. *S. alba, R. mucronata and X. grannatum* can also be found in the markets, but in lower quantities.

Depending on the route followed by mangrove products from harvesters to consumers, various actors are involved. These include transporters, wholesalers, retailers, and sometimes middlemen (see Fig. 3). The products are transported either by boat (most common in the Zambezi Delta), bicycle (common in Nhangau), motor vehicle, or by foot.

The first route for mangrove products identified was directly from harvesters to consumers, where the harvester takes the mangrove products directly to the consumer with the products transported by foot, mainly by the harvester himself.

The second route was from harvester to a primary buyer, then to secondary buyer, and finally to the consumer where both wholesaler and retailer markets are involved. The third route was from harvester to wholesaler, to retail seller and then to consumer. In the second and third routes there might be a transporter that takes the products from the harvesters to the wholesaler (mostly by boat). This is the most complex option where sometimes middlemen link the harvesters to the wholesaler and the latter to the retailer (Fig. 3 - A).

Wood products (wood, poles and *laca-laca*) are usually stored in the courtyard of the place of sale, organized by type and size of product and species. Int the Zambezi Delta, due to limited accessibility, there were few transport options for mangrove products from the production site to the marketplace. The middleman or wholesaler/retailer generally took responsibility for this. The most common means of transport observed was *bago* (slow moving wooden boat powered by an outboard engine), canoes which are manually operated, as well as by foot. In Nhangau the routes were similar to those it the Zambezi Delta (Fig. 3), although government authorities were also involved in providing technical assistance. The most common route followed by the products was from harvester to the consumer, where the harvester collects the poles (small and medium size) and sells directly to the final consumer. The charcoal value chain involves more stakeholders in the marketing process, and other routes were observed, where there might be a transporter that takes the products from the harvesters to the wholesaler (mostly by bicycle), with a middlemen sometimes linking the harvester to the wholesaler, and the latter to the retailer (Fig. 3 - B).

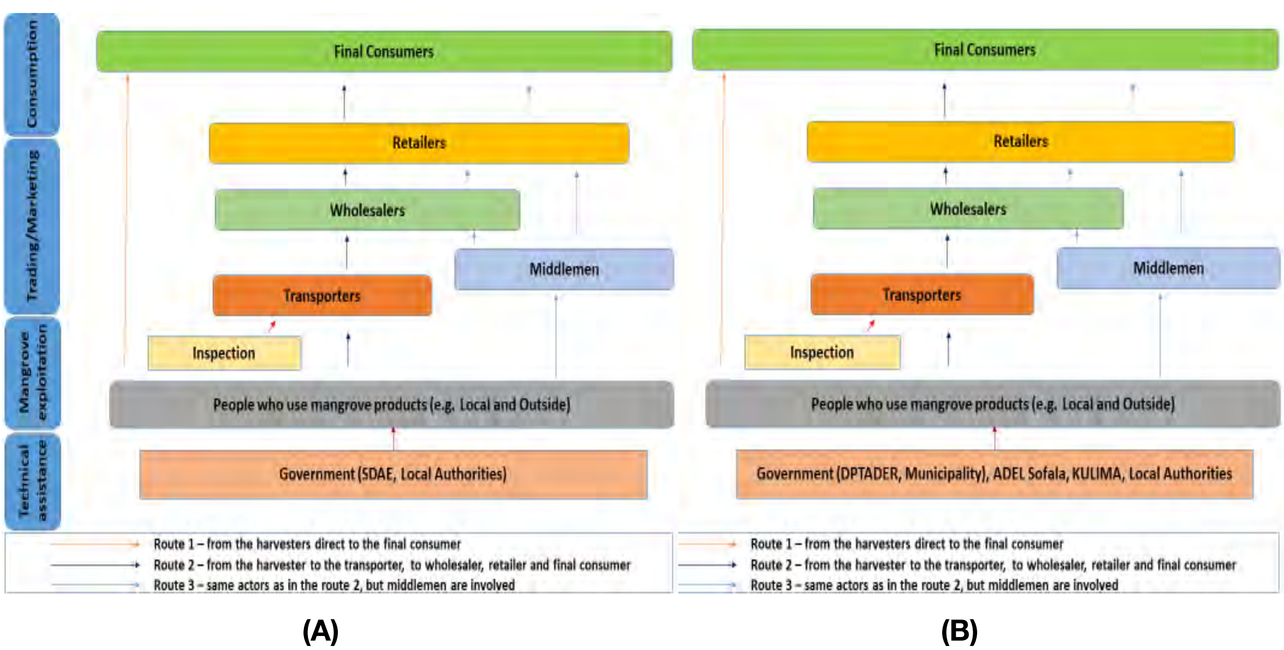

Figure 3. The value chain structure of mangrove products in the Zambezi Delta (A), where the Government is represented by SDAE (Distrital Services for Economic Activities) and Nhangau (B) where the Government is represented by DPTADER (Provincial Directorate for Land Environment and Rural Development) and the relationship between actors.

Economic benefits from mangrove forests in the Zambezi Delta and Nhangau

In the Zambezi Delta the commercialization of mangrove products plays a major role in local economies. Building materials made of large poles and *laca-laca* (small poles), charcoal, fish and prawns are all commercialized mangrove products. The price of poles varies significantly along the value chain and markets. Within the Delta the price of poles received by harvesters varies between 10 Mts (USD 0.15) to 30 Mts (USD 0.44) when sold in the local market or external market, respectively. When the poles get to Quelimane (distant external market) they are sold at two times the original price, at 60 to 75 Mts (USD 0.89 – USD 1.11).

In Nhangau, building materials such as large poles and *laca-laca*, charcoal and honey are commercialized, mostly by men. The price of mangrove wood products varies significantly along the value chain depending on the market where the product is sold. For instance, the price of poles, medium poles and small poles received by harvesters is 50 Mts (USD 0.74), 25 Mts (USD 0.37), and 15 Mts (USD 0.22), respectively.

Table 5 shows estimates of the distribution of incomes along the value chain in the Zambezi Delta and Nhangau.

Quantities of large poles collected on each occasion vary from 30 to 50 units per person while the number of small poles (*laca-laca*) harvested ranged from 50 to 75 units per person. All the FGD participants within women's groups stated that they collect firewood for their consumption.

In the Zambezi Delta charcoal is produced and sold locally. Both men and women are involved in charcoal production; however, the quantities produced vary between them (as detailed in Table 3). Table 5 shows that in the Zambezi Delta income and profits from mangrove wood extraction vary according to the product extracted. For small poles (*laca-laca)*, the income is higher at wholesaler level with 82.6% of profit accruing to them. However, for the larger poles, a greater portion of profit goes to harvesters who benefit from a share of the 125% profit. At Nhangau profits from *laca-laca* were 17%, 11.5% for medium poles, and 24% for larger poles, all accruing to the harvester. However, with charcoal, a greater portion of profits went to retailers with a share of 50 %. For honey production the producer accrued 47% of profit.

Table 5. Estimated distribution of income along the mangrove products value chain in the Zambezi Delta and Nhangau. 1 USD = 67.27 Meticais (Mozambican currency).

Item	Zambezi Delta						Nhangau						
	Poles			Small Poles			Charcoal	Poles	Medium poles	Small poles	Charcoal		
	Harvester	Wholesaler	Retailer	Harvester	Wholesaler	Retailer	Producer	Harvesters	Harvesters	Harvesters	Harvesters	Wholesaler	Retailer
Received Price (Mt)	30	60	75	10	35	45	130	50	25	15	200	250	850
Quantity[1]	75	75	75	120	120	120	20	50	50	120	10	3	3
Total cost (Mt)	1000	2675	4700	1000	2300	4400	1400	100	100	100	100	50	50
Production value[2] (Mt)	2250	4500	5625	1200	4200	5400	2600	2500	1250	1800	2000	750	2550
Net income[3] (Mt)	1250	1825	925	200	1900	1840	1200	2400	1150	1700	1900	700	2500
Cost/Benefit[4] (%)	44.4	59.4	83.6	83.3	54.8	81.5	53.8	0.04	0.08	0.06	0.05	0.07	0.02
Profit[5] (%)	125	68.2	19.7	20	82.6	22.7	85.7	24	11.5	17	19	14	50

The unit used for poles and small poles is numeric, and bags for charcoal | [2] Production value = Received price*Quantity | [3] Net income=Production value-Total cost | [4] Cost/Benefit Ratio= Total cost/Production Value | [5] Profit=Net income/Total cost

Discussion

Mangrove ecosystems are widely used in Eastern Africa (Bosire *et al.,* 2016a) and represent a critical and irreplaceable habitat for coastal communities (UNEP, 2014; Giri *et al.,* 2011). It is estimated that over 150,000 people in Rufiji Delta (Tanzania) alone earn their living directly from mangrove resources (Mangora *et al.,* 2016), which are widely used for firewood, building material (Mainoya *et al.,* 1986), medicine (Mangora *et al.,* 2016), tannin extraction from Rhizophoraceae species (Gupta and Roy, 2012), nursery grounds for fisheries (Masalu, 2003; McNally *et al.,* 2011), and honey production (Karengi, 2012).

Hoegh-Guldberg *et al.* (2015) rated mangroves as providing ecosystem services valued at USD 57,000 per ha/year in South – East Asian mangroves. In Mozambique it is estimated that mangroves contain 500 – 2000 poles per hectare (Bandeira and Paula, 2014; Paula *et al.,* 2014, Bandeira *et al.,* 2009, Nicolau *et al.,* 2017, Macamo *et al.,* 2018) and this study estimates that one mangrove pole is sold for 1 – 1.2 USD. Based on this assumption it is anticipated mangrove poles in Mozambique have a minimum value of USD 2 400 per hectare, excluding other wood and non-wood products, such as fisheries.

The Zambezi Delta harbours one of the largest mangrove forests in Africa, spanning some 200 km of coastline (Barbosa *et al.,* 2001). If exploited, it has been estimated that the inner Delta area of 37034 ha would yield both direct (timber, poles, firewood and charcoal) and indirect (regulating and climatic function) use value of USD 2 772 per ha/year (WWF, 2017). This amount is similar to that estimated in this study of USD 2 400 ha/year, however it may not be realistic to calculate the potential of harvesting the entire mangrove forest given the remoteness of the area which lacks road/transport infrastructure, has a low demand for mangrove products and low population densities.

At the Chiveve River non-extractable uses are predominant, as acknowledged by the community, through the ecological benefits of the river such as in flood control. The river runs through the city for around 3 km and plays a key role in reducing the impacts of floods and protecting the city infrastructure (e.g. buildings, roads), a function of particular importance in a city like Beira which, with an altitude below sea level, is rated as highly vulnerable to sea level rise and floods (INGC, 2012). In this context, the river was dredged in 2015 since silting was negatively affecting the delivery of this function. During the recent Cyclone Idai in 2019, the Chiveve River and other constructed drainage systems helped the city by buffering floods and storm water, protecting people and infrastructure (Charrua *et al.,* 2020). Cyclone Idai was one of largest to hit the southern hemisphere and left a trail of massive destruction and over 1000 dead in several southern African countries (Devi, 2019).

Additionally, the community confirmed that they did not extract wood products within the Chiveve River because the forest is relatively under-developed in terms of size, structure of the plants as well as species composition. Other well-developed mangrove forests near Beira (such as Nhangau) produce wood products with market value. These results are supported by a previous study by Uacane and Ombe (2016) in the same area, and in Kenya by Kairo *et al.* (2009) and Bosire *et al.* (2016b), who also reported valuable non-extractable uses in Gazi Bay. In this area, mangroves were found to be valuable assets for the purpose of ecotourism and recreation. Tourism around mangrove ecosystems is an area with great potential for development in Mozambique, and it can also be paired with conservation objectives, while providing livelihoods for communities.

The Nhangau area has a history of intensive, non-sustainable exploitation of mangrove woody resources dating back to the 1990s when former soldiers were demobilized (after the civil war ended in 1991) and had to rely on mangroves for livelihoods. A large part of the population engaged in mangrove harvesting resulting in uncontrolled exploitation that led to rapid deforestation and degradation of the mangroves, with social and ecological impacts. This community is now engaged in mangrove rehabilitation (Bandeira *et al.,* 2016a), but financial constraints are hindering the implementation of other management measures. Exploring mangrove tourism or financial compensation for other mangrove-related environmental services could provide alternative income to support conservation and management activities.

This study mapped the value chain for mangrove wood products in central Mozambique; commonly carried out to analyse the value of a resource (Brander *et al.,* 2010; Rosales *et al.,* 2017). These studies usually map the routes followed by a particular resource until the final consumer (Lowitt *et al.,* 2015; Kaplinsky, 2000). Studying the chain may show why pressure on natural resources can lead to degradation (Macamo *et al.,* 2018; Macamo *et al.,* 2016a) and unsustainable exploitation (Masalu, 2003), and can show how the "values" attached to each part of the chain are distributed (Thyresson *et al.,* 2013; Zafar and Ahsan, 2006; Sathirathai, 1998). Similar studies in different locations such as Asia (Hoegh-Guldberg *et al.* 2015, Tuan, 2013), Kenya (Huxham *et al.,* 2015) and Gambia (Njie, 2011) showed that natural resources such as mangroves can have a value chain at local level (O´Neill and Crona, 2017; Kaplinsky, 2000) as well as provide potential for regional international marketing (Crona *et al.,* 2016; Purcell *et al.,* 2017).

In the Zambezi Delta three routes were present, and when the route is more complex, such as where middlemen are involved, the product reaches as far as Quelimane Town (northern part of the Delta) where formal markets for mangrove products are well established. In Nhangau charcoal is the product that involves most stakeholders in the marketing process, and this explains how this product reaches formal markets such as in Beira City. Usually the longer chains are related to products with higher demand, and under higher exploitation pressure. These products also tend to be more expensive at the final destination.

In the Zambezi Delta and Nhangau a greater portion of profits went to the harvesters because they invest very little besides time into the activity, and obtain money by selling the products. However, this scenario can be controversial because the harvester receives the least income in the chain, with the price increasing by more than 100% in the next level (wholesale or retail). A pole that costs 30 Mts (USD 0.44) at the harvester level costs 60 Mts (USD 0.89) at the wholesale level, and the wholesaler usually obtains products from more than one harvester. For charcoal, a greater portion of profits went to retailers. This can be explained by the fact that the retailer byes the charcoal in bulk and has the option of selling bags individually or in small lots. In this scenario a bag of charcoal that initially costs 200 Mts (USD 2.96) at the harvester level, increases to 850 Mts (USD 12.57) at the retailer level.

Studies document that the income distribution (Kaplinsky and Morris, 2001; Kaplinsky, 2000) along the value chain is usually unequal (Wamukota *et al.,* 2004). The profits are widely different for different actors (Rosales *et al.,* 2017) contributing in the willingness of people to engage in mangrove marketing (UNEP, 2014; Vegh *et al.,* 2014) and in various parts of the complex value chain (Lowitt *et al.,* 2015; Adeyemi *et al.,* 2012).

As observed in the study areas, women benefit least monetarily from mangrove wood products (Kaplinsky, 2000; Kaplinsky and Morris, 2001; Adeyemi *et al.,* 2012). Both in the Zambezi Delta and Nhangau, women are mostly involved in fuelwood harvesting, and this activity is mainly for personal domestic use. Although the women do not harvest firewood for commercial purposes they benefit from the existing value (Brander *et al.,* 2010) were the money that could be spent to buy firewood is kept and used for another purpose in the household. In Quelimane Town, a few cases were found of women being engaged in commercial activities around mangrove wood products at the retail level in formal markets. This included a particular case of one woman well-known for doing a *"man's job"* by selling mangrove wood products.

The information regarding distribution of income according to gender can be important for decision making when targeting the issue of gender equity in the distribution of economic resources, as well as the empowerment of women around the use of natural resources. This is a global discussion, and is captured in Sustainable Development Goal 5 that focuses on the empowerment of women and gender equity in the use of natural resources. At a national level, Mozambican law is being developed taking the empowerment of women into consideration.

Mangrove ecosystems were initially perceived as wastelands (Kathiresan and Bingham, 2001), but in recent decades studies on mangrove forests (FAO, 2007; Giri *et al.,* 2011) have shown that they play an important role in providing a myriad of ecosystem goods and services (Donato *et al.,* 2011; Taylor *et al.,* 2003; Walters *et al.,* 2008), and contribute significantly to incomes (Lowitt *et al.,* 2015; Kaplinsky, 2000; Sathirathai, 1998).

Valuation of mangroves may encompass concepts such as Payment for Ecosystem Services (Engel *et al.,* 2008; Brander *et al.,* 2010; Taylor *et al.,* 2003) and global capital schemes known as REDD+ (Donato *et al.,* 2011; UNEP, 2014); such market schemes play an important role in conservation of biodiversity and maintenance of mangroves ecosystem services (Lee *et al.,* 2014; Engel *et al.,* 2008; Adeel and Pomeroy, 2002). Recent studies have used monetary valuation for environmental decision making for ecosystem management (Schaafsma *et al.,* 2017) and for design of polices for Payment for Ecosystem Services or other pricing mechanisms (Bouma and Van Beukering, 2015). The use of these tools has been criticized widely because of a lack of appropriate survey design (Kallis *et al.,* 2013; Splash, 2007) and according to some researchers can be improved (Carson, 2012; Loomis, 2011, Vossler and Watson, 2013).

Management of mangrove forests is essential as there is evidence of mangrove depletion in Moazambique (Macamo *et al.,* 2016b; de Boer, 2002). The current study provides information on the importance of mangrove products to the community (Kathiresan and Bingham, 2001; Cohen *et al.,* 2013; UNEP, 2014) and the people involved in their exploitation (Walters *et al.,* 2008; Taylor *et al.,* 2003), and can be used for better management of the resource (Lee *et al.,* 2014; Chevallier, 2013; Kairo *et al.,* 2009; Adeel and Pomeroy, 2002). This information can also be used to identify ways to improve the performance of value chains and the wellbeing of participants in the chain (Kaplinsky and Morris, 2001; Kaplinsky, 2000).

Mangrove sustainability in Chiveve/Beira City, where regulatory and climate value is dominant, will rely on active stakeholder engagement and sensitization. Furthermore, future studies need to attempt to identify and calculate the value of assets and infrastructure saved from destruction during extreme climate events such as in Beira during Cyclone Idai. Many studies have involved concerted public awareness (e.g. for Beira, those mediated by Beira Municipality, Government, NGOs, communities and research institutions), participation and engagement (Mojiol *et al.,* 2016; Olaleye and Omokhua, 2012) on best practices for mangrove protection and management as a way forward. This was also evident in the mega delta of Myanmar after a climate event in 2008 (Aung *et al.,* 2013). Mangrove harvesting management as observed in other parts of eastern Africa (Bosire *et al.,* 2016b; Lowitt *et al.,* 2015, Adeel and Pomeroy, 2002), coupled with strong community participation, is desirable for areas were direct wood extraction occurs, such as in the Zambezi Delta and Nhangau (Hulusjo, 2013; Tuan, 2013; Sathirathai, 1998). Furthermore, given the relatively successful mangrove restoration efforts in Nhangau (Macamo *et al.,* 2018), a REDD+ payment for ecosystem services initiative, as has been implemented in Gazi Bay, Kenya (Bosire *et al* (2016b; Kairo *et al.,* 2009), could be considered. This would require appropriate science and community issues to be properly addressed (Lopes and Videira, 2019). Global processes, especially those around achieving Sustainable Development Goal 14, offer opportunities for mainstreaming mangrove management and conservation with direct collaboration of key actors, including communities. The recent approval of the Mozambique Mangrove Management Strategy (2020-2024) represents an added opportunity for mainstreaming mangrove sustainability, and to emulate success stories from elsewhere in the WIO (Bosire *et al.,* 2016b; Kairo *et al.,* 2009) and in places such as the Philippines (Pulhin *et al.,* 2017) and the Indian sub-continent (Iftekhar, 2008)

Conclusion

This study highlighted the value chain associated with mangrove forests in central Mozambique, eastern Africa. Extractable use value was documented for the Zambezi Delta and Nhangau, focusing on timber for poles and charcoal production. The non-extractable value of mangroves is vital for Chiveve, which is located in low-lying Beira City, the second largest city in Mozambique, and highlights the role of mangroves in flood and storm water control, and also for carbon sequestration and as nursery grounds for fisheries, water purification, urban landscaping and as a space for cultural and recreation activities. Value chains are described, with the impacts of different locations and stakeholder involvement (harvesters, transporters, wholesalers, retailers and middlemen) on price, revenues and distribution of incomes clarified.

These results showed that goods and services provided by mangroves in Mozambique are important for the community, who benefit both directly and indirectly. This study estimated a minimum conservative mangrove value of USD 2 400 per ha/year. Such calculations of the economic value of ecosystem goods and services is increasingly being recognized as a necessary metric for integrated environmental decision-making towards mangrove sustainability and conservation.

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The role of indigenous knowledge in the management of marine resources: a case study of Kuruwitu and Mkunguni fishing areas in Kenya

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Abstract

Indigenous knowledge (IK) in the management of natural resources, and especially marine resources, has received increasing attention in recent years. The use of IK is due to its extensive contribution to the management of local resources and the spiritual, cultural and economic well-being of local communities. This study aimed to identify the existing types of IK and practices used in the management of marine resources. The study was conducted through a descriptive survey design using semi-structured questionnaires, Key Informant Interviews, field observations and Focus Group Discussions. The results revealed that the community relied on IK for weather forecasting to plan for fishing activities which subsequently regulated marine resource exploitation. The use of IK in the location of marine fish species and favourable conditions enables the fishers to understand the factors driving fish catches within these ecosystems. IK of sustainable resource-use allows the fishers to devise environmentally friendly fishing gears and reduce the use of deleterious fishing methods. Pearson's Chi-squared test was performed on selected variables that influenced the possession of IK among the residents in the two study areas. The Chi-square test revealed a significant association between IK and meetings ($p= 5.524e-09$), and IK and age ($p=0.023$), while IK and education level were not significant ($p=0.712$). The study recommends the development of conservation strategies that include IK for the management of marine resources at the local level, including consideration of all socio-economic factors.

Keywords: Indigenous knowledge, management, marine resources, livelihood, fishers

Introduction

Indigenous knowledge is a systematic body of knowledge assimilated by people through gathering experiences over time, and includes a good understanding of the environment in a given culture (Mazzochi, 2006; Abah *et al.,* 2015). This form of knowledge is in the hands of local institutions that play a crucial role in natural resource management by defining practices, assigning tasks and guiding interactions of people on issues related to resource-use (Masalu *et al.,* 2010). IK in conservation biology is often expressed in the form of customs, beliefs and taboos (Cinner, 2007; Maina, 2012). Some studies (Cinner, 2007; Rim-Rukeh *et al.,* 2013; Rocliffe *et al.,* 2014) have demonstrated the usefulness of indigenous knowledge in determining fish stocks and spawning grounds, regulating resource-use and the associated traditions. Based on this understanding, indigenous knowledge forms a rich cultural heritage that is complex and dynamic among communities (Kajembe *et al.,* 2000).

On the coast of Belize, for example, biologists used local fishers who have lived in that area since the 1920s to identify spawning sites for snappers and explain the snapper's relationship with whale sharks (Heyman *et al.,* 2001). In Madagascar, the Malagasy use taboos to regulate resource-use within and adjacent to all of the national marine parks (Cinner, 2007). Along the Kenyan coast, sacred forests (*kayas)* typify cases of the use of IK and culture in natural resource management (Wangila and Shauri, 2009). IK is still widely applied by many local communities in the management of marine resources in Kenya (Mcclanahan *et al.,* 1997; Ochiewo, 2004; Maina, 2012). The fishing communities

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in Kuruwitu on the north coast and Mkunguni on the south coast of Kenya have utilized coastal and marine resources for many years. As a result, the residents have developed a sound understanding of the natural processes regulating these resources.

The application of indigenous knowledge in the management of natural resources has, however, not been well documented in Mkunguni and Kuruwitu, two key fishing areas along the coast. There is a need for continuous documentation of IK and identification of its usefulness in the sustainable management of coastal and marine resources. The biggest challenge emanates from the fact that such crucial knowledge may not always be successfully applied to the sustainable use and management of marine resources alongside scientific knowledge. Documenting this IK will create a database for reference in the future when the older generation who are custodians of this knowledge are no longer present.

Materials and methods

Study sites

Kuruwitu fishing area

Kuruwitu is in Kilifi County on the north coast Kenya, some 27 km south of Kilifi town, off the Kilifi-Mombasa highway (Fig. 1). It covers an area of 56 km^2 with 774 households of 5-6 persons (KNBS, 2010). Kuruwitu is endowed with various marine resources such as mangroves, fish, sea turtles and coral reefs. Kuruwitu Conservation and Welfare Association (KCWA) is a community-based organization (CBO) focused on environmental and marine conservation in Kuruwitu and its environs. The CBO operates in the six landing sites of Vipingo, Kuruwitu, Kijangwani, Kinuni, Bureni and Mwanamia (KCWA, 2010; Abunge, 2011).

The communities living in the area are of mixed ethnicity; however, the Giriama and the Chonyi ethnic groups from the Mijikenda community are the majority (Cinner *et al.,* 2009). Community livelihoods in the area are heavily dependent on natural resources, and include fishing, peasant farming, tour guiding and trading, with some of the residents employed as casual labourers in the Vipingo sisal plantation on the mainland side of the Kuruwitu coast (KCWA, 2010).

Mkunguni fishing area

Mkunguni area is in Msambweni sub-County on the south coast of Kenya (Fig. 1). The area has 687 households with an average household size of 6-7 persons (CRA, 2012). Like Kuruwitu in the north, the area is endowed with numerous marine resources including mangrove forests, finfish, shellfish and sea turtles. There is a local CBO also focused on marine conservation (Msambweni Turtle Conservation Group (MTCG)). The CBO covers the four fish landing sites of Mwaembe, Mkunguni, Mwandamo and Munje (Tondwe *et al.,* 2015). The main tribe dominating the community in the Mkunguni area is the Digo, a subtribe of the Mijikenda community (Lehmann and Kioko, 2005). The majority of the Digo people adhere strictly to traditional practices (Mcclanahan *et al.,* 1997). Fishing is the dominant income-generating activity in the area, while crop farming, trading and tourism-related activities also provide substantial support to community livelihoods (Tondwe *et al.*, 2015).

Data collection, analysis and statistical tests

Kuruwitu area was purposively selected as it presents one of the pioneer locally managed marine areas (LMMA) in Kenya. The Mkunguni area has minimal conservation initiatives except for the sea turtle conservation group (MTTG) and was therefore selected as a non-conservation area for comparison with the LMMA in Kuruwitu. Purposive sampling was used to identify the village elders and enderly fishers in the areas. The village elders and elderly fishers were assumed to be rich sources of IK for inclusion as key informants. Simple random sampling was used to select the households interviewed. All households in each study area were given numbers and the Stat Trek's Random-Number Generator was then used to pick the selected samples from the total household data.

A semi-structured interview using questionnaires was administered to the household heads of 181 households in the two areas (99 in Kuruwitu and 82 in Mkunguni). The sample size was selected using the formula adopted from Ross (2002). Three key informant interviews were conducted per area. Key informants included Beach Management Unit (BMU) leaders and elders from the areas. One focus group discussion (FGD) involving members of the conservation groups, fishers and other residents involved in the exploitation of marine resources were conducted in each area. The FGDs comprised a maximum of 6-10 persons per session, with the majority of the groups having approximately 9 members. The participants were selected on the basis of their knowledge, active participation and experience on issues captured in the thematic areas of this study. Observations were used on various occasions, for example, in the identification of local fishing gears, gear assembling, and other related activities, to gain a greater understanding of existing knowledge.

Quantitative raw data collected was coded and entered into MS Excel®, then analyzed descriptively. Open-ended question and interview data were sorted into themes and any interview inconsistencies and unique statements noted and given particular attention in the analysis. An index of IK was generated from the questionnaire on questions that asked about knowledge related to the management of marine resources. A score was given if the answer fully matched the consensus responses obtained in the focus groups and the key informant interviews (Iniesta-Arandia *et al.*, 2015).

Further analyses using Chi-square tests were conducted to determine the significance of the views of surveyed respondents across the two areas using R. Additionally, a Pearson's Chi-squared test was performed on some variables that might have an effect on the possession of indigenous knowledge in the management of marine resources. The Chi-square test evaluates whether there is a significant association between the categories of the two variables. The null hypothesis was rejected if the p-value was less than the predetermined significance level of 0.05.
H0: The two variables are independent
H1: The two variables relate to each other.

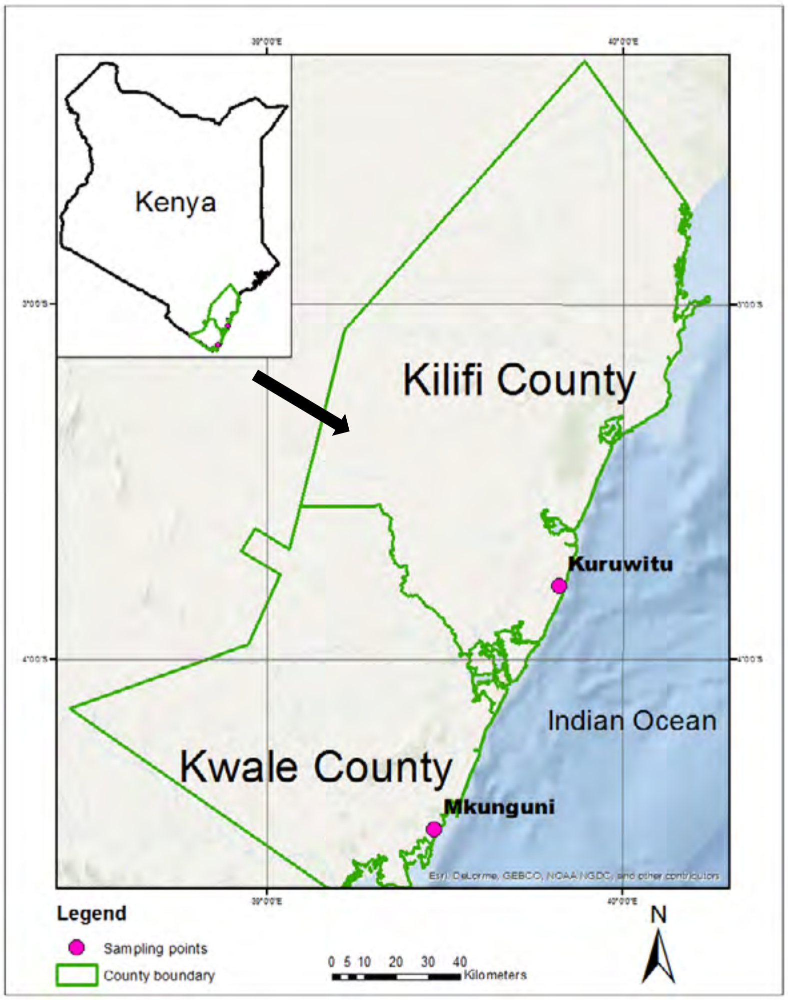

Figure 1. Map of Kenya (inset) showing the location of the study sites of Kuruwitu (north coast) and Mkunguni (south coast).

In the case of a null hypothesis, the chi-squared test is used to assess the two independent variables.

Results

Results of the Pearson's Chi-square test revealed a significant difference between the two variables of

Table 1. Socio-economic characteristics of respondents.

Socio Economic Factors	Kuruwitu		Mkunguni	
	Participants (n)	Proportion (%)	Participants (n)	Proportion (%)
Age Distribution by Fishing Area				
10-17	-	-	2.0	2.4
18-30	17.0	17.2	26.0	31.7
31-40	35.0	35.4	16.0	19.5
41-50	26.0	26.3	16.0	19.5
51-60	12.0	12.1	9.0	11.0
60+	9.0	9.1	13.0	15.9
Household Size by Fishing Village				
1-4	13.0	13.1	24.0	29.3
5-8	55.0	55.6	35.0	42.7
9-13	28.0	28.3	22.0	26.8
14-17	3.0	3.0	1.0	1.2
Highest Level of Education by Fishing Area				
None	32.0	32.3	20.0	24.4
Primary	47.0	47.5	16.0	19.5
Secondary	12.0	12.1	7.0	8.5
Vocational	6.0	6.1	9.0	11.0
Madrassa	2.0	2.0	30.0	36.6

indigenous knowledge and attendance in conservation meetings, and obtained the output χ^2= 44.313, df = 2, p=5.524e-09, indicating a very high relationship between both variables. A significance difference was also found between indigenous knowledge and age of the respondents (χ^2 = 13.017, df = 5), p=0.023). The Chi-square test on the variables of indigenous knowledge and education level obtained the output χ^2= 2.1294, df = 4, p=0.712, implying that there is no relationship between these variables.

Based on the results of the FGDs in the two areas, resource users had a similar understanding of the weather conditions and state of the sea, and its relation to marine resource access and use. For instance, the loud sound of waves splashing on the reef was an indication of impending rains and the beginning of a rough-sea period, often associated with the strong South-East Monsoon winds (SEM or *Kusi*). The resource users exercised extra precaution in their fishing activities at these times, often restricting fishing to the in-shore areas and around the reef entrance (*mlango*). This may also be partly attributed to the lack of mechanized boats capable of withstanding rough weather during the SEM period, as observed during the field survey in both fishing areas.

The resource users in both areas were conversant with the 14-day lunar cycle (cycle of the moon) which is locally referred to as *bamvua*, meaning "dead waters". The "dead waters" simply refers to the calm waters with lower tidal surges mainly aligned to the period when there is a change from spring to neap tides, or neap tides to spring tides. This period, especially for some days after the highest spring tide, present the best fishing conditions for the fishermen. In addition, fishers who used certain fishing gears, for instance, bottom-lines targeting big game fish, preferred night fishing to day fishing due to the state of the sea. After this period, the next 14-day cycle of the moon would begin with the next phase of spring tides (*mwezi-giza*) (Table 2).

Table 2. Phases of the moon and resultant influence on fishing activities in Kuruwitu and Mkunguni fishing areas in Kenya.

Phases of the moon	Tides	Tides in Kiswahili/ local name	Activities
New moon or Full moon (*mwezi mchanga /giza*)	– high tides: tides rise to highest water-mark, sea is rough – low tides: very low watermark	*Bamvua la uvuvi*	Line fishers (bottom and pelagic) targeting big fish prefer night to day time-fishing
Half-bright moon (mwezi umeandama)	High and Low tides almost the same	*Bamvua la maji-mafu*	Fishing at all times

Indigenous knowledge in the location of fish species and habitats

From the FGDs, the fishers grouped the different fish species into three major categories, with examples (Table 3); Category-1, small fish which they noted were abundant in the inshore areas, mostly within the seagrass beds, continental shelf and caves; Category-2 comprised the decapod crustacean species such as lobsters as well as cephalopods including octopus, where the resource users clearly indicated that the fishing grounds for these species were mostly located within the coral reefs and around caves where the species are found to feed on organisms including juveniles of other fish; Category-3 comprised the big fish mostly found off-shore feeding on small fish and other marine species.

Further, the fishers reported that they were able to easily identify migratory behaviours of some sea birds such as the white stork *Ciconia ciconia* (*korongo*

Table 3. Knowledge of fish species and their habitats in Kuruwitu and Mkunguni areas in Kenya.

Target Species	Swahili name	Habitats / areas found
Small fish species:		
Snapper	Changu/Tangu	Inshore, mostly around corals, caves and seagrass (*Bahari ya ndani sana sana hujificha kwenye matumbawe, mapango na chani*)
Parrot fish	Pono	
Rabbit fish	Tafi/Tasi	
Goat fish	Mkundaji	
Mullets	Mkizi	
Crustacean species:		
Lobster	Kamba mawe	In-shore in corals and caves (*Bahari ya ndani kwenye matumbawe na mapango*)
Shrimps	Kamba	
Octopus	Pweza	
Big fish species:		
Shark		Mostly found offshore (*Mara nyingi hupatikana katika bahari kuu/kubwa*)
Sail fish		
Queen fish		
Tuna		

mweupe) and the African fish eagle *Haliaeetus vocifer* (*mwewe*), and associate these with the location of good fishing grounds for certain species of fish.

Indigenous Knowledge in seasonality of marine resources

About 14.6% of the respondents in the Mkunguni area stated that the fish species mentioned were caught seasonally, compared to 4% of the respondents in Kuruwitu area who held the same view (Fig. 1 and 2). Thus the majority (96%) of the respondents in Kuruwitu area held the view that the fish species mentioned were caught throughout the year, compared to 84.5% in Mkunguni area. Fifty eight percent of the respondents in the Mkunguni area indicated that the occurrence of sea birds in the area was seasonal compared to 51% of the respondents in Kuruwitu area who held the same opinion. However, about 7% of the respondents in Kuruwitu area compared to 3% in Mkunguni area were not aware whether sea birds were seasonal or occurred throughout the year. Tests to establish if there were any significant differences in the awareness level of the availability of marine resources in the two areas revealed that there was no significant relationship at χ^2=1.675; df=2; p=0.196. The implication of this finding is that there was a high level of awareness of the availability of different marine resources in different seasons of the year in both Kuruwitu and Mkunguni.

According to the FGDs, tuna is one of the most preferred fish by the local communities in both Kuruwitu and Mkunguni. This is because they are easily caught by a variety of gears from hand lines, long lines, gill nets and drift nets. The tunas also have fewer intramuscular bones and are thus easily acceptable to wider range of family members including children. The respondents also indicted that tunas are also larger than most species hence when a fisher catches 1-2 tunas, the effort used is lower and the returns are higher than from other species. The participants noted that although the tunas may be caught all year round, they were more abundant during August through to December. The resource users also consider tuna as an indicator of the presence of smaller fishes, which comprise the food for the tunas as well as some target species for the small-scale fishers.

Surprisingly, from the FGDs, the resource users appeared to very knowledgeable on sea urchin– sea grass predation dynamics, the effect of the parrotfishes

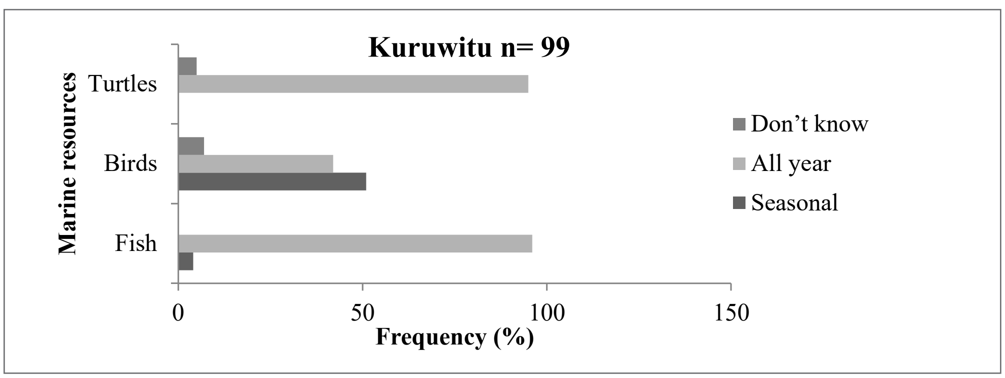

Figure 2. Availability of marine resources in Kuruwitu Village in Kenya.

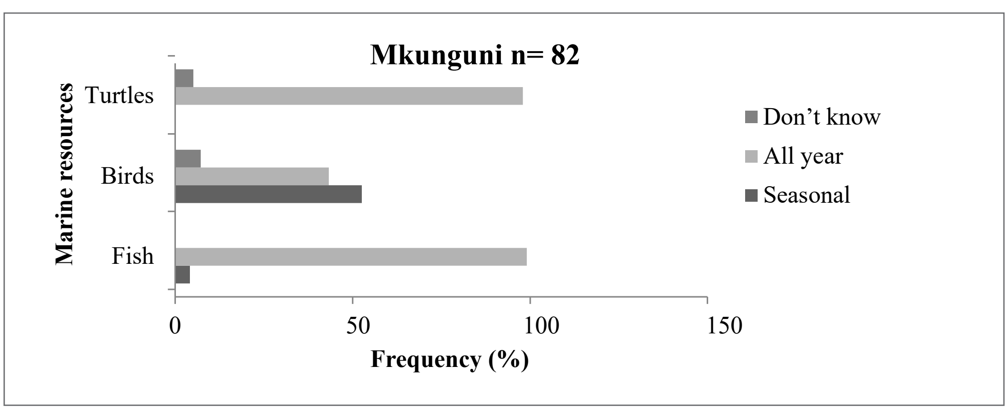

Figure 3. Availability of marine resources in Mkunguni Village in Kenya.

on seagrass populations, and the implications of sea urchin population explosions on the landings of fish from a fishery.

Indigenous knowledge on sustainable resource use

Field observation revealed that traditional fishing gears such as basket traps (*malema*) were made using different materials; for example, some fishers in the Mkunguni area used bamboo, others used metal rods, while others blended the two materials in making the traps (Fig. 4). Results of the FGDs indicated that the use of bamboo in making basket traps has greatly declined due to reduced availability of bamboo plants in the Mkunguni area. Therefore, some fishers have resorted to using wire mesh and other artificial materials, indicating an inherent knowledge among the resource users in seeking innovative alternative materials for use in making the *malema*. In addition, the respondents preferred *malema* made of wire mesh because they were more durable than bamboo that wore out quickly after contacting water when fishing.

Indigenous Knowledge in environmentaly friendly fishing methods

Field observation showed that most of the fishers in the Kuruwitu area preferred the use of spear guns while the traditional basket traps were more prevalent in the Mkunguni area (Fig. 4). Other types of fishing gears used in the two areas included hand lines and various types of nets such as gillnets, driftnets and monofilament nets. FGDs revealed that the traditionally fabricated fishing gears were more acceptable to the local community and categorized as "easy to operate".

Traditional fishing gears are known to harvest small quantities of fish compared to modern fishing gears such as trawlers and ring nets. The fisher communities in the study area demonstrated a good knowledge of fishing gear operation and the limitations of the various gears. The respondents in both sites reported that fishing nets with small mesh size were prohibited due to the possibility of catching small fish, which may eventually exhaust the "fish stocks" in the area. The spear gun fishing gear is used selectively, even in

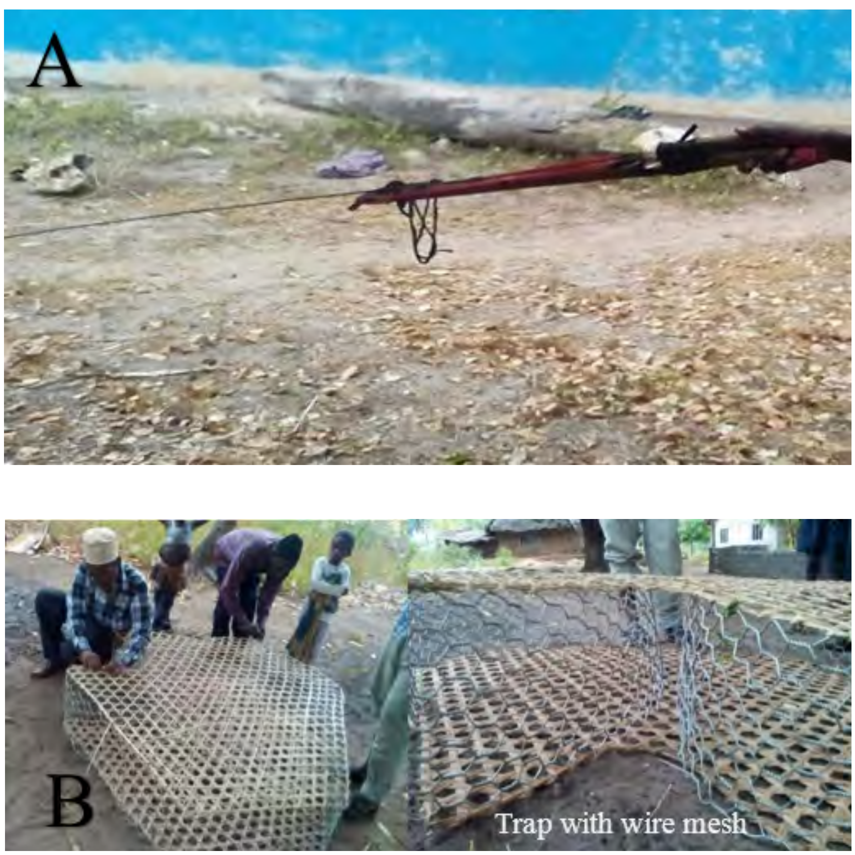

Figure 4. (A) Spear gun used in Kuruwitu fishing area, Kenya;
(B) Fishermen from Mkunguni fabricating a basket trap (*Malema*) blending both the traditional reeds and wire mesh.

the Kuruwitu area, taking care not to injure fish which were not caught or escaped the gear.

The fishers also operated different fishing gear types during different seasons of the year. For example, in the Mkunguni area, the fishers indicated that it was forbidden to use gillnets within the reefs during the SEM season (*kusi*) since it is rough and challenging to operate gillnets. It was also observed that different types of line fishing gear (hand lines, drop lines, bottom lines, as well as pelagic lines) were the preferred fishing methods for demersal (bottom) species in the shallow inshore areas, especially during rough/stormy weather.

Further, the respondents reported that the use of beach-seines and ring nets in coral reef systems was a forbidden fishing method because it destroyed corals reefs which act as fish habitats and the associated polyps which act as sources of food for certain species of fish. According to the FGDs, fishers in Mkunguni reported that they have resorted to the use of elders who use religious teachings and their wisdom to enforce the regulations. In Kuruwitu, the elders and BMU leaders were regulating the prohibitions.

Indigenous Knowledge of ecosystem degradation and pollution

The awareness level of respondents of different causes of pollution and degradation of the marine ecosystems was gauged using a presence/absence (yes/no) score, as shown in Figs. 5 and 6. Based on the analysis, 72% of the respondents in Kuruwitu area expressed their feeling that quarrying was a major cause of pollution in the area, compared to only 7% in the Mkunguni area. This may be attributed to the presence of a cement factory in the Vipingo area of Kuruwitu, as well as smaller private quarries which produce noise pollution, as well as limestone dust, which the fishers felt was impacting adversely on the fishing grounds. Further, a key informant in Kuruwitu reported increasing incidences of marine pollution and ecosystem degradation, saying "*Pollution is a constant problem we face... The water quality has reduced, and so has the marine environment in which we go fishing*", a clear indication that

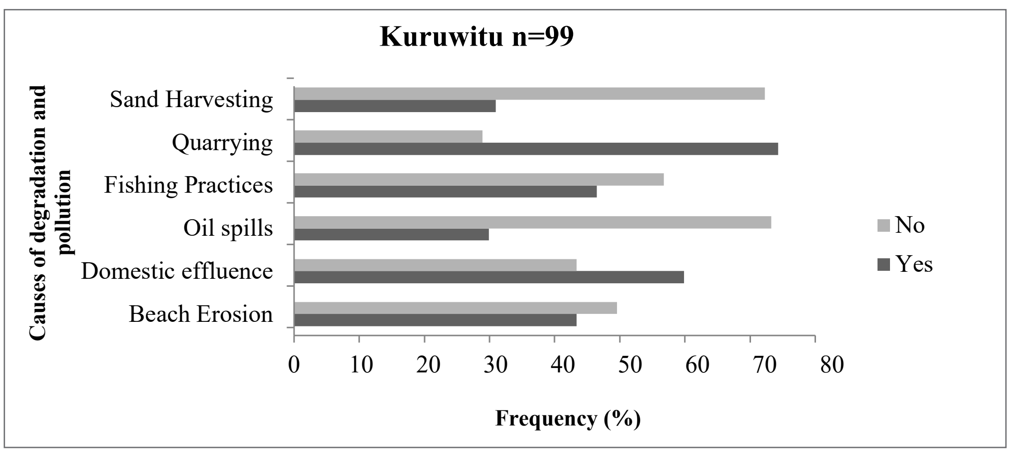

Figure 5. Knowledge of marine ecosystem degradation in Kuruwitu Village in Kenya.

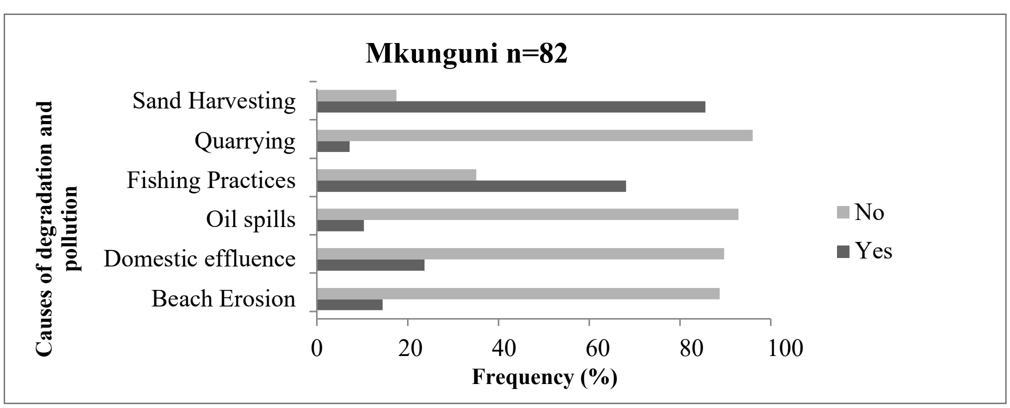

Figure 6. Knowledge of marine ecosystem degradation in Mkunguni Village in Kenya.

he understood the connection between marine pollution, ecosystem degradation and the likely impacts on their livelihood sources.

In Mkunguni, 66% of the resource-users listed deleterious fishing practices as the most serious causes of ecosystem degradation, compared to 45% of the respondents in Kuruwitu. Further inquiry through FGDs revealed that fishing practices such as the use of ring nets in coral reefs were to blame for marine resource degradation. In addition, the study noted that the emerging threat of illegal, unregulated and unreported (IUU) fishing along the coast was to blame for the decline of some of the fish stocks as well as destruction of marine habitats.

Sand harvesting was listed by 83% of the respondents in Mkunguni as a major threat to habitats, compared to 30% in Kuruwitu area. The FGD in Mkunguni revealed that sand harvesting was a major activity in the areas and a major threat to the marine ecosystems due to sedimentation which negatively impacts on the sea grass beds resulting in declining fish catches.

Oil-spill was listed as a threat by 29% of the respondents in Kuruwitu area compared to only 10% of the respondents in Mkunguni area. The resource users in Kuruwitu reported that oil spills had become more frequent as a result of increased traffic of marine vessels. The oil spills were associated with the ongoing development of the Lamu Port under the Lamu Port-Southern Sudan-Ethiopia Transport (LAPSSET) project, however, the resource users in Mkunguni did not associate the increased maritime traffic to marine degradation in the area. This might be because of the closer proximity of Kuruwitu to the shipping route and the port of Mombasa at Kilindini, compared to Mkunguni area. A further analysis of this data using the Chi-square test revealed that the awareness among the participants was significantly related in both the areas at $\chi^2 = 13.017$; df=5; p=0.001.

Discussion

Possession of IK knowledge is pegged on several factors such as age and attendance to management meetings. The strong association of age and IK found in this study could be explained by the fact that the elderly were more knowledgeable because of their experience and their involvement as elders in overseeing the rules and regulations pertaining to use of marine resources. There is an association between attendance to management meetings and IK. The management meetings were organized by the BMUs and attended by registered residents and were a forum that aimed at empowering the residents on how to conserve the environment. Meetings favour knowledge exchange and give people more opportunities to learn about their environment (Shackeroff and Campbell, 2007). There was no association between education level and IK in the present study. These findings are in agreement with Paniagua-Zambrana *et al.* (2014) and Iniesta-Arandia *et al.* (2015) who argue that formal education tends to detach learners from their physical environment and culture, thus limiting them from learning and participating in activities related to the transmission of IK from their elders.

The two communities have historically accumulated significant understanding of weather patterns based on their close association with the sea, and this has led to the evolution of fishing activities that are responsive to weather changes and the state of the sea. This form of indigenous knowledge serves the purpose of regulating marine resource exploitation and ensuring the safety of the resource users. Fishing is considered to be one of the most dangerous occupations (FAO, 2018), therefore understanding the weather is imperative if accidents are to be reduced and safety conditions improved (FAO, 2007). Similar findings have been reported where changes in monsoon weather patterns often limit fishing ventures on the southern coast of Kenya (McClanahan and Mangi, 2004; Okeyo, 2010), especially during the May-August period. The period of reduced fishing activities contributes to the prevention of depletion and rehabilitating of fish stocks (FAO, 2007). The phenomenon of using the moon cycle to guide fishing behaviour and patterns has been recorded in several areas of the world (Poisson *et al.,* 2010; Vinson and Angradi, 2014). In addition, these findings relate well with a study conducted in Brazil, where crustacean fishers applied indigenous knowledge of the tidal patterns to plan their fishing activities (Bezerra *et al.,* 2012).

Locating fish habitats is essential for maintaining healthy fish populations and designing best approaches for fishery management (MacNeill, 2010). By locating fish habitats fishers in both Kuruwitu and Mkunguni can harvest fish for food security and human development. This implies that fishers with such knowledge were able to save time in their fishing operations. These findings are in agreement with the results of Matiru *et al.* (2002), and Tunje and Muturi (2005) who observed that approximately 70-80% of the demersal fish catches are mainly harvested from the shallow waters and reefs. Additionally, Tunje and Muturi (2005) observe that the demersal catch within these coasts normally comprises parrotfish, rabbitfish, snappers and goatfishes, as well as decapod crustaceans including lobsters and shrimps, which are common in shallow waters and reef. The use of migratory birds to determine fishing points and speculate on the type of fish that can be caught has been noted in Kuruwitu and Mkunguni areas. Similar observations have been made in fisheries of the Western Indian Ocean where fishers locate areas of schooling tunas by watching for the Wedge-tailed Shearwater and the Red-footed Booby birds (Danckwerts *et al.*, 2014; Sebastian, 2011). This further lends credit to the idea that traditional knowledge is still helpful and being applied in the fishing activities of the residents in the two areas.

Indigenous knowledge accumulated over generations assists communities to anticipate how the availability of various marine resources varies. Indigenous knowledge of seasonality is critical since it influences the timing in species availability and consequently fishing patterns (Johannes *et al.,* 2000). The results on tuna abundance revealed in this study concur with those of a study by Gopalakrishna *et al.* (2012) which allude to the fact that tuna may be caught throughout the year but are generally a seasonal species.

Environmental sensitivity of the respondents in terms of gear use was based on suitability of the selected gears in different seasons and in enforcement of the gear use. For example, the use of the spear gun, although contested in some areas, was accepted in the Kuruwitu area because of the agreement that the gear should be used in a careful and selective manner. The spear gun used in Kuruwitu allows it to be used in a selective manner that does not damage non-target species. Therefore, despite it being an illegal gear, if well used, it could be considered as an option for selective harvesting.

Selection of fishing gears largely depends on the fishers' level of interaction with the environment and, by extension, the level of understanding of the ecology of the species. Kynoch *et al.* (2015) and Tunje *et al.* (2016) further confirm that the use of different fishing gear during different seasons was a way of ensuring that there is sustainability in the exploitation of the fisheries resources in different fishing grounds and seasons. The residents were aware that they faced resource limitations within the inshore waters and that poverty disenfranchised them from the sustainable use of the marine resources. Johannes *et al.* (2000) and Masalu *et al.* (2010) note that traditional fishing vessels without engines cannot withstand harsh conditions at sea, thus indirectly serving as a regulation of resource use. These findings are supported by a study by Daw (2008) which noted mass migrations of fish from disturbed fishing grounds to neighbouring habitats.

There is an increasing use of ring nets in the shallow waters on the south coast of Kenya, particularly in Vanga, Msambweni and Gazi, where they are threatening the shallow water ecosystems, and are a significant cause of resource use conflict (Okeyo, 2010). The opposition of local communities to the use of non-traditional fishing gears demonstrates that the residents understand the inherent threats of non-traditional fishing equipment to their efforts in the conservation and sustainable utilization of marine resources.

The use of wire mesh and similar innovations in replacing traditional materials with alternatives in the making of fishing gears has also been noted in other areas along the south coast such as Diani (Mbaru and McClanahan, 2013). These modified gears are more durable than the bamboo ruffians and their environmental impact is reduced as they are not abandoned or lost as often. The use of the mesh also ensures that damage to the environment (harvesting of materials for *malema*) is minimized. In addition, wire mesh is made of iron, and is bio-degradable. IK constantly evolves and may be based on the latest external knowledge adjusted to local circumstances (Fabricius *et al.,* 2007). Therefore, seeking alternative materials to ensure the continuity of traditional fishing gears such as basket traps is important in ensuring the continued supply of fish from the marine environment with reduced impact (Mbaru and McClanahan, 2013). Lastly, it reduces reliance on traditional materials that were used in the making of fishing gear, such as mangroves.

Sand mining in shallow nearshore or beach areas has resulted in negative impacts on adjacent coastal areas including sedimentation during heavy rains and stormy conditions that can impact the sea grass beds, key habitat for the majority of the demersal species targeted by the small-scale fisheries (Otay *et al.,* 2004). The residents noted that such a practice never existed in their collective recollection from the folklore handed down from the past. Therefore, within the meaning of their traditional knowledge, this is an invasion of modern-day extractive demands on the environment and reduces the quality of the shores and the ability of the marine environment to positively affect their lives.

Oil spills have both short- and long-term effects on the marine ecosystem, and high concentrations of the toxic components of oil could lead to the death of bottom-dwelling marine species (Ismail, 2005). While major oil spills have not been documented in Kenya, the effects of minor spills can have serious consequences on the environment, as evidenced in a study conducted by Ainsworth *et al.* (2018). Such effects have been witnessed on the shores of Kuruwitu and Mkunguni, impacting negatively on conservation efforts. The residents do not know traditional customs and practices for dealing with such spills since it was a non-existent phenomenon in their historical relationship with their marine environment.

The failure to manage environmental issues, and especially emerging problems as posed by modern industries such as sand mining or oil spills demonstrate the limitations of IK. Studies by Ruiz-Mallén and Corbera (2013) and Jauhiainen and Hooli (2017) assert that some communities are structurally thin and lack various crucial resources, and therefore capacity, in high-end development. This makes them rely greatly on external knowledge and experts (Ruiz-Mallén and Corbera, 2013). Further, Jauhiainen and Hooli (2017) adds that not all indigenous people have lived or are living in peace and harmony with nature. There are some world phenomena that are too complex to be explained into static conceptualizations (Mazzocchi, 2006). In order to manage these complex phenomena, there is need to maintain continuous openness, willingness to discover and learn from other civilization to the understanding of nature (Mazzocchi, 2006).

Conclusions and Recommendations

There are various types of IK used in the management of marine resources in the Kuruwitu and Mkunguni areas along the Kenya coast; for example, indigenous knowledge on weather and state of the sea have served the purpose of regulating marine resource exploitation and ensuring the safety of the resource users. Resource users demonstrated the use of IK in the identification of marine species and their habitats in both areas. This knowledge provided precision on target species and habitats, thereby reducing the time spent "searching" for fish. The fishers identified the different causes of marine pollution and degradation and were able to explain how they impacted fishing grounds, fish catches and ultimately, their livelihoods.

The County governments of Kilifi and Kwale should harness the IK in these local communities and also build the capacity of the residents in both areas to synchronize indigenous knowledge with new interventions in the effort to harmonize the management of marine resources. There is a need for an integrated approach to the management of marine resource to address concerns by communities. This will strengthen the different types of IK in the face of modernization and urbanization. Lastly, the County governments of Kilifi and Kwale and environmental agencies should actively get involved in creating awareness of ecosystem degradation and pollution and the impacts on marine resources.

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Spawning aggregations of fish in Cabo Delgado, Northern Mozambique: An interview-based survey of artisanal fishers

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Abstract

Seasonal aggregations at specific sites are common among some fish species. Experienced fishermen know where and when these aggregations happen, often targeting these spawning sites to increase their catch. This strategy can further contribute to endangering the survival of these species, especially for those already threatened by other forms of pressure. This study contributes knowledge to the spawning aggregation of fish in the north of Mozambique following survey work conducted around Cabo Delgado Province in six coastal villages in 2016, 2017 and 2018. The objectives of the study were 1) to identify the species and sites of spawning aggregation and 2) to determine the timing of spawning aggregations. Data collection consisted of interviews targeting the most experienced fishermen to obtain information on these subjects. The results indicate that out of 124 fishermen interviewed, 59% had knowledge of spawning aggregations. The information collected from fisher interviews revealed that there are at least six spawning locations and at least eight species aggregate to spawn (*Leptoscarus vaigensis*, *Lethrinus harak*, *Lethrinus nebulosus*, *Lethrinus obsoletus*, *Lethrinus olivaceus*, *Plectorhinchus gaterinus*, *Plectorhinchus schotaf*, *Siganus sutor*). Only *Siganus sutor* was reported to spawn in at least one of the fishing areas used by every village. The timing of spawning aggregations most reported by fishermen was during the Kusi (South) monsoon period.

Keywords: Coral fish, Spawning aggregations, Mozambique, Western Indian Ocean, Fisheries management

Introduction

Spawning aggregations occur in many reef species, grouping together large numbers of individuals at specific times and locations at approximately the same time of the year, lunar phase, and sometimes the same tide (Russell, 2001; Samoilys *et al.*, 2006; Sadovy de Mitcheson and Colin, 2012; Russell *et al.*, 2014).

The aggregation season for a given species in each location tends to be consistent, making these events predictable (Tamelander *et al.*, 2008; Nanami *et al.*, 2017). Fishermen usually use this knowledge to capture as many fish as possible during this key reproductive period, which can lead to a drastic reduction in the population density and unsustainable levels of fishing effort (Russell *et al.*, 2014). Knowledge of fish spawning aggregations, their location and timing are fundamental for population management, whether for the creation of marine protected areas (MPAs) or other non-permanent fishing management measures, such as closures (Samoilys and Church, 2004; Samoilys *et al.*, 2006).

Mozambique is not in the list of the 52 countries where spawning aggregations of fish occurs (Russell *et al.*, 2014), despite the existence of spawning aggregation records for *Caranx ignobilis* in Vamizi Island in northern Mozambique (Silva *et al.*, 2014) and Ponta do Ouro Partial Marine Reserve (PPMR) in southern Mozambique (Daly *et al.*, 2018; 2019). The present study aims to assess local knowledge of fish aggregations in northern Mozambique to contribute to future fishery management. Furthermore, the findings on fish aggregations in this study will contribute to the database on the Science and Conservation of Fish Aggregations (SCRFA).

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Methods

Field work was carried out in October 2016, June and September 2017 and July 2018 in six coastal villages of Cabo Delgado province (10°29´S, 35°58´E – 14°01´S, 40°35´E). Four rounds of interviews were conducted in the Palma District (Quirinde, Quiwia, Lalane and Nsangue), one in Mocimboa da Praia District (Malinde) and one in Mecufi District (Mecufi) (Fig. 1).

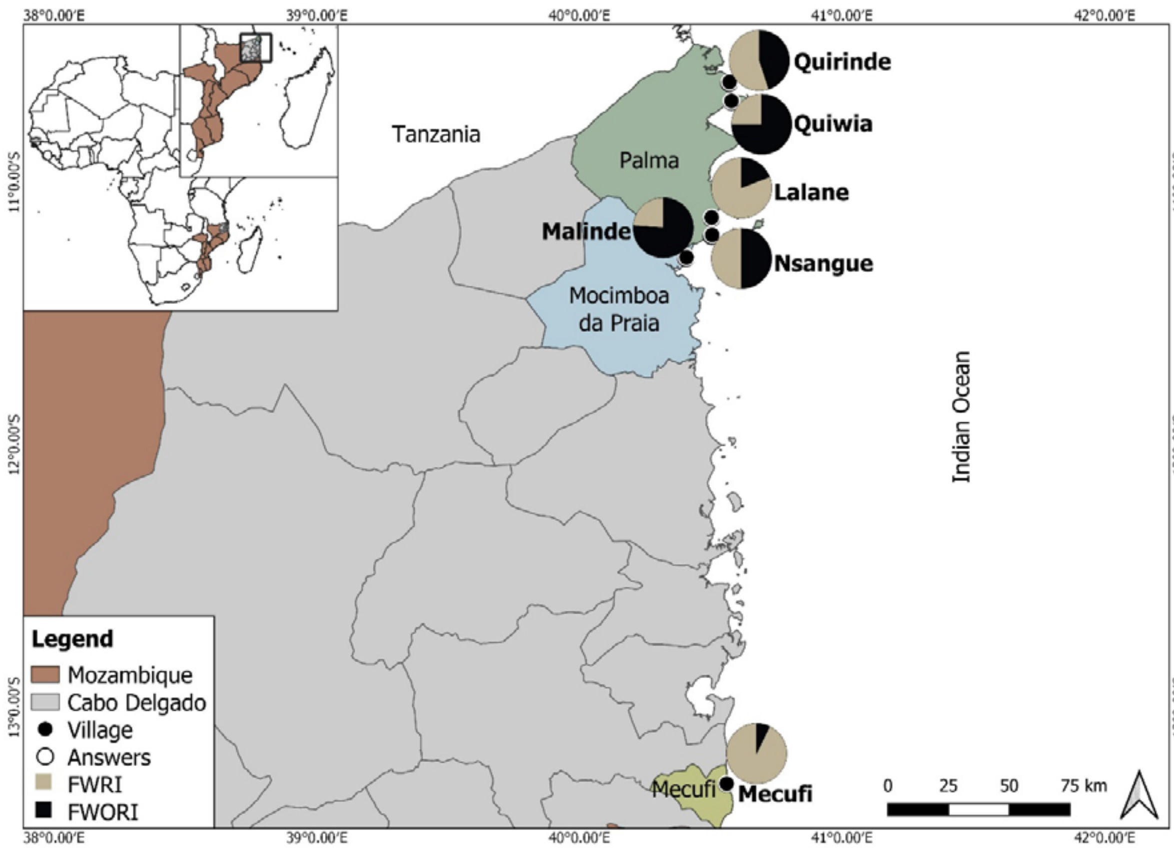

Figure 1. Coastal region of Cabo Delgado showing the percentage of responses of fishermen about the spawning aggregation phenomenon in each study village. The grey color shows the percentage of fishermen with reliable information who could provide reasonable evidence that the fishes were in spawning aggregations (FWRI=Fishers with Reliable Information). The black color shows the percentage of fishermen without reliable information who could not provide reasonable evidence that the fishes were in spawning aggregations (FWORI= Fishers without Reliable Information).

Data collection was carried out through semi-structured interviews (see supplementary material), based on the work of Robinson *et al.* (2004) and Samoilys *et al.* (2006). The interviews were conducted individually with fishermen and lasted approximately 15 to 25 minutes each. All interviews were conducted with the help of a local guide and included members of the local Community Fisheries Council (CCPs), technicians of Associação do Meio Ambiente (AMA - a local environmental NGO) and influential fishermen, to maximize data quality and diversity. The selection of fishermen and interviews were conducted for an average of two days for each village.

To assist with identification of the species and description of spawning aggregations, a field guide was prepared, featuring the species most likely to aggregate and spawn in the region, based on studies carried in the Western Indian Ocean (Samoilys *et al.*, 2006; Sadovy de Mitcheson and Colin, 2012; www.scrfa.org), and on the field guide of Coral Reef Fishes (Lieske and Myers, 2002).

After identification of the species and their sites of spawning, the fishermen chose one or two species for more detailed discussion, including on information on location, lunar phase, tide, size, habitat, trends in catch, fishing effort and the period of spawning aggregation.

Suggested spawning sites were recorded using local names and were located using participatory maps of marine resources already developed by the communities in other projects (Fig. 2).

Data Analysis

The validation and interpretation of the data was based on how information from the fishermen on spawning aggregations corresponded with the criteria of verification described by Robinson *et al.* (2004) and Samoilys *et al.* (2006): 1) verification of the positive response on the knowledge of spawning aggregation; 2) knowledge of the species mentioned by more than one fishermen; 3) knowledge of the sites of spawning aggregation or more than one species mentioned by more than one fishermen; 4) verification of the

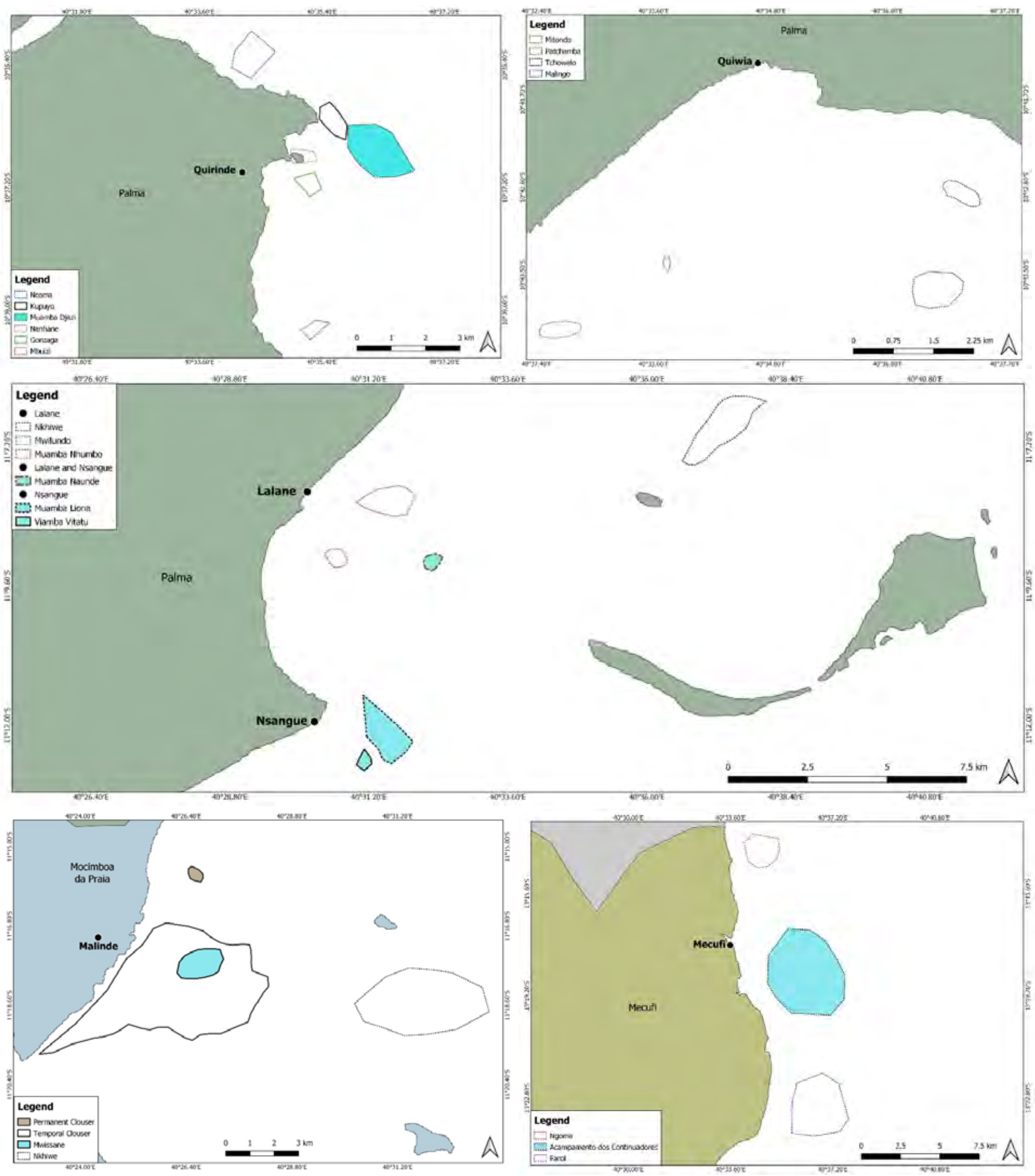

Figure 2. Spawning aggregation sites in all studied villages. The sites highlighted were the most reported.

probable species that aggregate to spawn according to Sadovy de Mitcheson and Colin (2012), Erisman *et al.* (2018) and the SCRFA database.

Only the responses in which the evidence for spawning aggregations was reasonable were used (Samoilys *et al.*, 2006). The questionnaires were discarded if the fishermen claimed that a species aggregated to spawn, but that throughout the interview they referred to the fish as “playing or feeding”. Whenever a fisherman misidentified a species or aggregated different species, the entire questionnaire was discarded. Sometimes, even though the fishermen showed knowledge of fish species and sites of spawning aggregation, the information was not enough to infer the occurrence of reproductive aggregation because it was not referenced by more than one fisherman. This information was then also discarded.

The data was reduced to a subset which was then analyzed in steps 2), 3) and 4) to determine the data with the highest probability of providing species information and reliable spawning sites, which further reduced the dataset.

The species selected were those that the fishermen gave more detailed information on in relation to the month, lunar phase, tide and period of spawning aggregation. The information was also crossed-referenced with the list of Reef Fish Spawning Aggregations compiled by Sadovy de Mitcheson and Colin (2012) and the list of Fish Spawning Aggregations (FSAs) (Erisman *et al.*, 2018).

Subsequently maps of spawning aggregation sites were produced in the QGIS v.3.8 software using the available coordinates obtained from a participatory map of marine resources already developed (Colin *et al.*, 2003).

Table 1. Species reported to spawn in aggregation by more than one fisherman in all villages. Species marked in bold were reported in five villages. The numbers indicate how many times the species were reported by more than one fisherman per site. **Siganus sutor* was reported in every village.

Family	Species	Muamba Djazi	Muamba Naunde	Muamba Liona	Muamba Vitatu	Mwissane	A. Continuadores
Serranidae	*Epinephelus tukula*			2			2
Lutjanidae	*Lutjanus fulviflamma*	3	3	3		2	3
	L. ehrenbergi						
	L. quinquelineatus						
	L. kasmira					3	
Lethrinidae	***Lethrinus harak***	2		4	2	2	2
	L. obsoletus		2	3		2	2
	L. nebulosus	2					
	L. olivaceus	2			2		2
	Gymnocranius grandoculis	5				4	5
Siganidae	***Siganus sutor****	6	4	7	2	4	18
Haemulidae	*Plectorhinchus flavomaculatus*			2		4	3
	P. schotaf		3	7		5	
	P. gaterinus	2	3	7	3	4	
Scaridae	*Leptoscarus vaigensis*			7		3	11
Caesionidae	*Caesio coerulaureus*	3					4
	C. lunaris	4					5

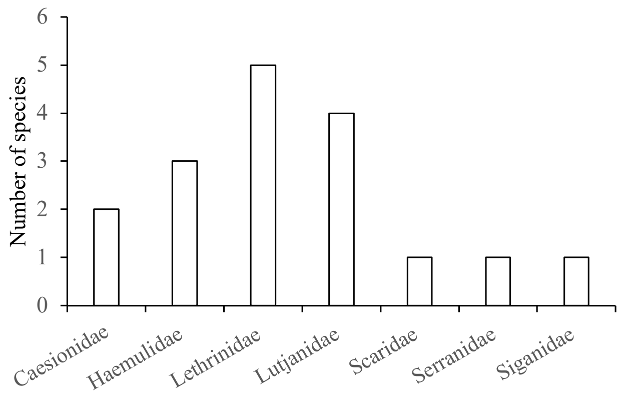

Figure 3. Number of species per family that aggregate to spawn.

Results

In total 124 interviews were conducted and 73 passed the validation criteria. Fifty one corresponding 41% interviews were discarded because the fishermen did not show knowledge of the phenomenon of spawning aggregation, 14 because the information was not co-validated by a second fisherman, and 37 because when asked the reasons why fish aggregate, they answered: "I don't know"; "They are always in this place"; "Playing"; "Feeding" (Fig. 1).

Overall, 17 species (Table 1) were reported to aggregate for reproduction, distributed in 7 families with a prominence within the group of emperors (Lethrinidae) followed by snappers (Lutjanidae) (Fig. 3). Eight species were common occurring in six sites (*Leptoscarus vaigensis*, *Lethrinus harak*, *Lethrinus nebulosus*, *Lethrinus obsoletus*, *Lethrinus olivaceus*, *Plectorhinchus gaterinus*, *Plectorhinchus schotaf*, *Siganus sutor*) (Table 1, species in bold). *Siganus sutor* was the only species reported in all studied villages.

In general, fishermen reported that most species spawned during the Kusi (South) monsoon period (dry season, April–July/August). However, some species were reported to spawn in Ulani (North) monsoon (rainy season, December–March) and inter monsoon period (Table 2).

Discussion

About one-third of the species reported by fishermen in this study are known to aggregate for spawning elsewhere in the world according to the list of Reef Fish Spawning Aggregations (RFSA) by Sadovy de Mitcheson and Colin (2012), and Fish Spawning

Table 2. Number of fishermen observations of spawning aggregations by month or period for the key species groups in all villages.
* no details were provided by fishermen for *Lethrinus nebulosus*.

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Caesio coerulaureus	1	1	1			2	2	3				1
C. lunaris							5	4		2		
Epinephelus tukula								2	1			
Gymnocranius grandoculis				2			3	3	2	1		
Leptoscarus vaigensis	1	2		1			9	4		4		
Lethrinus harak	1						2	1	1	1		
L. obsoletus		1					1	3				
L. olivaceus							1	1				
Lutjanus ehrenbergi							1	1				
L. fulviflamma			1		1	2	1	2	1	2	1	
L. kasmira	1					1	1	2	1	1		
Plectorhinchus flavomaculatus		1					1	1				2
P. gaterinus		2				1		1		3		
P. schotaf				2					1	1		
Siganus sutor	3			1		2	1	7	2	4		1

Aggregations (FSAs) by Erisman *et al.* (2018). The proportion found in this study is relatively consistent with a study carried out in Seychelles (Robinson *et al.*, 2004).

The families of the species that were reported to form spawning aggregations in Cabo Delgado are already known, as recorded in the RFSA and FSAs lists and others studies (Russell, 2001; Samoilys *et al.*, 2006; Flynn *et al.*, 2006; Sadovy *et al.*, 2008; Sadovy de Mitcheson and Colin, 2012; Kobara *et al.*, 2013; Farmer *et al.*, 2017; Nanami *et al.*, 2017; Fisher *et al.*, 2018; Erisman *et al.*, 2018). These include the Serranidae, Lethrinidae, Lutjanidae, Siganidae, Scaridae and Caesionidae. However, Haemulidae was reported for the first time in this study. The occurrence of spawning aggregation of the Caesionidae family in the villages of Quirinde, Nsangue, Malinde and Mecufi was only previously recorded by Samoilys *et al.* (2006) in Kenya and Tanzania. However, the confirmation of these spawning aggregations in the literature does not eliminate the need for evidence from direct observation and assessing the gonad index (Domeier and Colin, 1997).

The spawning aggregation of snappers (Lutjanidae) was observed by the fishermen between June and October. This pattern differs from a study in Kenya and Tanzania, in which the spawning aggregation season of the snapper species was identified as occurring during the month of October with a smaller peak occurring in January and February (Nzioka, 1979), and from patterns recorded in the Seychelles, where the season peak is March and April (Robinson *et al.*, 2004).

Groupers are some of the more common species known to aggregate (Domeier and Colin, 1997; Samoilys *et al.*, 2006), however, only one species, *Epinephelus tukula,* was recorded in this study. Three fishermen reported the aggregation and the spawning season of this species in August/September. However, large spawning aggregations of *Epinephelus lanceolatus,* the giant grouper, are known from Vamizi Island (north of Cabo Delgado) during December/January (Isabel da Silva, pers. obs.)

Finally, the fish most reported by fisherman to aggregate for spawning was *Siganus sutor*. This species makes up a high proportion of catches in artisanal fisheries in the region, where a variety of gears such beach-seine, gillnets, basket traps, handlines and spearguns are used (Fischer *et al.*, 1990; MGDP, 2016; Bilika *et al.*, 2019). Most fishermen (76%) reported spawning aggregation of *Siganus sutor* between June and October, 19% between December/January, while only one fisherman reported it for April. This result differs from a study conducted in southern Kenya, where most fishermen reported occurrences of spawning aggregation between November and February, with some reports from March to October, and no records during August (Maina *et al.*, 2013).

The most reported spawning season in this study (June to October) is not corroborated by similar work in Kenya and Tanzania (Samoilys *et al.*, 2006) where most species spawned during October–April, during the Northeast monsoon. A possible explanation for this contrasting result could be attributed to the climatic differences between these regions, which could affect spawning (Johannes, 1978; Heyman *et al.*, 2005; Choat, 2012; Kobara *et al.*, 2013; Rosli *et al.*, 2014).

One of the limitations established during interviews was that some fishermen suspected that the study would result in restrictions on the sites of their fishing activities. This was seen in the northern villages of Cabo Delgado, namely in Quirinde, Quiwia, Lalane and in Malinde. However, fishermen from the established permanent marine reserve area (Nsangue) and from Mecufi were extremely cooperative with the study. These challenges were also reported in the study conducted in Kenya and Tanzania (Samoilys *et al.*, 2006).

Further verification of these results is important to confirm the spawning aggregation described, through direct observation on fish abundance and by observing the gonad index for assessing maturation condition. If a species is known to aggregate to spawn it will be more susceptible to overfishing (Samoilys, 1997; Vincent and Sadovy, 1998; Johannes *et al.*, 1999; Samoilys *et al.*, 2006). It is important to include fish aggregation data in the management of fisheries, by proclaiming temporal closures or reserve areas that fit the local patterns of spawning and consequently increase the sustainability of the fisheries for these species.

Acknowledgments

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Supplementary material

Reef Fish Spawning Aggregations Questionnaire

Fieldworker: ____

Date: _____ / _____ / _____

Site: ____

ID number: ____

Section 1
1. Fish spawning aggregations

1.1. Have you fished/seen/or heard of this phenomenon? Yes/No

1.2. How many sites have you seen/did you see this occur? List names and/or locations.

1.3. What species/families were involved at each of the sites? If you can list the species per site write them in the space below for question 2.

1.4. Why do you think the species were aggregating: feeding, spawning, other, no idea? Give reasons for answer.

1.5. Why do you think they do it at the specific sites and nowhere else?

If the answer to Question 1.1 is YES, can you complete any of the following questions?

2. Species – obtain details about the aggregating species mentioned earlier in Question 1.

2.1. What type(s) (species or common name) of reef fish were involved in the spawning aggregation(s)? If there is more than one example, please list them all.

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Section 2

Questions in section 2 focus on one species at a time
Please fill out one table per species

	Questions	Answers
1.	**Species:** Clarify the species' identification using the fish id sheets	
2	**Location** Map out on chart/map if possible Mark GPS point if possible Use local reference points Be as specific per species as possible	ID:
2.1	Where were these fish spawning aggregations seen/found? Please provide as much information as possible; draw a map if needed	
3	**Habitat and depth**	Habitat types include: coral reef, sand; seagrass, Reef profile types include: reef crest; drop-off; pass; outer slope
3.1	Can you give details about the type of marine habitat where the aggregation occurred?	
3.2	What was the depth of the aggregation?	Minimum: Maximum:
4	**Time and conditions**	Use Gregorian year/months The season Record continuity over months Use the Islamic calendar if it helps but convert later The period of day (am, pm, night, midday)
4.1	At what time of year (month, lunar phase, time of day) did you fish/see the aggregation?	Season (e.g. NE, SE winds & inter-monsoon): Month (list every month observed): Lunar phase (new, full, 1st quarter, 3rd quarter): Time of day (dawn, am, midday, pm, dusk, night):
4.2	What were the conditions of the sea at the aggregation site?	Current (weak, moderate, strong): Tidal state (low, high, ebb, flow): Wind (NE/SE, strong, weak etc): Water temperature:
4.3	How long did the aggregation last? e.g. number of days	

5	Fishing pressure on the aggregation	
5.1	How often have you been fishing or noticing this aggregation?	
5.2	Do you still fish this site throughout the year?	Yes/No
5.3	Are you still fishing this aggregation and if so for what reasons?	
5.4	How many boats fish the site currently?	
5.5	Have you noticed an increase of other fishers/boats targeting this aggregation? If so, by how much?	
6	Catch size per fisher	
6.1	If (When) the aggregation is (were) fished, is (were) the average catch larger than usual on this site compared to other fishing sites? If so by how much?	
6.2	What was the average size of the fish when the fish were aggregating compared to other sites?	
6.3	Have you noticed a change in the fish catch since you first fished it? If so how has it changed? (increase/decrease)	
	If so, when did you first notice a change in catch at the site?	
7	Personal views on the aggregation	
7.1	Do you have any concerns about this aggregation?	
7.2	If so, do you have any suggestions to rectify or manage your concerns	
8	Fill out below any other points that you consider important regarding the fish spawning aggregation	

Characterisation of artisanal catches in selected fishing areas of the Lower Tana Delta and Malindi-Ungwana Bay, Kenya

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Abstract

Shore-based assessment of fisheries resources in Ngomeni, Kipini and Ozi fishing areas of Malindi-Ungwana Bay and the Lower Tana Delta on the north coast of Kenya was conducted from January to December 2017 to establish catch composition, species richness, and fishing effort (catch-rate, number and types of fishing gears and crafts) in the marine, estuarine and riverine habitats. Distinct catch composition ($R = 0.27$, $P < 0.05$) was observed across the three habitats. Catch composition differed significantly spatially and seasonally across the three fishing areas, and between the north east (NE) and south east (SE) monsoon seasons ($R = 0.332$, $P < 0.05$). The wolf herring, *Chirocentrus dorab*, was the most abundant fish species in Ngomeni, centrally located in Malindi-Ungwana Bay, while the catfishes, *Arius africanus* and *Clarias gariepinus*, were the most abundant species in Kipini and Ozi, respectively. Gillnets operated from dhows (*mashua*) and fibre-reinforced plastic (FRP) boats in Ngomeni (marine), and canoes using-basket traps in Ozi (riverine), landed significantly larger Spanish mackerel, *Scomberomorus commerson*, and sea catfish, *Arius africanus* (Kruskal Wallis test: Df = 2; $F = 197.141$; $p < 0.001$; Df = 2, $F = 490$, $p < 0.001$), respectively. Species diversity by area in combination with habitat and type of fishing craft showed higher diversity for Ngomeni in the marine habitat with *mashua* fishing crafts than in Kipini. Significantly different catch rates (Df = 2, $F = 10.43$, $p<0.001$; Df = 1, $F = 5.897$, $p < 0.021$) were observed in the three (3) fishing areas and during the NE monsoon and the SE monsoon, respectively. Canoes were the most common fishing craft used, especially in Ngomeni, accounting for 37.1%, and 97.5% in Ozi, while *mashua* crafts accounted for 44.5% of the total fishing craft in Kipini. Monofilament nets were most common in Ngomeni (34.0%) while basket traps dominated the Ozi site at 63.6%. The Kipini area was dominated by handlines (28.8%). It is therefore evident that the three (3) fishing areas of the Malindi-Ungwana Bay and Lower Tana Delta showed significant differences in catch composition and size of fish caught, attributed partly to the variation in habitat types and fishing methods between the sites. Overall, the Ngomeni area was characterized by more advanced fishing craft with the majority powered by engines, including *mashua* and FRP boats, compared to Kipini and Ozi fishing areas where canoes were dominant.

Keywords: Artisanal fisheries, Catch composition, Malindi-Ungwana Bay, Lower Tana Delta, Kenya

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Introduction

The value of fisheries resources to humanity has been extensively reviewed in numerous socio-economic systems (Cinner *et al.*, 2011; FAO, 2012; Metcalf *et al.*, 2015) and still receives special attention globally due to the dynamic nature of coastal and marine socio-ecological systems (Fuller *et al.*, 2017). Fisheries systems need to be regularly assessed in order to understand their current status. Aartisanal fisheries, especially in the tropics, have been variously characterized by different studies.

Rondeau *et al.* (2016) identified and characterized important sites for fish and invertebrates in the coastal waters of the Gulf of St. Lawrence, Canada with the aim of conserving and managing endangered species. Surís-Regueiro and Santiago (2014) described the relationship between coastal and marine fisheries dependency and employment by characterizing income and employment from fisheries in Galicia, Spain. Some studies have acknowledged the challenge on enhancing artisanal fisheries management due to their open access nature (KMFRI, 2008; González-Álvarez *et al.*, 2016; Siddons *et al.*, 2017). Other studies have narrowed the focus and characterized catch by different gears in different sites to determine fishing effort for fisheries management (Laurence *et al.*, 2015; Munga *et al.*, 2014).

Despite the significance of coastal and marine fisheries in supporting the commercial and subsistence fishery sub-sectors in the Malindi-Ungwana Bay and the Lower Tana Delta on the north coast of Kenya, the main fishing areas have not been extensively. The majority of the studies have concentrated on fisheries resources of the estuarine and marine environments, neglecting the riverine habitat (Abila, 2010; Munga, *et al.*, 2012; Munga, *et al.*, 2014). Studies have however described the impact of the semi-industrial bottom trawl fishery on the artisanal fishery, and the resultant conflict arising from targeting the same species and accessing the same fishing grounds (Munga *et al.*, 2014). Variations in the seasonality and bathymetry of decapod crustacean communities have aso been studies (Ndoro *et al.*, 2014). The trawl fishery is responsible for very high bycatch (71.9%) in the Bay (Fulanda, 2003). Importantly, these studies have demonstrated the effectiveness of government regulations that were imposed on the bottom trawl prawn fishery which had previously negatively impacted the fishery (KMFRI, 2008).

The Ungwana Bay ecosystem can be categorized into marine, estuarine and riverine habitats. The three main fishing areas are located at Ngomeni in the south of the bay, and Kipini and Ozi further north in the bay. This paper characterizes the artisanal catches in the three main fishing areas with reference to habitats types. Comparisons are made between seasonal and spatial (habitats) catch composition by species and size, and fishing effort in terms of catch rates, fishing craft and quantity of gear.

Materials and methods

Study area

The study was conducted in the Malindi-Ungwana Bay and lower Tana Delta on the north coast of Kenya covering the fishing areas of Ngomeni, Kipini and Ozi (Fig. 1). Ngomeni and Kipini are located within the bay while Ozi is located in the Lower Tana Delta on the Tana River. These areas experience two seasons annually; the North East Monsoon (NEM) from October to March, and the South East Monsoon (SEM) from April to September (McClanahan, 1998). The Malindi-Ungwana Bay and Lower Tana Delta are among the richest ecosystems along the Kenyan coast and support both artisanal and commercial fisheries (shrimp bottom trawl) and other socio-economic activities (Abila, 2010).

Data collection

Concurrent shore-based catch assessment surveys were carried out for 8 days of every month from January to December 2017 in Ngomeni, Kipini and Ozi fishing areas. Catch and landings were sorted to species level, and total weight (kg) by species recorded with a weighing balance, while individual total length (TL, cm) was measured using a measuring board. The species were identified using the FAO Species Identification Guide for marine resources in Kenya (Anam and Mostarda, 2012). For large catches, the total weight was first measured, and then a homogenous sub-sample was randomly taken from the catch where different fish species were separated before measurements were done. For small catches, a similar procedure was followed but without sub-sampling. The fishing time (hrs), type of fishing craft, crew size and the type of fishing gear used were recorded.

Data analyses

Seasonal catch rate (kg/fisher.hr^{-1}) was calculated for each fishing area. In each area, the total weight for each month was divided by the total number of crew (catch/fishers, W/f), and then divided by the total number of fishing hours from the same month (W/f.hr^{-1}). The seasonal average catch rates were then computed for each area. The Non-Metric Multidimensional Scaling (nMDS) technique was used to determine whether distinct seasonal catch composition existed across habitat types, and also across fishing areas. Differences in catch rates between seasons and across fishing zones were determined using the 2-way ANOVA test. Since data was non-parametric, transformed data log (X+1) was used for the 2-way ANOVA parametric test, and length between the different craft-gear combinations were tested using the non-parametric Kruskal-Wallis test. Rarefaction curves were used to determine species diversity across fishing zones with habitat and craft-gear combination. Craft and gear frequencies as well as the frequencies of the 5 most abundant species in each fishing zone were also determined using Microsoft Excel.

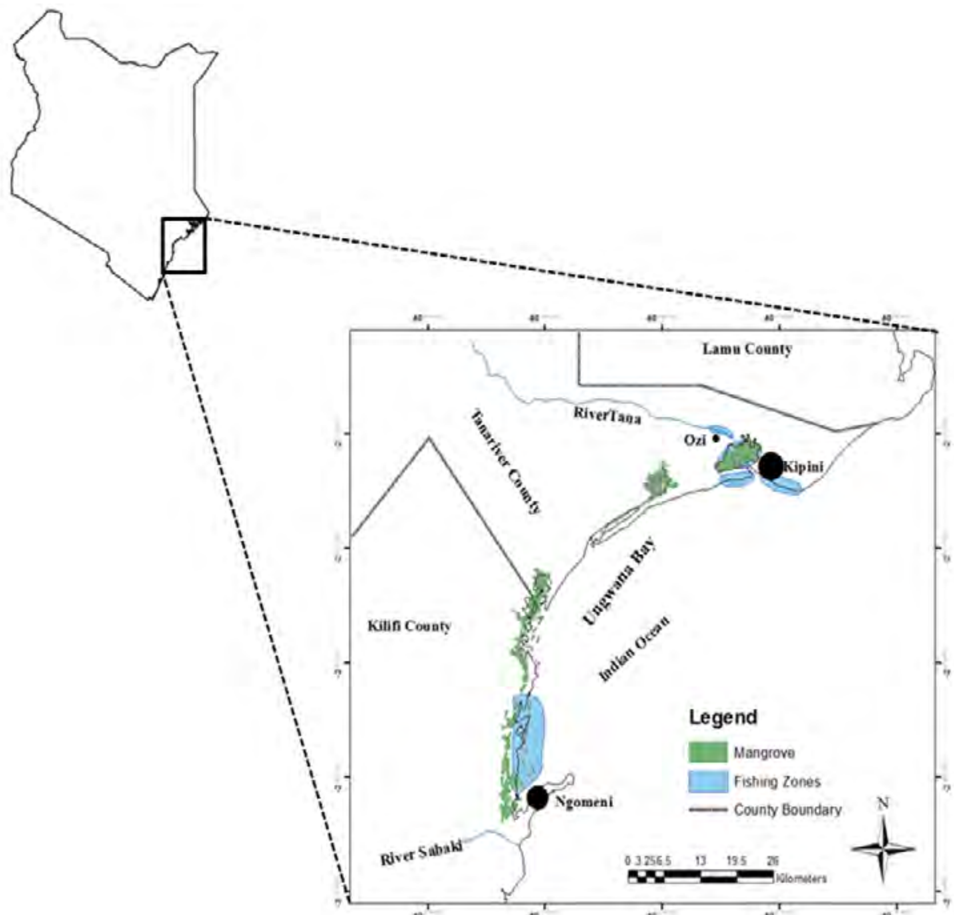

Figure 1. Map showing the fishing zones of Ngomeni, Kipini and Ozi in Ungwana Bay and Lower Tana Delta, Kenya.

homoscedascity of variances was tested using the Levene's test at $p > 0.05$. One-way ANOSIM was used to test significant difference in the seasonal catch composition across habitats and across the fishing areas. In both cases, 1-way SIMPER analysis was performed to identify which fish species contributed to the dissimilarity. Pair-wise comparison was conducted using the post hoc (Tukey HSD) test. These tests were conducted using STATISTICA statistical software v.7. Microsoft Excel was used to determine the mean length of the most abundant species in each fishing zone with craft-gear combination. The differences in species

Results

Composition of fin fish species in Ungwana Bay and Lower Tana Delta

During the study period a total of 191 fish species were identified, comprising 104 species recorded in the NEM season and 87 species in the SEM season. Kipini landed 33.4 Mt during the survey period followed by Ngomeni with 29.9 Mt, while Ozi landed the lowest catches with 2.2 Mt. From these landings, a total of 19,943 individuals were sampled in Malindi-Ungwana Bay and Lower Tana Delta during the study.

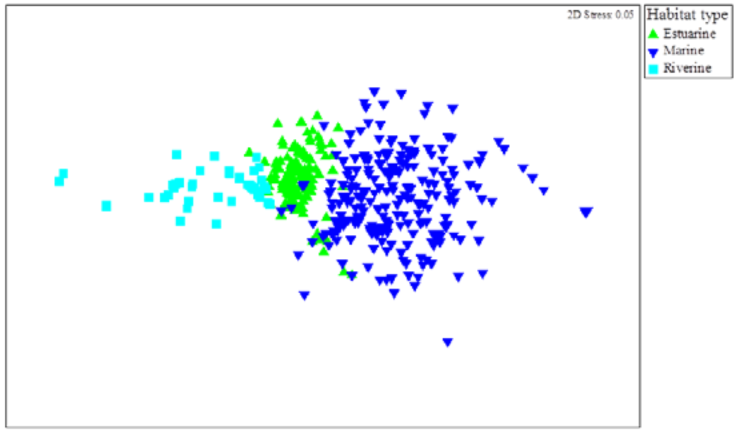

Figure 2. Non-metric MDS plots showing the composition of catches by habitat types in Ungwana Bay and Lower Tana Delta, Kenya based on species abundance from shore-based catch assessments.

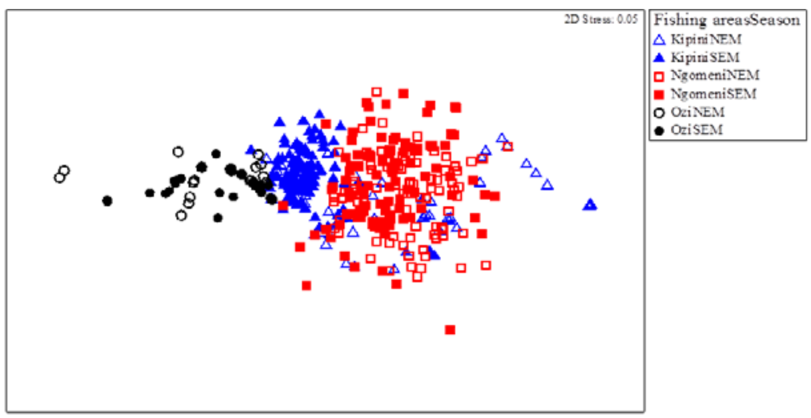

Figure 3. Non-metric nMDS plots showing the composition of catches by fishing zone with season combination in Ungwana Bay and Lower Tana Delta, Kenya based on species abundance from shore-based catch assessments.

Non-Metric Multidimensional (nMDS) plots showed distinct separation of samples across habitat types (Fig. 2). One-way ANOSIM indicated a significant difference in sample composition across the habitat types (R = 0.27; P < 0.001). Results of pair-wise comparison tests confirmed significant differences in the composition of samples across all habitat types (P < 0.05 in all cases). A distinct fin fish composition was also observed across the fishing areas with season (Fig. 3). Similarly, 1-way ANOSIM indicated a significant difference in sample composition across fishing areas with season (R = 0.332; P < 0.001). Results of pair-wise comparison tests confirmed significant differences in the composition of samples across all fishing areas with season (P < 0.05 in all cases), except Ozi which indicated no significant seasonal difference (R = 0.003; P < 0.421). Results of SIMPER analysis showed that while *Arius africanus, Otolithes ruber* and *Pelona ditchela* contributed most to the dissimilarity in the estuarine habitat, *Chirocentrus dorab, Pristipomoides filamentosus, Scomberomorus commersoni* and *Pristipomoides sieboldii* contributed most to the dissimilarity in the marine habitats of Kipini and Ngomeni (Table 1).

Species richness and abundance

Based on fishing areas, habitat and fishing craft type, rarefaction curves showed that the Ngomeni-marine-*mashua* category recorded the highest number of species, followed by the Ngomeni-marine-canoe category, while Kipini-estuarine-outrigger canoe, and Ozi-riverine-canoe categories recorded the lowest number of species (Fig. 4). Based on the types of fishing gear used, the rarefaction curves showed that monofilament nets caught the highest number of species, followed by gillnets, seine nets, handlines, basket traps, longlines and spearguns (Fig. 5).

Table 1. One-way SIMPER Analysis: Species contributing to the dissimilarity in terms of abundance (%) between habitat types (estuarine *versus* marine) with an average dissimilarity of 97.8%.

	Estuarine habitat	Marine habitat		
Species	**Average abundance (%)**	**Average abundance (%)**	**Average dissimilarity**	**Contribution (%)**
Arius africanus	**40.17**	1.01	19.90	20.35
Otolithes ruber	17.38	1.18	8.71	8.91
Pelona ditchela	**14.78**	0.33	7.48	7.64
Chirocentrus dorab	0.00	**14.00**	7.00	7.16
Pristipomoides filamentosus	0.00	**13.75**	6.88	7.03
Scomberomorus commerson	0.03	**11.73**	5.87	6.00
Pristipomoides sieboldii	0.00	**10.02**	5.01	5.12

For the Ngomeni fishing area, the 5 most abundant fish species sampled were *C. dorab*, *S. commersoni*, *Thunnus albacares*, *Euthynnus affins* and *Rastrelliger kanagurta* (Table 2). For Kipini, the 5 most abundant species were *A.africanus*, *O. ruber*, *P. ditchela*, *Argyrops spinifer* and *P. filamentosus* (Table 2). *C. gariepinus*, *A. africanus*, *P. limbatus*, *Oreochromis niloticus* and *Protopterus annectens* were the 5 most abundant fish species captured in Ozi (Table 2).

Artisanal fishing gear and craft

Comparisons on the types of artisanal fishing gear used in the study area showed that basket traps were most common in Ozi fishing area at 63.6%, followed by handlines (28.8%) in Kipini, and monofilament nets (34%) in Ngomeni (Table 3). Analysis of the fishing-craft types indicated that canoes were most common in Ozi (97.5%) with foot fishers accounting for ≈2.5%. Canoes were also most common in Ngomeni (37.1%) followed by *mashua* craft (32.6%), and FRP craft and foot-fishers at 26.4% and 3.9%, respectively. *Mashua* craft were most common in Kipini (44.5%), followed by foot-fishers (28.5%) and canoes (27.0%).

Fishing effort and species sizes

During the study period, the mean catch rate (kg/fisher.hr^{-1}) in the Malindi-Ungwana Bay and Lower Tana Delta was higher during the NEM season than the SEM season in Ngomeni and Kipini fishing areas (Fig. 6). However, the Ozi fishing area showed marginal differences of catch-rate between the seasons (Fig. 6). Generally, the Ngomeni fishing area recorded the highest catch-rate followed by Kipini and Ozi, respectively (Fig. 6). The Two-way ANOVA test indicated a

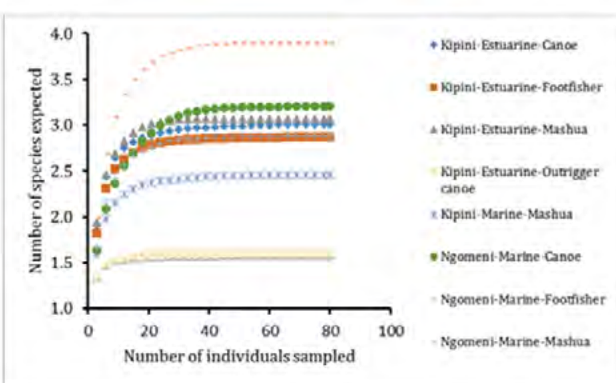

Figure 4. Rarefaction curves showing the expected total number of species caught with increase in sample size for the different fishing zones with habitat and fishing craft combination in Ungwana Bay and Lower Tana Delta, Kenya.

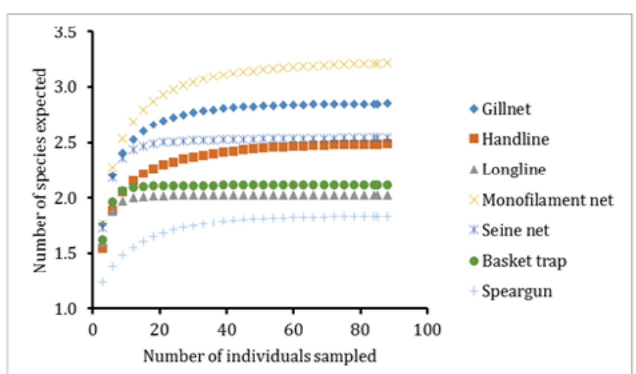

Figure 5. Rarefaction curves showing the total expected number of species caught with increase in sample size for the different types of fishing gears in Ungwana Bay and Lower Tana Delta, Kenya.

Table 2. Five most abundant fin fish species by fishing zone in Ungwana Bay and Lower Tana Delta, Kenya.

Ngomeni	Number of individuals sampled	(%)
Chirocentrus dorab	1560	31.2
Scomberomorus commerson	644	12.9
Thunnus albacares	228	4.6
Euthynnus affinis	185	3.7
Rastrelliger kanagurta	180	3.6
Kipini		
Arius africanus	2396	26.6
Otolithes ruber	1426	15.8
Pelona ditchela	1261	14
Argyrops spinifer	583	6.5
Pristipomoides filamentosus	566	6.3
Ozi		
Clarias gariepinus	2672	44.9
Arius africanus	1829	30.8
Plotosus limbatus	748	12.6
Oreochromis niloticus	522	8.8
Protopterus annectens	158	2.7

significant difference in catch rate across fishing zones (Df = 2, $F = 10.43$, $p < 0.05$) and between the seasons (Df = 1, $F = 5.897$, $p < 0.05$). The Tukey HSD post-hoc pair-wise comparison test confirmed that the catch-rates were significantly different between Ngomeni and Ozi as well as Kipini and Ozi ($p < 0.05$ both cases). The seasonal catch rate was significantly higher in the NEM than the SEM season for Ngomeni ($p < 0.05$), but not for Kipini and Ozi ($p = 0.82$ and $p = 1.00$, respectively). Based on species caught with craft-gear combination, *S. commersoni* was the most abundant species in Ngomeni while *A. africanus* and *O. ruber* were the most abundant in Kipini, with *A. africanus* also being most abundant in Ozi (Fig. 7). In Ngomeni, the gillnets used with FRP boats and *mashua* landed significantly larger individuals than those landed by monofilament nets with canoes (Kruskal Wallis test: Df = 2; $F = 197.141$; $p < 0.05$). The Pair-wise comparison test confirmed

Table 3. Composition of artisanal fishing gear types sampled in Ungwana Bay and Lower Tana Delta, Kenya.

Types of gear	Kipini	(Freq %)	Ngomeni	(Freq %)	Ozi	(Freq %)
Basket traps	1	0.2	0	0.0	180	**63.6**
Gillnets	174	27.4	144	27.0	34	12.0
Handlines	183	**28.8**	174	32.5	1	0.4
Longlines	51	8.0	11	2.1	19	6.7
Monofilament nets	159	25.0	182	**34.0**	0	0
Ring nets	0	0.0	3	0.7	0	0
Scoop nets	0	0.0	1	0.2	0	0
Seine nets	68	10.6	1	0.2	40	14.1
Skin diving	0	0	1	0.2	0	0
Spearguns	0	0	18	3.1	9	3.2

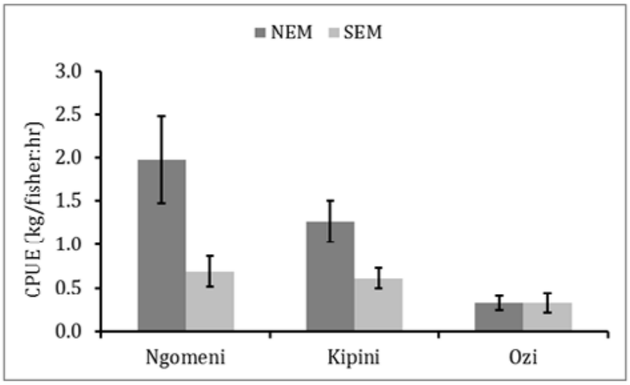

Figure 6. Seasonal catch rate by fishing zone for the Ungwana Bay and Lower Tana Delta artisanal fishery, Kenya.

significant differences between *mashua*-gillnet and canoe-monofilament, and between FRP boat-gillnet and canoe-monofilament ($p < 0.05$ in both cases). All the craft-gear combinations used in Kipini landed significantly larger sizes of *A. africanus* and *O. ruber* (Kurskal Wallis test: Df = 6, $F = 327$, $p < 0.05$), except foot fisher-monofilament ($p = 0.09$). In the Ozi fishing area, the canoe-basket trap landed significant larger specimens of *A. africanus* than canoe-gillnet and canoe-seine net (Kruskal Wallis test: Df = 2, $F = 490$, $p < 0.001$). The pair-wise comparison test confirmed significant differences between canoe-basket trap and canoe-gillnet, and canoe-basket trap and canoe-seine net ($p < 0.05$ in both cases).

Discussion

Fisheries of the Malindi-Ungwana Bay and Lower Tana Delta on the north coast of Kenya focus on resources associated with marine, estuarine and riverine habitats. Ngomeni, Kipini and Ozi fishing areas show distinct fisheries catch composition attributed to differences in habitat type. Ngomeni is exclusively a marine habitat while Ozi is entirely riverine. Kipini is composed of both estuarine and marine habitats. Though not investigated in this study, the differences in environmental elements (nutrients, temperature, depths and turbidity) in different habitat types are the

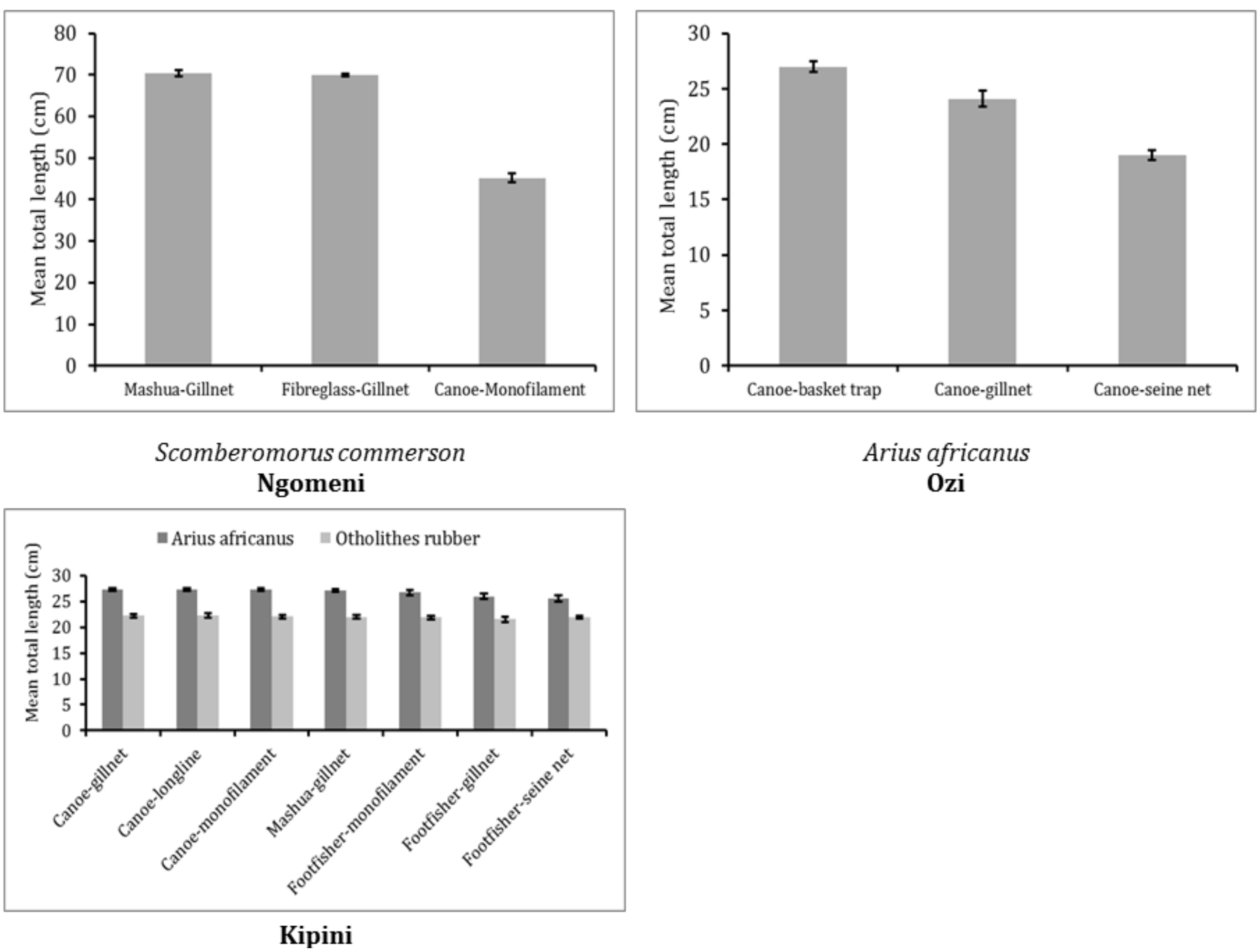

Figure 7. Mean total length of the most abundant fin fish species across zones with craft-gear combination in Ungwana Bay and Lower Tana Delta, Kenya.

key factors contributing to the distinct catch composition across habitat types and fishing areas (Winemiller and Leslile, 1992; Munga *et al.*, 2013). For example, Winemiller and Leslie (1992) observed that the differences in environmental variables (depth, water type, substrate type and turbidity) in habitats determined the distinct assemblage of fish resources in tropical freshwater and marine ecotones. Munga *et al.* (2013) also made similar observations where the differences of depth, turbidity and season in Malindi-Ungwana Bay were the main environmental factors driving the distinct composition of panaeid shrimp species. The variations in environmental parameters in the 3 habitats are likely to be the key factors for the distinct catches experienced by the artisanal fisheries in Ngomeni, Kipini and Ozi.

In this study it was found that the marine habitat is rich in species diversity compared to the estuarine and riverine habitats. High species richness was observed in catches made by *mashua* boats in Ngomeni fishing zone. The *mashua* boats are equiped with outboard engines and sails and are able to exploit fisheries resources over longer periods during the year by accessing deeper offshore waters with high species diversity and landings (Munga *et al.*, 2014). However, estuarine habitats are generally characterized by higher species diversity than the marine and riverine habitats. Murase *et al.* (2014) for instance, observed a higher species diversity in the estuarine habitat (53.6%) than the marine habitat (46.4%) in the gulf of Nicoyaon the Pacific coast of Costa Rica. In the present study, the higher species diversity in the marine habitat may be attributed to the differences of fishing effort in the three (3) fishing areas. The Ngomeni fishing area (marine habitat) recorded the highest catch-rate compared to Kipini and Ozi. In addition to habitat and craft, high species richness was also associated with gillnets commonly used with *mashua* boats, leading to a catch with the highest species diversity (Munga *et al.*, 2014).

Ngomeni, Kipini and Ozi reported different catch-rates associated with different fishing gears and craft. Ngomeni had considerably better fishing crafts including *mashua* and FRP boats. Kipini fishers also employed *mashua* boats but not the FRP boats, while FRP boats were absent in Ozi. The seasonal catch-rate was the during NEM season than the the SEM season. Mwangudza *et al.*, (2017) also observed higher catch-rates in the NEM season in Malindi-Ungwna Bay. The differences in weather conditions between the NEM and SEM seasons are a key factor in determining differences in catch-rates between the seasons (Munga *et al.*, 2014) because the NEM season is characterized by warm temperatures and calm waters while the SEM season is associated with cool temperatures and rough waters (McClanahan, 1998).

In Ngomeni, the most abundant species landed with craft-gear combination was *S. commerson*. Largest fish were landed by *mashua*-gillnets confirming the observation made by Munga *et al.* (2014). This was associated with the ability of *mashua* boats (fitted with larger mesh-sized gillnets) to access offshore areas and larger fish (Munga *et al.*, 2014). Like other tropical estuarine habitats, Kipini is characterized by a multi-gear and multi-species fishery. *A. africanus* and *O. ruber* were the most abundant species in Kipini, caught by seven (7) different craft-gear combinations. Siddique *et al.*, (2013) made similar observations on muti-gear and multi-species catches in the estuarine habitat of the Meghna River, Bangladesh. *A. africanus* was also the most abundant species in the Ozi fishing area with canoe-basket trap combinations landing the largest sizes of this species. The Ozi fishing area borders on the Kipini estuarine habitat and is occasionally characterized by brackish waters which supports some of the marine-estuarine species including *A. africanus*.

Conclusion

Ngomeni, Kipini and Ozi fishing areas in Malindi-Ungwana Bay and the Lower Tana Delta have distinct catch compositions attributed to the existence of marine, estuarine and riverine habitats. The fishing zones are also characterized by different catch-rates mostly associated with differences in fishing methods. Marine habitats in the syudy area are rich in species diversity with larger sized individuals compared to the estuarine and riverine habitats. While *mashua*-gillnets and canoe-basket traps landed the largest sizes of the most abundant species in Ngomeni and Ozi respectively, multi-craft and gear combinations landed the largest fish in Kipini. Marine habitats were associated with larger sized individuals, suggesting that artisanal fishers would benefit from appropriate fishing crafts such as *mashua* and FRP boats to enable them to exploit the deeper offshore waters. It is recommended that artisanal fishers in these fishing areas are assisted to obtain the craft necessary to venture into the deeper marine habitats, which appear under-exploited, compared to the estuarine and riverine habitats.

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Effect of initial handling by artisanal fishermen on the quality of penaeid shrimps in Kurawa on the north coast of Kenya

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Abstract

This study was conducted to determine the effect of initial handling on the quality of shrimps during and after catch by the artisanal fishermen in Kurawa on the north coast of Kenya. Fishermen collected shrimps from salt ponds and carried them using both insulated and bucket containers. A portion of samples was preserved with ice immediately after catch (control), while the rest were carried in buckets to the landing site and a portion preserved immediately upon arrival (0-hr). The remaining samples were sub-sampled and preserved with ice after 2 hours (2-hr), 4 hours (4-hr) and 6 hours (6-hr), respectively. Biochemical parameters (Total Volatile Bases - Nitrogen, Trimethylamine-Nitrogen, Peroxide Value, p-Anisidine Value) and proximate composition parameters (dry matter, protein, fat and ash content) were used to monitor quality changes of samples with delayed icing. Results showed a significant increase ($p < 0.05$) in biochemical parameter values over time. This indicated progressive deterioration in quality of shrimp with increased delay in icing. Samples preserved immediately after catch (control) exhibited best quality, followed by 0-hr, 2-hr, 4-hr and 6-hr samples, respectively. In general, increased delay in icing caused significant deterioration of shrimp quality although most samples remained within acceptable standard quality limits for the 6-hr delayed icing period.

Keywords: Shrimps, artisanal, handling, quality, icing, Kurawa

Introduction

Decapod crustaceans including penaeid shrimps are economically important marine resources in the world with increasing demand in both domestic and export markets (Sawant *et al.*, 2012). Shrimps are highly susceptible to post harvest spoilage and therefore require handling at low temperatures (Chatzikyriakidou and Katsanidis, 2011). It has been established that initial handling activities such as delayed icing, temperature variation during handling and mode of packaging have contributed majorly to quality loss of captured shrimps (Tsironi *et al.*, 2009; Ali *et al.*, 2013; Imran *et al.*, 2013). Proper handling to ensure maintenance of shrimp quality is therefore essential from an economic point of view as well as for human health considerations. In most cases, artisanal fishers fail to adhere to proper handling practices due to a lack of proper fish handling facilities at the landing sites. This, coupled with negligence, results in serious shrimp quality loss. In Bangladesh, Nowsad (2010) reported serious post-harvest losses in the fisheries sector on an annual basis due to ignorance and negligence in handling and processing of fish products at different stages of the supply chain.

In Kenya, shrimp fishing takes place in Malindi-Ungwana Bay where artisanal and commercial/semi industrial bottom trawl fisheries are conducted (Fulanda *et al.*, 2011; Munga *et al.*, 2013). The artisanal fishers mostly utilize the shallow region of the bay

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while the commercial fishers fish the deeper parts (>3 nautical miles offshore). The penaied shrimp species exploited in Malindi-Ungwana Bay are mainly *Fenneropenaeus indicus*, *Penaeus semisulcatus*, *Penaeus monodon, Penaeus japonicus* and *Metapenaeus monoceros* (Munga *et al.*, 2013). A preliminary study on the status of the artisanal shrimp fishery in the Malindi-Ungwana Bay (KMFRI, 2014) reported the existence of poor handling by artisanal fishermen and lack of adequate handling facilities. However, the extent of quality loss was not yet established quantitatively.

Biochemical quality parameters have been used to quantify the extent of quality losses in seafood products, and standard acceptable limits have been established (Lannelongue *et al.* 1982; Bono and Badaluco, 2012; Okpala *et al.*, 2014; Codex Alimentarius Commission, 2015). This includes the use of Total Volatile Bases-Nitrogen, Trimethylamine-Nitrogen, Peroxide values, *para*-Anisidine values and Thiobarbituric acid parameters as indicators of quality loss. Total Volatile Bases Nitrogen (TVB-N) in particular, has been reported (Malle and Poumeyrol, 1989) to be one of the most widely used methods to estimate the degree of quality deterioration in fish, cephalopods such as squid, and crustaceans. TVB-N includes the measurement of trimethylamine (produced by spoilage bacteria), dimethylamine (produced by autolytic enzymes during frozen storage), ammonia (produced by the deamination of amino-acids and nucleotide catabolites) and other volatile nitrogenous compounds associated with seafood spoilage. Trimethylamine (TMA-N) provides an accurate indication of bacterial spoilage in some species with its presence being due to the bacterial reduction of trimethylamine oxide (TMAO) which is naturally present in the living tissue of many marine fish species (Malle and Poumeyrol, 1989). Peroxide (PV) and p-anisidine value (p-AV) on the other hand are standard oxidative quality parameters based on measurements of oil primary oxidation products (peroxides) and secondary oxidation products (aldehydes), respectively (Kasmiran *et al.*, 2016). Oil oxidation is an undesirable series of chemical reactions in which oxygen is added, or hydrogen/electrons are withdrawn, that degrades the quality of an oil giving rise to flavour quality loss, often referred to as rancidity (Kasmiran *et al.,* 2016). According to the FAO/WHO Codex Alimentarius Commission (2015), quality standard acceptability limits for PV is set at 5 $meqO_2$/kg while that of p-AV is set at ≤ 20 $meqO_2$/kg. Any value above the set standard is considered undesirable. Proximate composition determination is also required as it is also affected as quality deteriorates, especially due to deamination of amino-acids and nucleotide catabolites. Poor handling (lack of immediate icing) in the study area was likely to enhance the processes of quality deterioration and compromise the quality of shrimps. This study was undertaken to quantify the effect of delayed icing on shrimp quality after catch to establish the extent of quality loss for purposes of effective management during initial handling.

Materials and Methods

This study was conducted at Kurawa landing site on the north coast of Kenya in Malindi-Ungwana Bay. The study site lies between latitudes 2°30´–3°30´S and longitudes 40°00´– 41°00′E. Kurawa is located in the vicinity of salt ponds that were constructed for salt production, and fishermen harvest shrimp from the ponds. Water is introduced to the ponds using water pumps. Fishermen utilize the ponds situated closest to the water inlet where the brine is less concentrated. Since the ponds restrict the movement of shrimps to the sea, shrimp fishing in this area continues throughout the year with variations in catches experienced during the northeast and southeast monsoon periods. Seine nets are the dominant gear used for shrimps harvesting. However, some fishermen deploy their nets in the pump inlet area to trap the shrimps that are sucked through the pump together with water during pumping periods (twice a day during high tides). According to fishermen in Kurawa, spring tides provide better shrimp catches than neap tides. Use of ice is rarely practiced here, except for by the shrimp dealers who bring small quantities in non-insulated containers and gunny bags. Motorcycles are the primary means of transport for the shrimp dealers who mainly transport the product to Malindi town for sale.

Sampling design

Completely randomised design was adopted for this sampling. Six identified fishermen collected samples from the various fishing grounds within Kurawa salt ponds, using both insulated containers (for immediate preservation at the point of catch using ice) and bucket containers (for carrying the remaining sample to the landing site for preservation). The samples from the six fishermen were used as replicates. The sample immediately preserved in ice in an insulated container was considered as the control. The samples carried in buckets to the landing site by each fisherman were placed on separate mats and each immediately sub-sampled and preserved in ice using an insulated container (0-hr sample). The rest of the samples were sub sampled every 2 hours for a period of six hours (2-hr, 4-hr and 6-hr samples), respectively. Samples that were iced immediately at the point of catch before landing were labelled as Control, while those sub-sampled immediately after landing were labelled as 0-hr. Those sampled and iced 2, 4, and 6 hours after landing were labelled as 2-hr, 4-hr and 6-hr samples, respectively. All the preserved samples were thereafter transported using insulated containers to Kenya Marine and Fisheries Research Institute (KMFRI) in Mombasa for laboratory analysis.

Sample treatment

In the laboratory, a 250 gm sub-sample was taken from each of the 0-hr, 2-hr, 4-hr, and control samples for quality evaluation. The samples were homogenised using a mincer and subjected to laboratory biochemical (TVB-N, TMA-N, PV) and proximate composition (% Dry matter, % protein, % fat, and % ash) analysis. The analyses were independently conducted for samples of each fisherman (six replicates), and results recorded appropriately. A total of 36 samples were analysed in triplicates.

Laboratory analysis of biochemical parameters

Total volatile basic-nitrogen (TVB-N)

A sample of approximately 10 g of ground shrimps was homogenized with 10 ml of 20% Trichloroacetic acid (TCA) (w/v) using a magnetic stirrer. The homogenized sample was then cooled for 5 minutes and the TVB-N determined according to the standard methods of analysis adopted from Siang and Kim (1992) using a Conway's Micro diffusion Unit. The TVB-N was calculated using the following formula:

TVB-N (mg/100 g samples) = (14 x N x(X-y) x 100)/ (weight of sample (g))

Where:
N = Normality of the H2SO3
X = Volume (ml) of H2SO4 required for titration
y = Volume (ml) of H2SO4 required for blank

Trimethylamine-Nitrogen (TMA-N) analysis

Trimethylamine in shrimp samples were determined by the Conway technique (Siang and Kim, 1992), which is the same as the TVB-N determination except that prior to addition of potassium carbonate (K2CO3), 1 ml of 10% neutralized formalin was pipetted into the extract to react with ammonia, and thus allow only the TMA-N to diffuse over the unit. The TMA-N was calculated using the following formula:

TMA-N (mg/100 g samples) = (14 x N x(X-y) x 100 x 100)/ (weight of sample (g))

Where:
N = Normality of the H2SO3
X = Volume (ml) of H2SO4 required for titration
y = Volume (ml) of H2SO4 required for blank

Peroxide Value (PV) analysis

Crude fat was extracted according to the Bligh and Dyer (1959) method and determination of PV was done according to Kirk and Sawyer (1991), with some modifications. Approximately 0.3 g of whole shrimp oil was dissolved in 10 ml chloroform and 15 ml acetic acid. The homogenate was shaken vigorously for 30 seconds and drops (1 ml) of fresh saturated aqueous potassium iodide solution added to the mixture and allowed to stand in the dark for 5 minutes. Approximately 75 ml of distilled water was added to the mixture to release the iodine from solution and titrated with 0.01 M sodium thiosulfate solution against a blank. The PV was then calculated as follows;

Peroxide Value (meq O_2/kg) = (10 x volume of titrant (ml))/(weight of oil in kg)

p-Anisidine Value (p-AV) analysis

The Anisidine value was determined according to the American Oil Chemists Society (AOCS) official methods (1997). The reaction produces a solution that is measured through spectrometric methods at 350 nm. A 0.3 g of extracted oil sample in a 10 ml volumetric flask was diluted to volume with isooctane. The absorbance (As1) of the solution was measured at 350 nm wavelength using a spectrophotometer with solvent as reference (Ab2). Approximately 2.5 ml of the oil solution was pipetted into the first test tube and another 2.5 ml of solvent into the second test tube. Approximately 0.5 ml of p-Anisidine reagent was added to each and shaken. After 10 minutes, the absorbance of the sample (As2) was taken at 350 nm using the solution of the second test tube as reference (Ab2). The value was expressed as;

p-AV meq O2/kg = (10 x (1.2 x As_2-Ab_2) - (As_1-Ab_1))/M

Where:
As_1 and As_2 = first and second measure of absorbance of samples
(As_1 = samples with no p-Anidine reagent, As_2 =samples solution + p-Anisidine reagent)
Ab_1 and Ab_2 = first and second measure of absorbance of the blank

(Ab_1= solvent with no p-Anisidine reagent, Ab_2= solvent +p-Anisidine)
M = weight of the sample (g)

Determination of Proximate Composition

Crude protein analysis

Crude protein content in shrimp meat was determined based on the Kjeldahl method (AOAC, 1990). A sample of 5 g was digested in sulphuric acid in the presence of copper sulphate as a catalyst. Thereafter, the sample was placed in the distillation unit (2400 Kjeltec Auto Sample System). The acid solution was made alkaline by adding sodium hydroxide solution. The ammonia was steam distilled into boric acid with indicators. The boric acid was then simultaneously titrated with 0.02 M H_2SO_4.

Calculation of % N = ((A-B) x N x 1.4007)/ (w)

Where:
A and B are volume (ml) of sample titrant and Blank titrant respectively
N is the normality of the titrant
W is the weight of sample (g)

Crude fat content analysis

Crude fat content in shrimp flesh was determined by the AOCS (1997) official method of analysis. The sample was extracted with petroleum ether, with a boiling range of between 40-60° C. The extract was recovered using a rotary evaporator. The extract was dried, weighed and the fat content calculated as follows:

% crude fat content = ((weight of fat + container) - (weight of container)/ (weight of sample (g)) x100

Dry Matter analysis

Dry matter was calculated by analysing moisture content according to AOCS (1997) official method of analysis, after which the moisture (%) content was subtracted from 100%. 5 g of crushed whole shrimps was dried for 24 hours on a pre-weighed aluminium foil in an oven at 105° C and cooled in a desiccator to room temperature. The weight was then taken and recorded accordingly. Calculation of the moisture content was carried out as follows:

Moisture content (%wet basis) = (Initial weight-final weight)/(initial weight) x 100
Dry matter was calculated as follows:
Dry matter (%) = 100% - % moisture content

Ash content analysis

Ash content was determined according to the AOCS (1997) official method of analysis. A shrimp sample weighing 5 g was dried for 24 hours in an oven at 105° C and cooled in a desiccator to room temperature, weighed and recorded accordingly. The samples were put in a micro furnace at 450° C for six hours on pre-weighed aluminium foil to ash. The ash content was calculated as follows:

% Ash content = (initial weight before ash-final weight after ash)/(initial weight before ash) x100

Data Analysis

Data were analysed using MINITAB® 14 statistical software. All data was tested for normality using the method of Shapiro Wilk (1965) before being subjected to one way analysis of variance (ANOVA). Where differences were noted, tests for significance differences in means were conducted using Turkey's pairwise comparison analysis. All tests were considered significant at a confidence level of 95% ($\alpha = 0.05$).

Results

Changes in proximate composition of shrimps during initial handling

The results of proximate composition were as indicated in Table 1 below.

The results show an increase in percentage of dry matter as delay in icing increased. However, only the 6-hr delayed icing samples were significantly different from the rest. The Control sample (shrimp iced immediately after catch) gave the lowest value (20.10 ± 0.70%) while the 6-hr sample gave the highest value (27.90 ± 1.07%). A pairwise comparison test did not show any significance differences between the control, 0-hr, 2-hr and 4-hr samples for dry matter content. For protein content (%), the 4-hr and 6–hr samples differed significantly ($p < 0.05$) from the control, 0-hr and 2-hr samples. Samples for both fat (%) and ash (%) content did not show significance difference ($p > 0.05$) for the 6-hr delayed icing period. The increase in dry matter with time during delayed icing was mainly attributed to decrease in moisture content as a result of drying through evaporation when preservation was delayed. However, even though an increase in the dry matter (%) was detected, a significant difference was only apparent in the sample with a delayed icing period of 6 hours.

Table 1. Turkey's pairwise comparison on mean shrimp proximate composition during delayed icing at Kurawa sampling station.

	Control	0-hr	2-hr	4-hr	6-hr
Dry matter	20.10±0.70[a]	22.86±0.83[a]	23.33±0.90[a]	23.99±1.06[a]	27.90±1.07[b]
Protein	12.04±0.28[a]	12.04±0.28[a]	12.95±0.12[a]	11.55±0.24[b]	14.59±0.25[c]
Fat	1.22±0.05[a]	1.28±0.16[a]	1.43±0.07[a]	1.43±0.10[a]	1.42±0.12[a]
Ash	2.85±0.29[a]	3.02±0.16[a]	3.41±0.35[a]	3.43±0.23[a]	3.85±0.20[a]

N = 6. Different letters (superscripts) in the same row indicates significance difference ($p < 0.05$). Values are given as mean ± standard error (SE). Units of the parameters are given in percentages.

Changes in biochemical quality parameters during initial handling

During the delayed icing period, there were significant changes in TVB-N, TMA, PV and the p-AV with all the biochemical parameters increasing with time (Table 2).

Changes in TVB-N during the 6 hours delayed icing period ranged from 1.84 ± 0.30 mg to a maximum of 16.04 ± 0.78 mg N/100 g. The results showed a consistent increase in the level of TVB-N values as delay in icing period increased. However, the values were still within the edible acceptability limit (≤ 20 mg N/100 g) despite the significant loss in quality as icing was delayed.

Changes in TMA-N followed the same pattern as those of TVB-N since TMA-N forms part of the TVB-N. The TMA-N results were 1.58 ± 0.25 mg N/100 g for the control and 4.38 ± 0.25 mg N/100 g for the 6 hours delayed icing samples respectively. Taking into consideration that the limit of acceptability for TMA-N was considered at 5 mg N/100 g (Bono and Badaluco, 2012), the quality loss within the 6 hours delay in icing did not surpass the limit of acceptability. However, there was appreciable loss in the quality of shrimps due to delay in icing.

PV increased significantly with delayed icing period. Values ranging from 4.03 ± 0.30 meq O2/kg for the control to a maximum of 16.25 ± 0.90 meq O2/kg for the 6-hr sample were observed. Turkey's pairwise analysis showed that the differences were mainly attributed by the control and 0-hr samples only. Otherwise, the 2-hr, 4-hr and 6-hr samples were not significantly different. Consumer acceptability of PV value in fish was given as 0-2 mmol/kg as very good, 2-5 mmol/kg as good, 5-8 mmol/kg as acceptable and 8-10 mmol/kg as spoilt (Okpala *et al.*, 2014) Conversion of these values to meq O2/kg gives values of 0-4 meq O2/kg as very good, 4-10 meq O2/kg as good, 10 -16 meq O2/kg as acceptable and 16 - 20 meq O2/kg as spoilt. Going by the results obtained in this study,

Table 2. Turkey's pairwise comparison on mean biochemical quality parameters during delayed icing at Kurawa sampling station.

	Control	0-hr	2-hr	4-hr	6-hr	Standard limits of acceptability
TVB-N	1.84±0.30[a]	5.34±0.55[b]	8.60±0.43[c]	13.16±0.83[d]	16.04±0.78[e]	< 25 mg N/100g (Bono and Badaluco, 2012)
TMA-N	1.58±0.25[a]	2.00±0.28[a]	3.02±0.56[b]	3.35±0.28[b]	4.38±0.25[b]	5 mg N/100 g (Bono and Badaluco, 2012)
PV	4.03±0.30[a]	8.85±0.59[b]	13.00±0.78[c]	14.04±1.20[c]	16.25±0.90[c]	10-16 meq O_2/Kg (Okpala *et al.*, 2014)
p-AV	4.32±0.44[a]	2.88±0.10[a]	11.62±0.35[b]	28.37±0.56[c]	50.85±0.83[d]	≤ 20 meq O_2/Kg (Codex Alimentarius commission, 2015)

N = 6. Different letters in the same row (superscripts) indicates significance difference ($p < 0.05$). Values are given as means ± standard error (SE). TVB-N and TMA-N are given in mg%. PV and p-AV are given in meq O_2/kg.

all sample were still within the acceptable range, though delayed icing for six hours pushed the shrimp quality almost to the spoilt end of the spectrum.

Para-anisidine values showed a significant increase with delayed icing period. There was significant differences in the 2-hr, 4-hr and 6-hr samples. However, the control and 0-hr samples did not exhibit any significant difference. The Codex Allimentarius Commission (2001) sets the limit of acceptability for p-Anisidine values at < 20 meq O2/kg. Results showed that the 4 hours delayed icing period pushed the quality indicator value beyond this limit of acceptability.

Discussion

Changes in proximate composition of shrimps during initial handling

Proximate composition of the samples showed insignificant changes in fat and ash content throughout the delayed icing period. Dry matter and protein changed significantly after four and six hours delayed icing respectively. Shrimp protein content (%) of between 12.04 and 14.59 indicates a good protein source similar to those reported by Sephan and Benjakul (2012). The deamination of amino-acids and nucleotide catabolites by bacterial activity did not affect protein composition significantly as it was seen to remain stable throughout the six hour delayed icing period. Equally, no major effect was noted in the fat and ash content indicating no or little effect on the quantity of the two parameters with a delay in icing.

Changes in biochemical quality parameters during initial handling

Total Volatile Bases-Nitrogen (TVB-N)

TVB-N is one of the most widely used methods to estimate the degree of decomposition of volatile nitrogenous compounds in seafood spoilage (Malle and Poumeyrol, 1989; Riquixo, 1998). TVB-N occurs due to continuous production of volatile bases caused by a breakdown of proteins through the action of microbes (Babu *et al.*, 2005). TVB-N scale of acceptability has been reported to range from <12 mg N/100 g for fresh raw shrimps, 12 – 20 mg N/100 g for edible but lightly decomposed, 20 – 25 mg N/100 g for borderline and > 25 mg N/100 g for inedible and decomposed (Lannelongue *et al.*, 1982; Bono and Badaluco, 2012; Okpala *et al.*, 2014). Several reports (Boee *et al.*, 1992; Mahmud *et al.*, 2007) observed an even increase in TVB-N during shrimp storage, indicating continued decomposition leading to quality loss. Similarly, in this study, there was a continuous significant increase in TVB-N values with the control sample giving the least TVB-N value and the 6-hr sample giving the highest value. These changes were attributed to the delay in icing of shrimp during initial handling. However, as much as TMA-N values increased with a delay in icing, they remained within standard limits of acceptability (< 25mgN/100g) for the six hour period.

Trimethylamine –Nitrogen (TMA-N)

TMA-N is formed in spoiling fish by the action of certain species of bacteria on the substance trimethylamine oxide (TMAO). Determination of TMA content is a measure of bacterial activity and spoilage (Aitken et al. 1982). TMAO is said to be an important compound for maintenance of physiological functions in fish and shellfish and also a key substance in the spoilage of raw or processed seafood (Norman and Benjamin, 2000). In this study TMA-N values ranged between 1.58 mg N/100 g and 4.38 mg N/100 g for the control and 6-hr sample, respectively. Similar results were reported in other studies (Mahmud *et al.*, 2007; Okpala *et al.*, 2014). The increase in these values were mainly attributed to a delay in icing. However, the standard limit of acceptability for TMA-N (5mgN/100g) was not surpassed within the six hour delay in icing. The shrimps were therefore still edible despite the delay before icing.

Peroxide Value (PV)

Lipids contain high levels of polyunsaturated fatty acids (PUFA) which are highly susceptible to oxidation. According to Boran *et al.* (2006), the degree and rate of lipid oxidation is influenced by the composition of fatty acids, oxygen concentration, temperature, surface area and water activity. In this study, significant change in PV with increased delay in icing period was observed similar to those observed by Nirmal and Benjakul (2009) as well as Chaijan (2011). This was attributed mainly to a delay in icing favouring the oxidation process. The increasing PV value observed from the sample preserved immediately after catch to the 6-hr sample indicates decreasing quality with time. Taking in consideration that the standard limit of acceptability has been set at 10-16 meq O_2/kg (Okpala *et al.*, 2014), the six hours delay in icing lowered its quality to the borderline limit of acceptability. This indicates that rancidity increased with delay in icing.

Anisidine Value (p-AV)

Typically, quantification of primary lipid oxidation products (peroxides) is done using peroxide value (Chaijan, 2011). Alternatively, the increase in concentration of hydro-peroxides results in a wide variety of secondary oxidation products such as aldehydes (Sephan and Benjakul, 2012) measured using Anisidine Value. In this study, there was a significant increase in Anisidine value with the highest value being observed in the 6-hr sample, while control gave the lowest value. Similar observations with storage time was reported by Okpala *et al.* (2014) who associated this with the generation of secondary lipid products, largely non-volatile compounds (aldehydes). The increase in secondary products indicates continued lipid oxidation leading to rancidity. In relation to the control sample, delayed icing enhanced lipid oxidation leading to the observed increase in values of p-Anisidine. With the limits of acceptability being ≤ 20 meqO2/kg (Codex Alimentarius Commission, 2015), the delay in icing of shrimp beyond 2 hours resulted in quality loss beyond the acceptability limit.

In general, delayed icing during initial handling by artisanal fishermen had a major effect on the quality of penaeid shrimps, while icing at the point of catch gave the best quality. The period at which biochemical quality parameters remained within acceptable ranges for all parameters tested was 2 hours. However, TVB-N, TMA-N and PV were within limits of acceptability up to the six hour period. It is recommended that delay in icing of shrimps for more than 4 hours after landing be discouraged and that further research on other quality factors such as microbial load and melanosis should be conducted to provide more information on the general quality attributes of shrimps during initial handling. At the same time, sensitization of fishers on the extent of spoilage due to delay in icing at the initial handling stage should be continually carried out to ensure maintenance of shrimp quality in the small-scale shrimp fishery.

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Leveraging integrated spatial planning for sustainable regulation of coastal tourism activities in Malindi town, Kenya

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Abstract

Unprecedented demand for both land and ocean space within the coastal zone to support tourism has continued to negatively impact the coastal marine environment leading to degradation. Poorly planned and regulated tourism activities on land and sea have led to degradation of environmentally sensitive marine areas, encroachment on public beaches, erosion of the shoreline and blockage of public access points to the beaches. These impacts transcend the land and ocean continuum necessitating the need for regulation. Spatial planning is one of the key tools that provides a pre-emptive strategic framework for regulating tourism uses so as to prevent harmful development and mitigate the impact of potentially polluting activities. However, spatial planning as applied in Kenya has focused on the regulation of physical developments on land such as the construction of hotels but not on the related tourism activities that emanate from such developments. In this case, activities that tourists engage in outside of the physical hotel structure such as swimming, leisure walks, sport fishing, souvenir collection, and snorkeling are not the subject of spatial planning leading to unsustainable use within the coastal zone. This study makes a case for adopting an integrated spatial planning approach as a lever for regulating tourism activities within this expanded lens, beyond just the buildings and activities that take place within the hotel establishments. The spatial planning approach would include a holistic regulation of coastal tourism activities within both terrestrial and marine spaces in order to attain sustainable management of the marine ecosystem.

Keywords: Tourism, Spatial Planning, Blue Economy, Coastal Zone, Pollution, Kenya, Malindi

Introduction

Despite coastal zones being recognized as highly productive ecosystems, they continue to face degradation and pollution mainly from anthropogenic activities (UNEP, 2006). The coastal zone refers to the land, sea and atmosphere interface (FMI, 2018), and is defined as "the geomorphologic area where the land interacts with the sea and comprises of both terrestrial and marine areas with coexisting biota and abiotic components" (NEMA, 2017). The coastal zone has natural systems that offer essential goods including gas, minerals, oils, fish and services such as space for recreation, and natural safeguarding of the beaches from storms and tidal waves (FMI, 2018). Coastal resources such as mangrove forests trap sediments from inland areas decreasing the chances of siltation of seagrass and coral reefs and also regulate freshwater output through evapotranspiration (Muigua *et al.*, 2015). According to UNEP (2006) more than one third of the total population in the world reside in coastal areas and on small islands, which constitute about 4 percent of the planet's total land area.

Coastal zones are therefore essential for the realization of a sustainable blue economy for the countries and populations that depend on it. Within the coastal zone, the blue economy encompasses a sustainable ocean-based economic model that is largely dependent on coastal and marine ecosystems and resources (UNDP, 2018). Thus, the concept of blue economy within the coastal zone includes all activities that explore and develop ocean resources,

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use ocean space, protect the ocean environment, use ocean products as a main input and provide goods and services to support ocean activities. In specific terms, the coastal zone blue economy includes activities such as tourism, mineral exploration, aquaculture, fisheries, mariculture, port development and maritime security (UNECA, 2016a). In Africa, the ocean resource base in the 38 African coastal states includes a geographical jurisdiction of about 13 million square kilometers including territorial seas and Exclusive Economic Zones [EEZ] (UNECA, 2016a). A sustainable blue economy refers to freshwater and maritime economic activities that contribute to the overall sustainability of lakes, rivers, oceans, seas and coasts (UNECA, 2016b).

Tourism has evolved across the globe to become one of the most dynamic, diverse and expansive blue economy sectors of the 21st century (UNWTO, 2015a). The same situation in evident in Africa where coastal tourism is one of the main driving sectors of the blue economy followed by oil and gas, minerals, blue carbon, and fisheries (AU-IBAR, 2019). The global tourism sector contributes approximately 10.3 per cent to the global GDP, accounting for some 300 million jobs (WTTC, 2020a). Similarly, Africa's tourism sector contributes around 7.1 per cent to the continent's GDP, employing some 24.6 million people (WTTC, 2020b). The continent is now regarded as the world's second fastest growing tourism regions, after the Asia-Pacific (Töre, 2019). According to the Africa Blue Economy Strategy, coastal tourism is estimated to grow in value from about US$ 80 billion in 2018 to about 140 billion in 2030, and 180 billion by 2063 (AU-IBAR, 2019).

The Western Indian Ocean (WIO) region's economic value in terms of coastal and marine tourism represents about 69 per cent (US$14.3 billion annually) of ocean output, making it the largest economic contributor to the WIO's economy (Obura, 2017).This includes coastal tourism within the 10 countries of the WIO region; namely Somalia, Kenya, Tanzania, Mozambique, South Africa, Comoros, Seychelles, Madagascar, Mauritius and France's Reunion Island (Obura, 2017). Kenya, in its economic blue print named Vision 2030, identified tourism as one of the sectors to spur growth and development in its quest to transform into a newly industrialising, middle-income country providing a high-quality life to all its citizens by the year 2030 (GOK, 2007). This is because tourism contributes about 10% to GDP and 9% of total formal wage employment (JICA, 2018). Tourism is Kenya's third largest foreign exchange earner after tea and horticulture. According to the Kenya National Bureau of Statistics, tourism earnings grew by 3.9 per cent from KSh 157.4 billion in 2018 to KSh 163.6 billion in 2019 (KNBS, 2020). This contribution to the country's GDP emanated from its five tourism destinations including the Coastal, Central highlands and Rift Valley Region, Western, Northern and Southern circuits (GoK, 2015). Among the five tourism destinations, coastal tourism is the most vibrant and preferred by visitors as demonstrated by the highest proportion of hotel bed-nights occupancy at 38.2 per cent (KNBS, 2020). Kenya's coastal tourism destination includes a coastline that stretches over 536 km along the Indian Ocean covering a total land area of 569,140 sq. km (GoK, 2009; FAO, 2018).

Tourism constitutes a vital developmental aspect in coastal areas, characterized by leisure and recreationally-oriented activities that occur in the land-sea interface and in offshore coastal waters (Polyzos and Tsiotas, 2012). The dominance of tourism in the coastal zone arises from natural, unblemished scenery, mountains, beaches, traditional historical picturesque towns and villages as well as historic monuments (Vehbi, 2012). However, the rising levels of tourism growth within the coastal zone degrades the fundamental ecological resources on which tourism is dependent; largely due to competing needs. The massive demand of coastal space has resulted in an increase in the number of actors such as the local population, businesses, tourists, local authorities as well as national government agencies (Kiousopoulos, 2010). This massive demand leads to space contestation which in turn leads to degradation, especially when there is no deliberate spatial planning mechanism to structure the various land and sea uses. Inadequate planning controls is one of the core factors triggering degradation and alteration of the natural environment within the coastal zones (Vehbi, 2012).

Spatial planning provides one of the key approaches that is essential in the sustainable management of the coastal zone. Spatial planning is a public and political process of examining and allocating the spatial and temporal distribution of human activities (Hoi and Hein, 2014). Spatial planning stretches past "traditional" land use planning and outlines a strategic framework to guide impending development and policy interventions whether or not these are related to formal land use control (Okeke, 2015). According to Hersperger *et al.* (2018), spatial planning is wider in scope and includes four main typologies; project-master-, land-use- and strategic planning. Spatial planning involves the integrated and rational intervention in the distribution of both the land and sea regions for a number of functions, considering socioeconomic development and environmental needs (COBSEA, 2011). Spatial planning has a major role in enhancing the local and natural environment by averting both new and contemporary development from being placed at undesirable risk from, or being harmfully impacted by, unacceptable levels of soil, air, water or noise pollution (Westminster City Council, 2014). Spatial planning contributes to the harmonization of sectorial plans and strategies that respond to uses within a similar geographical area. It also goes beyond providing guidelines on physical developments on land to integrate these developments into the wider natural environment.

In this paper, both procedural and substantive aspects of spatial planning are assessed as applied in the regulation of tourism activities within the coastal zone in Kenya. The procedural aspects assessed include the institutional framework for planning and public participation in the process of spatial planning. The substantive aspects involved assessment of data on specific spatial planning tools applied in the regulation of land uses within the coastal zone. Using Malindi Town as a case study, it is argued that spatial planning has not been effectively applied due to the lack of an approved spatial plan targeting regulation of tourism activities within both the terrestrial and marine area in Malindi, and disproportionate focus on regulating land-based physical tourism accommodation facilities without concomitant attention to auxiliary tourism activities such as snorkeling, souvenir collection, leisure walks and swimming, and poor institutional coordination. It is argued that there is need for a review of the current planning approach to incorporate a more integrated framework to ensure sustainable management of the coastal zone.

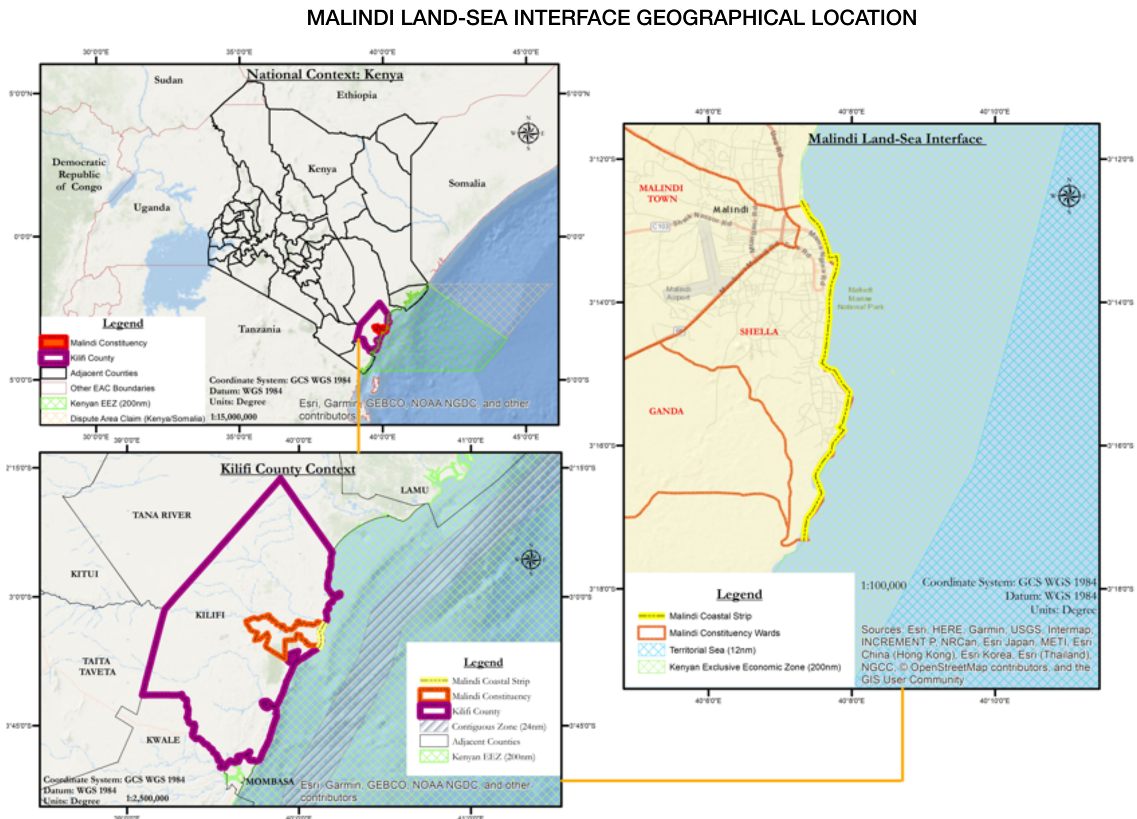

Figure 1. Map of the study area showing Kenya, Kilifi County and Malindi.

Materials and methods

The study area was restricted to Malindi which is one of the towns located within the coastal zone of Kenya. Other towns on the coast include Mombasa, Kilifi, Watamu and Lamu. Malindi is located in Kilifi County, which is one of the 47 counties comprising the territory of Kenya. The Indian Ocean is a major feature in Malindi with a coastline of about 155 km running from Mida to Ungwana. Malindi lies between latitude 2°20° and 4° South and longitude 39° and 4° East (Kitsao, 2010). It has an outstanding history dating back to the 14th century which attracts significant tourism. Some of these historical attractions include the Vasco Da Gama Pillar and the Portuguese Chapel. Malindi also has a rich repository of creeks, coral reefs, silvery white sand beaches that are lined up with palm trees, and marine parks and mangrove forests which have social, economic and environmental significance.

Using a mixed research design, data was collected on tourist facilities within the coastal zone in Malindi, the spatial planning tools used to regulate these touristic activities, the process of spatial planning, and the roles of various institutions involved in the regulation process. Data collection involved integration of quantitative and qualitative methodologies in the research process (Terrell, 2012). This mixed approach was useful for the purposes of ensuring that all research questions were answered and for triangulation of findings (Omukoto *et al.*, 2018). Data was collected through document analysis, questionnaire administration, key informant interviews and participant observation. Document analysis involved developing a thorough understanding and scholarly critiques of specific written materials (Mugenda, 2013). These included published reports, journal articles, case law, policies and legislations.

A semi-structured questionnaire was used to collect quantitative data from tourism activity managers/owners in hospitality facilities such as beach hotels and holiday apartments. The questionnaire covered areas such status of application of spatial planning, challenges and suggestions for improvement. This study administered 46 questionnaires to hospitality facilities. A structured interview guide was used to collect qualitative data from 5 key informants. The interviews were conducted face to face. The key informants interviewed were the Kilifi County Physical Planning Officer, the Kilifi County Fisheries Officer, the Kilifi County Land Surveyor, the Warden in Charge of Malindi Marine Park, and the National Environment Management Authority, Kilifi County. These interviews were conducted within the months of June and July 2019. Qualitative data was also collected using 3 focus group discussions with fishermen, Beach Management Units, and boat operators.

Results and Discussion

Types of Tourism Activities within the Coastal Zone in Malindi

Tourism is defined as the set of permissible activities visitors get involved in by reason of their movements, including the attractions and the means that originated them, the facilities created to satisfy their needs and the economic, social, cultural, psychological, political, geographic and environmental phenomena as well as relationships resulting from all of the above (Cunha, 2014). Tourism is therefore an interrelated system of demand (international tourist markets, domestic tourist markets and residents' use of tourist attractions, facilities and services) and supply factors (attractions and activities, accommodation, other tourist facilities and services, transportation and other infrastructure) (UNWTO, 1994). Coastal tourism takes place within a unique resource combination at the interface of land and sea which has amenities such as water, beaches, scenic beauty, rich terrestrial and marine biodiversity, diversified cultural and historic heritage (UNEP, 2009). This form of tourism involves both consumptive activities such as fishing, shell and coral collection and non-consumptive activities such as swimming, diving, boating, surfing, wind-surfing, jet skiing, bird watching, and snorkeling (UNEP, 2009).

As a result of the accumulated effects on tourism, the coastal zone experiences biodiversity reduction, resource depletion and human health problems. Kenya's coastal tourism continues to experience a proliferation of tourism activities estimated to be a key user of the coastal zone at 45% (GoK, 2009; FAO, 2018). These activities which include accommodation, tourist attractions such as national parks, reserves and coastal beaches, food and beverage facilities, snorkelling, swimming, recreational fishing, leisure walks, collection of corals and tour services have an impact on the sustainable use of the coastal zone. Oyieke (2001) observed that Kenya's coastal zone has an array of tourism activities which generate challenges that include habitat degradation and unsustainable utilization of natural resources.

Accommodation facilities, which include serviced apartments, beach hotels, restaurants, health and spa resorts, private residences and member's clubs, are the major tourism use of the coastal zone within Malindi. Assessment of the classification of these accommodation facilities demonstrated that 68 percent of them were above the 3-star level. Hotel classification, which involves ranking by use of nomenclature such as stars or diamonds, is used as an indicator of the level of service and standards found within an individual establishment (UNWTO, 2015b). For example, one star denotes basic facilities while five star denotes luxurious facilities and services (UNWTO, 2015b). While hotel classification is mainly used as an indicator by potential guests on what to expect, they also implicitly demonstrate the level of pollution emanating from such establishments. In a study of the impacts of solid waste pollution from beach hotels on the Kenyan South Coast, Muthini *et al.* (2003) note that there is a correlation between the amount of waste generated by the beach hotels and their level of classification and bed occupancy rates.

In addition to their primary function of accommodation and related to their classification levels, tourism accommodation facilities in Malindi also offered extra services. Approximately 60 percent of the facilities offer swimming pool services which emerged as the main type of amenity among categories of extra services. Other types of extra services offered by the tourism establishments included spas offered by 20 percent of facilities, laundry services together with a convenience shop each offered by 8 percent, restaurants and tennis courts offered by 2 percent while the rest did not have any additional amenities. Depending on the nature of these additional services, they add to the polluter effect of the general establishment. According to Rajak (2019), this is due to concentration of human and machine activities to support these additional services such as additional air conditioning, automobile emissions from generators and increased solid and liquid waste from restaurants, spas, laundries and swimming pools.

Snorkelling offers tourists an opportunity to sample the natural resources underneath the ocean surface but also contributes to its pollution and degradation. It provides a distinct way for tourists to observe coral reefs, mudflats, mangroves, sea-grass beds and the diverse species of fish found in the waters of the Indian Ocean at Malindi. It is a tourist activity undertaken mainly in Malindi Marine Park offered by the local tourist operators under supervision of the KWS warden. Divers and snorkelers cause degradation of reefs through damage from fin kicks, pushing or holding coral, dragging gear, and kneeling/standing on coral (Roche *et al.*, 2016).

Recreational fishing constitutes another tourist activity. It involves "fishing of aquatic animals that does not constitute the individual's primary resource to meet nutritional needs and are not generally sold or otherwise traded on export, domestic or black markets" (FAO, 2016). The Malindi Fisheries Resource Officer reported that recreational fishing is mainly undertaken by foreign tourists who hire boats for their fishing expeditions. Apart from the direct impact on fish resources, this tourism activity contributes to degradation of the land-sea interface through damage to coral reefs due to anchoring of boats, pollution through littering in the ocean and loss of scenic beauty due to indiscriminate anchoring and abandoned boats. According to Reef Resilience Network (2020), boat anchors within areas of heavy recreational boating can cause considerable damage to coral reefs through coral breakage and fragmentation.

Swimming and leisure walks are core tourism activities that also contribute to pollution of the land-sea interface. As one of the oldest coastal tourist areas in Kenya, the Malindi land-sea interface offers swimming as a coastal recreational activity carried out on Malindi beach, in Malindi Marine Park and tourism hospitality facilities such as serviced apartments and beach hotels. Malindi beach has golden-brown sand where may tourists enjoy leisure walks. Swimming and leisure walks contribute to the degradation of coral reefs through trampling especially in areas with high human use. Similar findings were reported in a study in the United States that argued that damage of coral reefs is found at shoreline access points where people stand or walk to enter or exit the ocean water (Waddell, 2005).

Vending of curios made from corals is also an important tourism-related economic activity within coastal regions but also leads to degradation of the coral reefs. Curio vending in Malindi is mainly an afro-craft outdoor tourist activity located along the land-sea front characterized by existing curio stalls and vending shops where tourists buy an assortment of souvenir items. The collection of corals for curios and souvenir purposes may lead to conservation challenges as reported by the United Nations Environment Programme study on marine and coastal area problems in Bangladesh (UNEP, undated).

As tourism increases, there is an increase in coastal user conflicts, and greater stress is placed upon the environment on which it depends (Omboga, 2000). The increased development of accommodation facilities within the fragile coastal and marine ecosystem has led to the destruction of coral reefs, lagoons, and sandy beaches (GoK, 2009; 2012). More often than not these tourism activities use the ocean for wastewater disposal thus the potential exists for pollution due to poor waste management (GoK, 2012; Munga *et al.,* 2006). The Museum and the Marine Park attract visitors who stay in the accommodation facilities but contribute to the degradation of the coastal zone by overcrowding, trampling, over exploitation of marine resources and indiscriminately dumping solid waste such as water bottles along the beach as they enjoy their leisure walks. Tourism accommodation facilities have also encroached into the 60-meter setback line endangering the fragile beach and marine ecosystem. Boats used for recreational fishing and tours also need adequate space planned and allocated for docking or when carrying out mechanical repairs in a manner that they do not lead to either visual pollution due to interference of the scenic beauty or pollution from oils used in the engines.

Spatial Planning Tools for Regulation of Tourism Activities

The basic ideology of spatial planning is the control of development on land and sea through rules for land and sea use, including prohibitions and sanctions, that are unambiguous to enable efficacious implementation by enforcing agencies and the courts (COBSEA, 2011). The rules, prohibitions and sanctions under spatial planning are preventive in nature and implemented through tools such as development control permits, zoning ordinance, and building standards usually contained in approved statutory spatial plans (Wehrmann, 2011; Okeke, 2015). Environmental tools including environmental impact assessments (EIAs), plans and environmental audits are also applied concurrently with the tools contained in the spatial plans to regulate physical developments.

Presently, spatial planning tools applicable in Kenya for regulating all land use activities including tourism are based on the national physical and land use development plan, county physical and land use development plans, and local physical and land use development plans, which are prepared for city, municipality, town or urban centre jurisdictions. The provisions for the preparation of these spatial plans and the ensuing tools is contained in Part III of the Physical and Land Use Planning Act of 2019. Accordingly, the spatial plans applicable in Malindi are the National Spatial Plan (NSP) 2015-2045, and the Malindi Physical Development Plan. However, the presence of the Malindi Marine Park which is a Marine Protected Area has led to the application of a marine management plan as provided in section 44 of the Wildlife Conservation and Management Act of 2013.

The National Spatial Plan (NSP) 2015-2045 approved in 2015, provides a framework for better national organization and linkages between different sectors within the national space. This Plan recognises Coastal circuits as one of the 5 tourism circuits in Kenya. In respect to coastal areas, the NSP calls for strict regulation of marine resources through the preparation of coastal management plans. In addition, it provides that spatial development plans shall be prepared to guide implementation of flagship projects for the tourism sector. Although the NSP serves as a vital spatial planning tool that provides a broad national framework for coastal zone management, it hasn't exclusively stipulated provisions on regulation of tourism activities within the land-sea interface. It has left the focus on specific zoning rules and prohibitions on use and development within the coastal zone to be provided by lower level plans such as the coastal management plans which are yet to be prepared. This means that the NSP is not effective in regulating tourism uses in the coastal zone, and leaves this to lower level plans to provide detailed and specific allocation of user zones, development control guidelines, and building regulations in the Malindi coastal zone.

The other type of statutory plan applicable at the county level is the Malindi Physical Development Plan which was prepared in 1979. The plan has been the basis for regulating spatial activities and uses including tourism within the terrestrial areas of the Malindi Municipality. However, the plan does not zone the allowable uses within the Indian Ocean's territorial zone. Thus, it is vague as to where the demarcation of the land-sea interface begins and ends, and the uses therein. In addition, the plan lacks zoning regulations such as guidelines for specific densities, plot ratios and permissible auxiliary tourist activities. This has limited its efficacy as such regulations are important in providing specific rules and prohibitions to aid in the implementation of the spatial plan. This is because they contain the criteria against which planning applications are assessed and development control permits issued in line with the approved plan. Hence, without such regulations, developers are not clear on the nature and character of allowable development. Moreover, the plan become obsolete in 2009 having been in place for 30 years which is the statutory time limit for a long-term plan.

However, in 2007 the Municipality engaged in an exercise to update the plan by preparing zoning guidelines. The draft 2007 guidelines are currently being implemented in the regulation of uses even though they have not been formally approved as per the requirement of the Physical and Land Use Planning Act 2019. Section 47 of the Act requires public participation, while section 50 requires approval of such guidelines by the respective County Assembly; in this case the Kilifi County Assembly, before being gazetted by the County Executive. Thus, the continued application of unapproved guidelines together with an obsolete plan limits their efficacy as the decisions made by the agency responsible for development control can be challenged in court as being illegal, null and void. In addition, these guidelines make no mention of the undertaking of environmental impact assessments (EIA) before approval of proposed development or commencement of works on site. This limits the vital role of EIA as a tool for evaluating potential impacts of a proposed development and in consequently providing mitigation measures if the project is permitted, as provided by schedule three of the Physical and Land Use Planning Act and section 58 of the Environmental Management and Coordination Act of 1999. These draft zoning guidelines also do not have explicit regulations to ensure orderly development of tourism activities on the seafront or even the territorial sea.

Another key limitation in the application of the Malindi Physical Development Plan is that it does not apply within the jurisdiction of the Malindi Marine Park which is managed using a different type of plan prepared pursuant to section 44 of the Wildlife Conservation and Management Act (GoK, 2013). The Marine Park is managed using a management plan which is not defined as a spatial plan as per part III of the Physical and Land Use Planning Act 2019. Nonetheless, the management plan provides for the administration of various resources found in the park including fringing reefs, coral gardens in the lagoons, sea grass beds, mangroves, mudflats, marine mammals, turtles and various species of shorebirds. Whereas it provides useful guidelines for tourism activities allowable within the park such as glass bottom boat rides, snorkeling, camping and beach walks, the plan does not have a zoning map and is also not available to the public.

In addition, this management plan only regulates tourism activities taking place within the jurisdiction of the Marine Protected Area (MPA) in ocean waters and not on land where accommodation facilities are found. The MPA is outside the scope of the Physical and Land Use Planning Act limiting involvement of the County Government of Kilifi in carrying out its development control role as provided by section 56 of the Act. Further, neither the Wildlife Conservation and Management Act or the Physical and Land Use Planning Act provides for, or requires, institutional coordination. This limits utility of the management plan in regulating the entire land-sea interface in Malindi where the majority of other tourism activities occur and which also have an impact on the MPA.

Process of Spatial Planning within the Coastal Zone and Challenges Faced

There are four critical procedures that are important in spatial planning. These include: the intention to plan; formulation of the plan; plan approval; and a mechanism for redress. The process of preparing a spatial plan starts with the issuance of an intention to plan articulated through an advertisement by the owner of the plan (government department, county or agency). The notice is publicly displayed to inform the stakeholders of the commencement of the spatial planning process for a particular geographical scope. The geographical scope is based on a cadastral map which demarcates the area that would be subject to the spatial plan. This is in line with section 15 of the Land Registration Act cap 300, that requires the Director of Surveys to "prepare and maintain a map or series of maps, to be known as the cadastral map, for every registration unit". In the context of spatial planning for the coastal zone such demarcation provides the foundation of land and sea use by defining property boundaries, parcel shapes, and plot locations (Libecap and Lueck, 2011).

A clearly demarcated boundary is essential for effective division of a state's administrative responsibility and managing property rights regarding individuals and organizations (Srebro, 2013). The coastal zone requires clarity on boundary demarcation to ensure that the jurisdiction and extent of application of any spatial plan is consistent and clear. More importantly, the Survey Act cap 299 under regulation 110. (1) provides that a strip of land not less than 60 meters in width should be reserved above the high-water mark, held by the State as a public trust and to function as a buffer zone. This study noted a lack of clarity on the demarcation of the extent of the coastal zone in Malindi for purposes of preparation of spatial plans and compliance of tourism activities with the 60-meter buffer zone. According to the Malindi Municipality Land Surveyor, the Government has not undertaken a survey of the coastal zone to produce cadastral maps which would clearly show the spatial extent of the coastal zone in respect to the 60-meter buffer zone and the territorial sea. This lack of an authenticated cadastral map has negatively affected implementation of spatial planning and development control measures. This is due to lack of a clear legitimately enforceable map that lucidly demarcates the extent and boundary of the three jurisdictions of land, territorial sea and the interface between the two where tourism activities thrive. This was demonstrated by about 96 percent of tourist accommodation facilities being situated within the 60 meters baseline.

Formulation of a spatial plan starts with determining the current situation of the planning area as identified in the notice of intention to plan. The current situation then informs the development of scenarios to illustrate possible future development options based on identified challenges and potentials. Thereafter, strategies, policies and measures to address the challenges, and harness opportunities in order to achieve the stated plan objectives and vision are developed. These proposals (strategies, policies and measures) are represented on maps and in text describing the desired spatial structure. The maps and text constitute the spatial plan as a tool for regulating land uses. In the regulation of tourism uses within the coastal zone through spatial planning, it is important that the strategies in the spatial plan address tourism activities on land, sea and the interface between the land and sea.

However, the spatial plans currently being used in Malindi have a land-based focus, as attested by 97 percent of the respondents managing accommodation facilities. This means that the vast majority of respondents viewed the plans as being unconcerned with tourism issues related to the ocean in Malindi. This phenomenon corresponds to various commentators such as Álvarez-Romero *et al.* (2011), Smith *et al.* (2010) and UNEP (2009) who have noted an unprecedented focus in the regulation of land-based activities while neglecting sea-based activities or even those activities that occur on both the land and the sea. Thus, the Malindi coastal zone is still left highly vulnerable to both single and cross-system threats from tourism activities such as pollution, erosion and encroachment of developments fronting the ocean.

The stage of plan formulation also involves public participation and access to information as provided by article 10 and 35 (3) of the Constitution of Kenya 2010, and under section 23 (1) (c), section 40 and section 55 (1) (g) of the Physical and Land Use Planning Act 2019. Under these sections, public participation is enabled through publication of plan completion notices which allow the stakeholders to access information on the draft plans for comments and input. However, 87 percent of the accommodation facility managers in Malindi asserted that they had not engaged in preparation of any spatial plans. This lack of public participation affects the efficacy of these plans associated with the Malindi land-sea interface, as members of the public are not aware of the regulations and user guidelines that they contain. According to Lausche (2019) and UNEP (2009) the limitation of public participation as well as inadequate consultations fundamentally affects user awareness and comprehension of the spatial plans, further limiting implementation and sound decision making. The lack of adequate public participation affects the sustainable management of the coastal zone in Malindi as the people who carry out tourism activities are not empowered to make sound decisions relating to the use of the space. The lack of adequate public participation limits the integration of local knowledge to inform the planning process, implementation and monitoring of development.

Plan approval involves a number of administrative steps to make the plan legally enforceable. For example, spatial plans that are prepared by the county government are presented to the County Assembly, which is constituted by representatives of the people at the ward level, for debate and approval. Once the County Assembly has approved the spatial plan, it is signed by the Governor on behalf of the County Government and gazetted in both the Kenya Gazette and County Gazette. This makes the spatial plan a legal policy document that can then be used to enforce development control. In Malindi, the spatial plan currently being used to regulate tourism uses has not been approved, as noted by the Municipal Physical Planner.

Mechanisms for redress are important for any spatial planning process as it provides aggrieved parties with an opportunity to challenge decisions relating to preparation and implementation of development plans. In Kenya, the redress mechanism as it relates to spatial planning is through administrative mechanisms as provided under part VI of the Physical and

Land Use Planning Act 2019. The Act provides for the establishment of physical and land use planning liaison committees at the national and county government levels to hear and determine appeals against decisions made by the planning authority. One of the key functions of the liaison committees is to hear appeals in respect to physical and land use development plans. The decision of the liaison committee is to be filed with, and considered as a judgment of the Environment and Land Court in line with section 80 (3) of the Physical and Land Use Planning Act 2019. However, if a complainant is not satisfied with the administrative mechanism in relation to the dispute relating to spatial planning, they can thereafter seek further redress from the Environment and Land Court which has jurisdiction on issues touching on land in respect of its use, planning, possession, control, title, compulsory acquisition or any other dispute as upheld in the case of Republic v County Government of Nairobi, Kilimani Project Foundation & 21 others (eKLR, 2020).

Institutional Roles and Responsibilities

The Constitution of Kenya 2010 redefined the institutional framework for spatial planning and development control. Through this Constitution, Kenyans settled for a multi-dimensional approach to the organization and management of governance and state power and hence the devolved system of government as provided in Article 10(2)(a). Article 175 the Constitution created two levels of government, namely national and county governments. Article 186 assigned functions to the two levels of government, allocated finances to the two levels and demarcated geographical territory for each county. As a result, the preparation of spatial plans which was hitherto a preserve of the national government was devolved, giving county governments more responsibility in the preparation and implementation of spatial plans as provided in the Fourth Schedule of the Constitution of Kenya.

Article 67 of the Constitution also established the National Land Commission (NLC) with the responsibility to monitor and have oversight responsibility over land use planning throughout the country. In relation to the coastal zone, article 62 (3) of the Constitution provides that such land shall be held by the national government and administered by NLC. However, Section 6, 10, and 11 of the Physical and Land Use Planning Act has allocated specific spatial planning roles to other National Government agencies including the National Physical and Land Use Planning Consultative Forum, the office of the Cabinet Secretary responsible for land and physical planning, and the Director-General of Physical and Land Use Planning.

The National Environment Management Authority (NEMA) is charged with general supervision and co-ordination over all matters relating to the environment in line with Section 7 and 9 of the Environmental Management and Coordination Act (EMCA). NEMA is mandated by section 9 and 12 of EMCA to coordinate various environmental management activities being undertaken by the lead agencies and may direct such agencies to perform such roles as relates to environmental management. Such coordination by NEMA is supposed to realise integration of environmental considerations into development policies, plans, programmes and projects for proper management and rational utilization of environmental resources. Thus, the Authority is mandated to ensure that all proposed developments undergo environmental impact assessment to demonstrate their impacts on the environment. In doing so, the Authority is supposed to ensure stakeholder participation by publishing the report in the Gazette and newspaper to enable persons to submit their comments. The Authority also involves the other sectoral agencies by requiring them to comment on the proposed developments within their areas of jurisdiction.

On the other hand, the County Government of Kilifi has overall responsibility for planning and development control within their area of jurisdiction. In undertaking this mandate the county is expected to perform the functions of formulating county specific policies, strategies and guidelines, preparation of county spatial plans and urban spatial plans, implementation of the plans, undertaking of research on spatial planning within their area of jurisdiction and participating in the preparation of regional spatial development plans. Section 56 of the Physical and Land Use Planning Act 2019 expressly mandates the county governments to carry out development control within their areas of jurisdiction by ensuring that no development is carried out without approval.

However, this responsibility does not extend to the land between the high and low water marks, the territorial sea, the EEZ and the sea bed which constitute the land-sea interface, as these are under the administration of the NLC. The implication of this is that the responsibility of the county to implement spatial planning starts from the high-water mark, but as noted earlier, the lack of a survey plan demarcating this boundary has led to poor implementation of this role by the County and NLC as demonstrated by encroachment of tourism developments within this space.

Due to the diverse socio-economic activities and natural resources occurring in Kenya's land-sea interface, there are also other sectorial government agencies involved in its planning and regulation. The leading agencies dealing with coastal and marine related issues include: the Kenya Wildlife Service (KWS) which manages Marine Parks and Reserves through preparation of management plans (Malindi Marine Park) in line with the Wildlife Conservation and Management Act No. 47 of 2013, section 6 and 7; the Kenya Forest Service (KFS) who is mandated to conserve, protect and manage all public forests including mangroves such as in the Malindi Mida Creek Mangrove Forest as per the Forest Conservation and Management Act No. 34 of 2016 section 7 and 8; and National Museums of Kenya who are responsible for forests within the coastal zone that are declared as protected areas, and also monuments such as the Vasco Da Gama Museum in Malindi, based on National Museums and Heritage Act No. 6 of 2006 section 25.

The State Department of Fisheries, Aquaculture and the Blue Economy is mandated to develop and implement appropriate legislative measures as well as to enforce the guidelines for sustainable economic development in line with the Fisheries Management and Development Act, 2016. This is under the directive of the Cabinet Secretary responsible for agriculture, livestock and fisheries. In particular, the State Department is to govern mariculture, fishing, inclusive of trawling, and other sustainable tourism activities encompassing the sea grass and coral areas. They therefore control all fishing activities that take place within Malindi Marine Park. With respect to managing fisheries at the County level, the Beach Management Units (BMUs) serve as the main bodies established by the Kenya Fisheries (Beach Management Unit) Regulations, 2007. The BMUs are supposed to co-manage fisheries and associated resources with the aim of reducing degradation, pollution and over-exploitation of coastal and marine resources.

The assessment of mandates of the national government agencies shows overlap with the overall mandate of the county government. For example, counties have no mandate for marine parks, yet they give development control permits on contiguous land where some of these developments have a direct impact on the sustainable management of the marine park. They also regulate waste disposal from tourist establishments located in the terrestrial space but whose impacts affect marine parks especially when there is illegal discharge of wastewater into the ocean. In addition, the Malindi Fisheries Officer noted that the County government has an essential role in the fishing jurisdiction where the County is expected to provide and regulate fish landing sites. This, the officer argued, is a challenge when the County is not in charge of licensing the various fishing activities including those carried out by tourists. On the same note, the warden in charge of Malindi Marine Park also noted that they face a challenge in regulating sport fishing vessels and gear which are under the jurisdiction of the State Department for Fisheries Aquaculture and Blue Economy.

These institutional challenges are attributed to bureaucratization and fragmentation of government that induces contradictory mandates and goals (Lausche, 2019). This fragmentation results in poor coordination as more actors, i.e. quasi-governmental corporations and private entities, operate in different sectors and levels of government. This consequently leads to weak collaboration in the management of cross-cutting spatial issues of the land-sea interface (Lausche, 2019). This challenge was also noted by Okidi (2008) who argued that there is potential for user conflict within the interface among legally permissible activities such as exploration and production of oil, laying of submarine cables, and mariculture. The current scenario hampers effective management of the interface leading to unsustainable use.

Conclusion and recommendations

Coastal tourism can be a catalyst for growth and development, but it can also be an engine of destruction and environmental degradation if not properly regulated. Tourism activities occur on both the land and in the territorial ocean space. Activities such as construction of hospitality facilities, curio vending, and leisure walks occur mainly on the terrestrial space, while boat snorkeling, swimming and sport fishing mainly use the ocean space. Some activities use both the terrestrial and ocean space. For example, boats used for fishing and snorkeling require space for docking and space for maintenance and servicing in the terrestrial space. Whereas accommodation facilities are located on terrestrial space, their impacts traverse both spaces. This demonstrates the need to ensure that the spatial planning applied responds to both terrestrial and ocean space use.

Tourism accommodation facilities are physical developments on land and are thus subject to regulation through spatial planning. This is because they are within the definition of development as provided in the Physical and Land Use Planning Act of 2019. Section 2 of the Act defines development as "carrying out any works on land or making any material change in the use of any structures on the land". However, other auxiliary tourism activities such as snorkeling, leisure walks on the beach, visitation to the Vasco da Gama Pillar Museum, collection of souvenirs made from corals, recreational fishing, and swimming in the ocean, which are supported by the accommodation facilities, are not subject to regulation by the Planning Act as they do not constitute material change in land use. Nevertheless, these touristic activities in their totality have generated demand for both land and ocean space, creating conflicts over use and having a significant impact on the environment, thus requiring regulation through spatial planning (Akama, 1990; CDA 1996; GoK, 2009).

To sustainably manage the coastal zone, there is need for integrated spatial planning that addresses itself to the interdependence of land and ocean where tourism activities occur. Such spatial planning should be undertaken using the Integrated Coastal Zone Management (ICZM) approach. UNEP (2009) notes that ICZM is an adaptive, multi- sectoral approach, which strives for a balance between development, use and protection of coastal environments, based on the principles of good governance, inter and intra-generational solidarity, safeguarding the distinctiveness of coasts, and the precautionary and preventive principle. The ICZM approach is based on the "need for cooperation between stakeholders and translation of broad resource planning into more specific zoning and land use planning" (UNWTO, 2013). The zoning and land use plans are vital in providing details and a legal basis for spatial differentiation of developments and activities allowable with reference to the ICZM process which provides broad strategies for treatment of different coastal activities (UNWTO, 2013). As argued by Crist *et al.* (2009), integrated spatial planning will be effective in addressing the human use of land and marine resources while also working to maintain the integrity of terrestrial, aquatic, and marine ecosystems within the coastal zone. The integrated spatial planning proposed for the coastal zone in Malindi should involve geographical, functional and policy integration.

Geographical integration would involve planning of land and ocean space as a holistic space due to the fact that tourism activities thrive in the transition zone between land and the ocean. This would lead to the preparation of a specific tourism spatial plan that regulates tourist activities within both the terrestrial and ocean space based on the ICZM approach. This plan would designate allowable tourism uses within these areas. The plan would also provide strategies to prevent the natural heritage from being further destroyed and protect environmentally sensitive areas such as sandy beaches that are particularly threatened by the growing tourism sector. The spatial plan would also designate the location of areas at risk, buffer such areas and set mechanisms for regulating all tourism uses including physical developments and auxiliary tourist activities. Functional integration would then be realized with all sectoral management bodies involved in the preparation of the integrated plan based on common development objectives and strategies. Policy integration would involve ensuring that sectoral management policies, strategies and plans are incorporated in the overall tourism spatial plan.

For both policy and functional integration to be realized, the institutional architecture should also be reformed to clarify the mandates of the national and county government agencies, especially in matters of preparation of spatial plans and development control. This should be through administrative reform where the National Land Commission, which is mandated with the administration of the coastal zone land, provides procedural guidelines on how each agency should carry out its sectorial mandate based on the integrated spatial plan. This will ensure that the responsibilities of the various institutions are harmonized and effectively communicated to the public. The reviewed legal framework should also include robust public participation guidelines which are able to demonstrate the threshold of adequate participation in the process of preparation of spatial plans. This would allow the regulator to benefit from local knowledge while developing the capacity of the public to comply with the spatial planning regulations.

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Adsorption-desorption of chlorpyrifos in soils and sediments from the Rufiji Delta, Tanzania

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Abstract
Batch adsorption-desorption equilibrium techniques were used to investigate the adsorption capacity and influence of salinity on partitioning of the insecticide chlorpyrifos between water and soil or water and sediments from the Rufiji Delta. The data were fitted to different adsorption-desorption models and the hysteresis index was calculated using the ratio between the Freundlich exponents for desorption and adsorption, and secondly, the difference in area under the normalized adsorption and desorption isotherms using the maximum adsorbed and solution concentrations. The data showed non-linear adsorption and that chlorpyrifos was strongly adsorbed to soil and sediments from the Rufiji Delta. The linearized adsorption coefficient (K_D) and Freundlich adsorption coefficient (K_f) correlated significantly with organic carbon content. Chlorpyrifos adsorption as well as hysteresis calculated by both methods decreased with salinity (i.e. the sediment adsorbs increasing amounts of chlorpyrifos with decreasing salinity). This indicates that settling of freshwater sediments is among the major removal pathways of the chemical from the water column, but increased turbulence during high tides may resuspend settled sediment simultaneously increasing salinity and re-dissolve chlorpyrifos. However, discharge of fresh water, particularly during heavy rains, increases the trapping efficiency of the sediments. The theoretical approach developed showed that the Langmuir model describes the desorption data better than the Freundlich model, and that a better index of hysteresis is one that considers areas under the adsorption and desorption isotherms, provided the desorption isotherm is described by the normalized Langmuir isotherm and the adsorption isotherm by the normalized Freundlich isotherm.

Keywords: Hysteresis, Langmuir isotherm, Freundlich isotherm, Salinity, High tide,

Introduction
The Rufiji Delta supports the largest estuarine mangrove forest on the eastern seaboard of the African continent (UNEP, 2001). At 1,022 km^2, it hosts a rich biodiversity of both environmental and economic significance. The Rufiji Delta is considered a wetland of international importance under the 'Ramsar Convention on Wetlands' due to a unique biodiversity (Nasirwa *et al.*, 2001). Economically, the delta is a very productive ecosystem supporting important fisheries and agricultural activities. The area accounts for 80% of all prawn catches in Tanzania (Mgana and Mahongo, 1997; Scheren *et al.*, 2016) while agricultural activities are dominated by rice farming. Rice farming within the delta is described in the vernacular language as 'mangrove rice farming'.

Crabs foraging on the rice seedlings are considered a major problem by farmers engaged in mangrove rice farming. The use of pesticides and rice husks against the crabs is a common practice in rice fields within the mangrove forest of the Rufiji Delta (Standlinger *et al.*, 2011). Many organophosphorous pesticides (OPPs) with high acute toxicity have been found in fairly high

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concentrations in water, soils and sediments from the delta water during the farming season (Mwevura, 2007), thus posing a threat to the aquatic ecosystem in the delta.

At low tide, the pesticides are spread, often together with rice husks as bait, in piles in the fields. The rising tide inundates the fields spreading the pesticides widely in the fields, but when the tide falls pesticides recede into the water of the delta. In spite of the obvious risks to the environment, the fate of pesticides in the Rufiji Delta, or similar environments in the tropics, has not been well investigated. A thorough understanding of the processes and the effects of environmental conditions is necessary for the prediction of pesticides movement and fate in the delta. Pesticide adsorption-desorption plays a major role in the environmental fate of pesticides. These processes have a major effect on the physical accessibility of the pollutants to microorganisms and affect a variety of other fate processes such as volatilization, bioavailability, photolysis, leaching and hydrolysis (Schwarzenbach *et al.*, 2003).

The partitioning of an organic compound between water and particles is affected by a number of factors such as absorbent properties and the nature of the adsorbate, and the environmental variables. Adsorbent properties of soil or sediment that may considerably affect the adsorption of a given pesticide include organic matter and clay content, cation exchange capacity (CEC), pH, hydrous oxide content and metal ions (Schwarzenbach *et al.*, 2003; Lu and Pignatello, 2004). Compound-specific physico-chemical properties of importance include water solubility, hydrophobicity, polarity, and acid-base properties (Schwarzenbach *et al.*, 2003; Boethiling and Mackay, 2000). Properties of the aqueous phase, such as pH, and temperature (Hulscher and Cornelissen, 1996; Rani and Sud, 2015) are also important.

Apart from the factors that affect pesticide sorption in all environments, the salinity variations in a delta environment adds to the complexity. The salinity will vary both spatially, with lower salinity in the inner parts of the delta, and temporally, with tidal action. To understand the behavior of a pesticide within a delta it is therefore important to investigate the adsorption-desorption behavior and the partitioning of pesticides at different salinities.

Chlorpyrifos (O,O-diethyl-O-(3,5,6-trichloro-2-pyridinyl) phosphorothioate, CAS RN 2921-88-2) was found in high frequency and relatively high concentrations in the Rufiji Delta (Mwevura, 2007). It is an OPP with broad-spectrum insecticidal activity against a number of pests. Various formulations have been developed to maximize stability and contact with pests while minimizing human exposure. Four formulations, Dursban, Gladiator, Terraguard, and Pyrinex 48 EC02, have been registered in Tanzania, of which Dursban formulations are the most common. According to its registration status, chlorpyrifos is used against a wide range of insect pests including chewing and sucking insects and subterranean termites in coffee, rice and beans. It is also registered for control of sugarcane grubs as well as for use in public health programmes against mosquitoes (TPRI, 2020). Based on its low water solubility (1.4 mg/L) and high hydrophobicity (log $K_{ow} = 5.27$) chlorpyrifos partitions strongly to aquatic sediments and macrophytes where it can pose dangers to benthic organisms (Tomlin, 2006).

It is difficult to address the complexities of changing salinities found in the intertidal environment using the traditional methods of calculating adsorption coefficients and description of desorption isotherms. Development of the theoretical models to address the situation was therefore necessary. The present study elucidated the adsorption-desorption behavior of chlorpyrifos in soils and sediments and the influence of salinity variations on these processes. While evaluating the results, complexities were found that were not well described by traditional methods of calculating adsorption coefficients and description of desorption isotherms. The new approaches described in this paper should be useful in other contexts such as the estimation of sorbed pesticides in rice farms affected by coastal flooding.

Methodology

Sampling and sample handling

Soil and sediment samples were collected from two sites within rice farms (Ruaruke and Matosa) in the Rufiji Delta (Fig.1). Ruaruke is a relatively new cultivated area with rice farms established in 2002. The farms are located along the northern banks of the Kikunya River channel and are surrounded by dense mangrove stands. Farmers prefer to clear mangroves to create areas for new farms because of higher fertility and the absence of weeds. Matosa rice farms are among the oldest farms in the delta, established in the 1970s. They are located along the northern banks of the Simba Uranga River channel and are characterized by the presence of dense weeds.

Soil samples were collected on the farms while sediment samples were collected from riverbanks adjacent to the farms. Samples were collected by scooping the top layer (0-20 cm) using a stainless cylindrical spoon and then wrapped in aluminum foil. Soil and sediment samples were analyzed for physico-chemical parameters including pH, particle size, total carbon and organic carbon (OC) (Table 1; FAO, 2006).

The samples were air-dried at room temperature (<25°C), carefully ground in a mortar and sieved through a 2 mm sieve. The prepared samples were then stored in sealed glass containers until the adsorption-desorption experiments were conducted.

Preliminary experiments were conducted to determine the optimum sorbent:solution ratio and equilibration time. These experiments showed that a sorbent:solution ratio of 1:5 was ideal and equilibrium was established within 18 hrs of shaking. To make timing of the experiments easier, each batch of samples was shaken for 24 hrs.

Pesticide adsorption on soil from Ruaruke and Matosa, and sediments from Ruaruke were determined using the OECD standard batch equilibrium technique (OECD, 2000). The sorbent (2 g) was placed in a 25 ml Teflon tube with Teflon-lined screw cap and conditioned with the background solution (10 ml) by shaking overnight. The background solution was made up of $CaCl_2$ in deionized water (0.001 moles/l). ^{14}C-labeled chlorpyrifos was spiked to the conditioned mixture at four initial concentrations (0.056, 0.112, 0.168, 0.224 mg/l) in duplicate. These initial concentrations were achieved by spiking 12.5, 25, 37.5 and 50 ml of 112 mg/ml ^{14}C-labeled chlorpyrifos. The mixture was shaken for 24 hrs on a shaking table to equilibrate and then centrifuged at 3,500 rpm for 30 minutes. An aliquot (1 ml) of the supernatant was transferred to a scintillation vial with OptisafeHisafe 2 (Wallac, Turku, Finland) scintillation cocktail (5 ml). Radioactivity was quantified by liquid scintillation counting

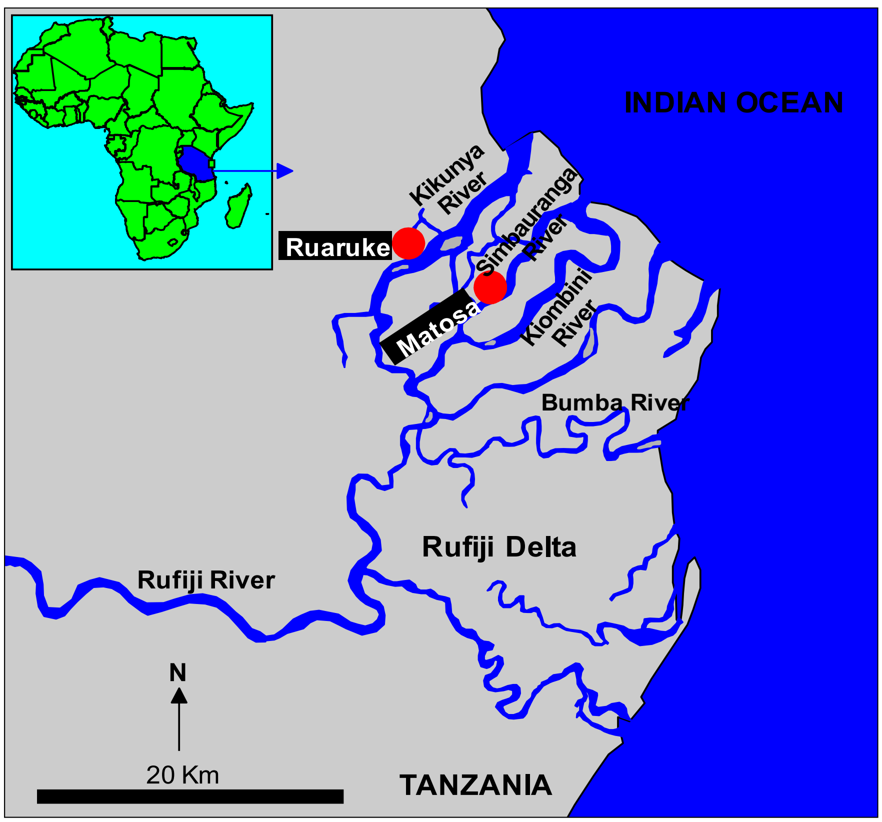

Figure 1. Map showing the location of study area and sampling sites (red dots).

Experimental procedure

Uniformly labeled ^{14}C-chlorpyrifos [pyridine-2,6-^{14}C] (purity 99%) from American Radiolabeled Chemicals, (St. Louise, MO, USA) was used. Calcium chloride ($CaCl_2$) and sodium chloride (NaCl) used were of analytical grade (Merck, Spånga, Sweden), while the water used was from a MilliQ purification system with an additional filtration through activated carbon.

(LKB Wallac 1217 Rackbeta). Internal standards from Wallac (C-14 Wallac product No. 1210-122) were used to correct for sample quenching. Blanks (no chlorpyrifos added) were run to correct for background radioactivity. The blank readings and conversion of radioactivity readings into concentrations of pesticide are presented in supplementary Table S1.

Adsorption – Desorption experiment using Ruaruke sediment

The air-dried sediments (2 g) were conditioned with 10 ml of low salinity background solution (0.001 moles/l$CaCl_2$ in deionised water) in the 25 ml Teflon centrifuge tubes by shaking overnight. Adsorption was initiated by spiking 10, 20, 30, 40 and 57 ml of 112 mg/ml ^{14}C-labeled chlorpyrifos into the conditioned sediment:solution mixture to give five initial concentrations of 0.045, 0.09, 0.135, 0.180 and 0.255 mg/l, respectively. Four replicates were used for each initial concentration. The mixtures were shaken for 24 hrs and centrifuged at 3,500 rpm for 30 minutes. An aliquot (1 ml) of the supernatant was processed for scintillation counter analysis as described in the adsorption experiment. The remaining supernatant was carefully decanted off immediately after removing the aliquot for the adsorption data.

The desorption experiments were conducted by successive dissolution techniques of the adsorbed material by adding fresh background solution (10 ml) free from pesticide. Each desorption cycle was conducted as described above. The adsorption-desorption procedure was repeated using background solutions of 0.001 moles/l $CaCl_2$ in water of 36 ‰ salinity to generate high salinity adsorption/desorption data.

Data analysis and interpretation

All adsorption data were fitted to the linear model (Eq. 1):

$$S = K_D C \tag{1}$$

and to the log-transformed form of the Freundlich equation (Eq. 2):

$$\log S = \log K_f + N \log C \tag{2}$$

Where S is the sorbed concentration (mg/kg), C is the aqueous phase concentration (mg/l), K_D (l/kg),K_f ($l^N mg^{1-N}$/kg) and N are constants (Schwarzenbach *et al.*, 2003). The Freundlich isotherms were plotted (log S against log C), and K_f and N were obtained from the slope and intercept of the isotherms. The desorption data were fitted to the Langmuir isotherm (Eq. 3):

$$S = \frac{S_{max} kC}{1 + kC} \tag{3}$$

Where S_{max}(mg/kg) is the maximum adsorption potential and k (l/mg) is the affinity coefficient.

Since K_D-values for the Freundlich isotherm are concentration dependent, several approaches were taken to linearize the isotherms and obtain K_D values that are not concentration dependent.

Assuming that the linear isotherm and the nonlinear isotherm have equal amounts of solute adsorbed at a given concentration *Cmax.*, K_{D1} is the linearized sorption coefficient (Eq. 5)

$$\int_0^{C\max} K_D C\, dc = \int_0^{C\max} K_f C^N dc \tag{4}$$

$$K_{D1} = \frac{2K_f C\max^{N-1}}{N+1} \tag{5}$$

Finding an average K_D from a nonlinear isotherm at C_{max}., K_{D2} is the linearized sorption coefficient (Eq. 6).

$$K_{D2} = \frac{\int_0^{C\max} K_f N C^{N-1}}{\int_0^{C\max} dC} dC = K_f C\max^{N-1} \tag{6}$$

Using the K_{D3} = NK_f-value at C=1 (mg/l) from the relationship:

$$S = K_f C^N ; K_{D3} = \frac{dS}{dC} = NK_f C_{max}^{N-1} \tag{7}$$

Linearized sorption coefficients (K_{D1}, K_{D2} and K_{D3}) from the three approaches and K_D from the linear isotherm (Eq. 1) were then normalized to the organic carbon content of the corresponding sorbents to give K_{DOC}, K_{D1OC}, K_{D2OC} and K_{D3OC} that were used to compare between low and high saline soil and sediment samples.

The desorption data were fitted to the linear form of the Langmuir equation (Eq. 3) and the parameters S_{max} and k were calculated from the linear plot of C/S against C (Schwarzenbach, *et al.*, 2003). Similarly, the desorption data were also fitted to the Freundlich isotherm (Eq. 2).

Hysteresis indices (H) were calculated by two different methods. The first was to take the ratio between the Freundlich exponents for desorption and adsorption ($H = N_D/N_S$). If H = 1 there is no hysteresis, while a decreasing H ($H < 1$) indicates increased difficulty of the sorbed pesticide to desorb from the matrix, which is called positive hysteresis. Conversely,

Table 1. Physical and chemical properties of the tested soils and sediment.

	pH (1 mM Ca^{2+})	Sand %	Silt %	Clay %	Total C %	OC %
Ruaruke Soil (RSO)	7.0	24.3	23.6	52.1	2.05	1.96
Ruaruke Sediments (RSE)	7.2	28.5	25.2	46.3	1.32	1.24
Matosa Soil (MSO)	6.8	20.3	29.3	50.4	1.84	1.79

an increasing H (H > 1) is called negative hysteresis, which indicates that a sorbed substance is readily desorbed to solution (Huang and Weber, 1997; Chefetza *et al.*, 2004). In the method described here, however, this is carried out for each desorption loop where there is no single index of hysteresis for a given set of experimental data.

In the second method, the adsorption and desorption data were normalized to the maximum adsorption point at equilibrium and fitted to the Langmuir or Freundlich equations for desorption and to the Freundlich equation for adsorption. The magnitude of the hysteresis was obtained by taking the area difference under the Langmuir or Freundlich fitted desorption curve and expressing it as a percentage of the area under the normalized adsorption Freundlich isotherm (Brown, 1994). The normalization technique coalesced the desorption loops into one and thus simplified the comparison of the two salinity conditions. This leads to $0 \leq H < 100$. When there is no hysteresis H = 0. The larger the value of H, the more hysteresis there is in the system.

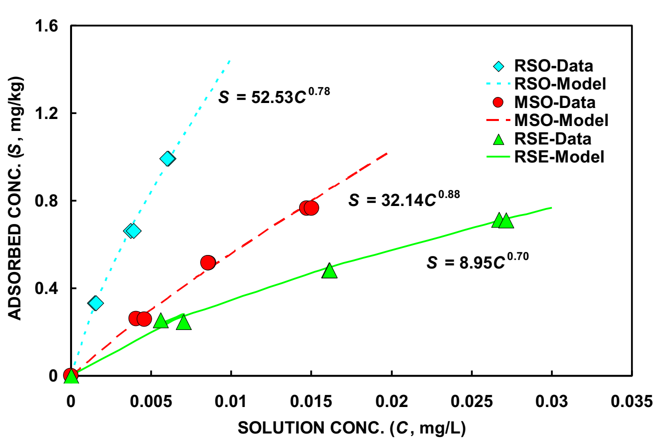

Figure 2. Chlorpyrifos adsorption isotherms for Ruaruke soil (RSO), Matosa soil (MSO), and Ruaruke sediment (RSE). 'Data' refers to the actual measurements, and 'model' to the isotherm calculated from the respective set of data.

Results and Discussion

Adsorption of chlorpyrifos

Soil and sediment properties from the two sites are given in Table 1. All samples were dominated by clay content which contributed between 46.3 and 52.1 % of the soil. The organic carbon and total carbon content ranged from 1.24 - 1.96 % and 1.32 to 2.05 %, respectively. The highest percentages of clay and organic carbon contents were measured in Ruaruke soil (RSO) followed by Matosa soil (MSO). Ruaruke sediment (RSE) gave the lowest percentages of clay and organic carbon content.

The results of chlorpyrifos adsorption experiments are summarized in Table 2. Nonlinear isotherms were obtained for all adsorbents indicating that chlorpyrifos has a preferential adsorption to soils and sediment initially, and adsorption decreases as more pesticide is adsorbed (Fig. 2). The adsorption data were better described with the Freundlich equation with R^2 values between 0.983 and 0.996 compared to R^2 values of the linear isotherms which were between 0.957 and 0.981. In a case like this the linear isotherm model should not be used to interpret the data since the slopes of the chlorpyrifos Freundlich isotherms (N) were less than 1. N values which indicate the dependence of adsorption on concentration were 0.78, 0.88 and 0.70 for RSO, MSO and RSE, respectively.

Effects of organic carbon and clay contents on adsorption

The linearized K_D values from the Freundlich isotherms indicated that RSO had higher adsorption capacity for chlorpyrifos than MSO while RSE had lower adsorption capacity than MSO. The linearized K_D values increased in the order RSE < MSO < RSO (Table 2). The adsorption parameters (normalized K_D and K_f) increased with increasing OC and clay contents (Table 1 and 2) indicating that the OC content was not the only factor responsible for the adsorption. Jeong *et al.* (2008) reported that the nature of the OC may influence adsorption. Dissolved OC particularly affects the adsorption capacity of sediment in wetland areas and in turn the bioavailability of contaminants (Huang and Lee, 2001; Goedkoop and Peterson, 2003; Widenfalk, 2005). The trend of the linearized K_D values reflects the OC content of the respective sorbent (Tables 1 and 2). However, the carbon normalized adsorption coefficients (K_{DOC}, K_{D1OC}, K_{D2OC}, and K_{D3OC}) had different values (Table 2). In particular K_{DOC} values were much larger than the other three. This is a result of using the wrong model of a linear isotherm. The other three approaches of linearized $K_D$were calculated at C = 1 μg/ml. In most investigations K_{OC} is calculated for nonlinear isotherms using K_f which is equivalent to using Eq. 6 at C_{max} = 1. The K_{OC} value is numerically equal to K_{OC} obtained with Eq. 6. Therefore Eq. 6 K_{OC} values are preferred. Interestingly, the trend in all calculated K_{OC} values was RSE < MSO < RSO. These observations suggest that a linear isotherm model should not be used to calculate K_{OC} if the isotherms are nonlinear, and that the acceptable linearized K_D model is one that calculates the average K_D at the equilibrium solution concentration (C) of interest. K_{OC} values determined in this study (722–2680) are within the lower range (1250–12600) reported in the literature (Tomlin, 2006).

As mentioned above, the adsorption coefficients also correlated with the clay contents (R^2 = 0.9963 for K_{D2}). In most investigations OC has been the more important factor for the adsorption of pesticides, while the clay content contributes significantly in soils with low OC content (Green and Karickhoff, 1990). The OC rich soil and sediment from the Rufiji Delta stand out to some extent in that the clay content contributes to the adsorption of chlorpyrifos. Thus, not only the quantity of the OC, but the quality and composition of the OC as well as the mineral component of the soil or sediment are of importance (Jeong *et al.*, 2008; Kile *et al.*, 1999; Mitra *et al.*, 2003).

Table 2. Adsorption and desorption parameters of soil and sediment.

Adsorption							
	K_D L/kg	K_f ($L^N mg^{1-N}$)/kg	N	K_{DOC} L/kg	K_{D1OC} L/kg	K_{D2OC} L/kg	K_{D3OC} L/kg
RSO[a]	169.74	52.53	0.78	8660	3011	2680	2090
MSO	53.95	32.14	0.88	3014	1910	1796	1580
RSE	27.86	8.59	0.70	2247	849	722	485
RSEL	37.86	26.93	0.91	3053	2274	2172	1976
RSEH	53.09	19.50	0.76	4281	1787	1573	1196

Desorption					
	Non-normalized: Freundlich			Non-normalized: Langmuir	
	K_{fd}	N_D	H	S_{max}	K
RSEL	0.37–1.31	0.11–0.09	0.12–0.08	0.21–0.99	3236–1125
RSEH	0.47–1.27	0.13–0.06	0.17–0.08	0.22–1.05	9099–1901

	Normalized: Freundlich			Normalized: Langmuir		
	K^*_{fd}	N^*_D	H	S^*_{max}	K^*	H
RSEL	1	0.08	0.09	1	27.03	73%
RSEH	1	0.06	0.08	1	39.10	59%

[a] RSO = Ruaruke soil; MSO = Matosa Soil; RSE = Ruaruke Sediment; RSEL = Ruaruke sediment, low salinity conditions; RSEH = Ruaruke sediment, high salinity conditions.

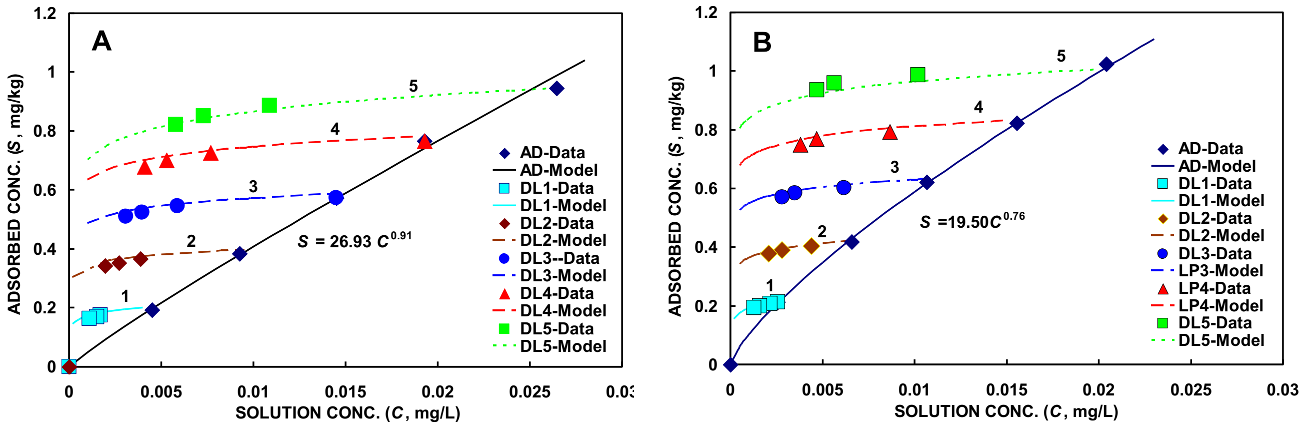

Figure 3. Non-normalized isotherms for chlorpyrifos adsorption-desorption in Ruaruke sediment. A=Low salinity, adsorption-Freundlich and desorption-Freundlich isotherms; B=High salinity, adsorption-Freundlich and desorption-Freundlich isotherms. AD refers to the adsorption phase and DL to the respective desorption loop. 'Data' refers to the actual measurements and 'model' to isotherms subsequently calculated from the data.

The strong adsorption of chlorpyrifos in both soils and sediment suggests that adsorption plays an important role in the overall fate of chlorpyrifos in the Rufiji Delta. Similarly, suspended sediment can absorb substantial amounts of chlorpyrifos in a wetland (Moore *et al.*, 2002) and more than 50% of the measured chlorpyrifos in aquatic bodies is associated with sediments.

Desorption and hysteresis

During adsorption the low salinity sediments (RSEL) adsorbed more chlorpyrifos than the high salinity sediments (RSEH) and both isotherms were nonlinear. The K_{OC} values calculated using Eq. 6 were 2172 and 1573 for RSEL and RSEH, respectively (Table 2). Under both low and high salinity conditions, the desorption data fit the Freundlich isotherm (Fig. 3). The desorption coefficient (K_{fd}) of the desorption loops increased as the initial equilibrium solution concentration increased, but the N_D values decreased (Fig. 3). Based on the Freundlich model for both adsorption and desorption isotherms, the hysteresis index average for all five loops was close to H = 0.1 for both RSEL and RSEH. Based on the method of calculating H that uses the N_D/N_S ratio, there was no difference in hysteresis between low salinity (H = 0.12 - 0.08) and high salinity (H = 0.17 - 0.08) sediment treatments.

The adsorption data were described by the Freundlich isotherm and the desorption data by the Langmuir isotherm (Fig. 4). Since desorption was initiated from the maximum equilibrium concentration of a given desorption loop, it is apparent that the Langmuir model is more appropriate than the Freundlich

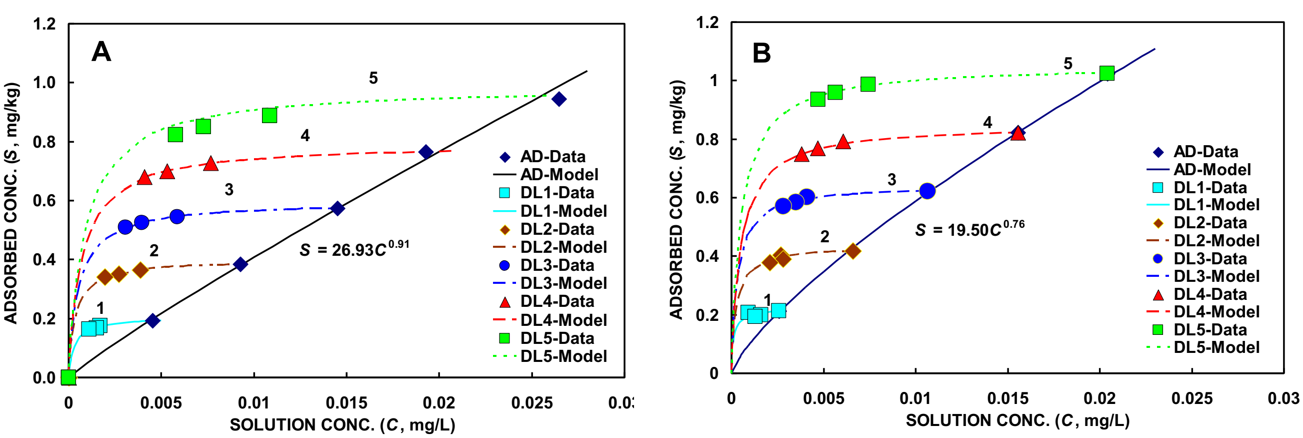

Figure 4. Non-normalized isotherms for chlorpyrifos adsorption-desorption in Ruaruke sediment. A=Low salinity, adsorption-Freundlich and desorption-Langmuir isotherms; B=High salinity, adsorption-Freundlich and desorption-Langmuir isotherms. AD refers to the adsorption phase and DL to the respective desorption loop. 'Data' refers to the actual measurements and 'model' to isotherms subsequently calculated from the data.

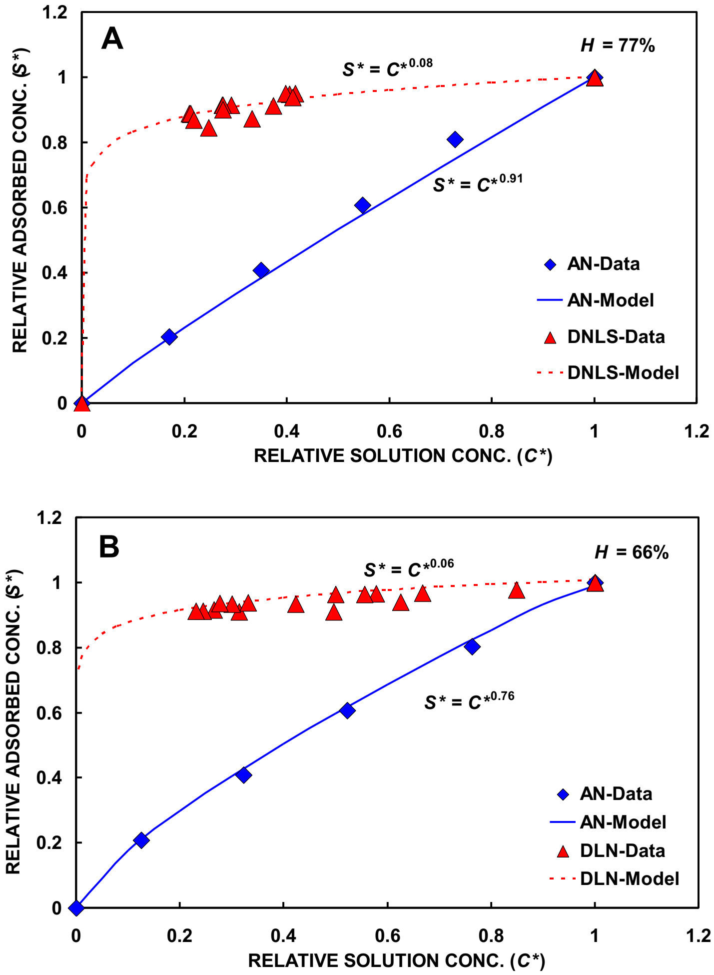

Figure 5. Normalized isotherms for Ruaruke sediment. A=Low salinity, adsorption-Freundlich and desorption-Freundlich isotherms; B=High salinity, adsorption-Freundlich and desorption-Freundlich isotherms.

model. It appears that the Langmuir model describes the desorption data better than the Freundlich model (Fig. 3 and 4). For both low and high salinity sediment treatments the S_{max} increases as the initial concentration of the desorption loops increases. However, the affinity coefficient (*k*) decreases with increase in initial concentration for desorption (Fig. 4 and Table 2).

The adsorption and desorption solution and adsorbed concentrations were normalized with the respective maximum concentration. The normalized data were then fitted to the Freundlich model (Fig. 5). For both low and high salinity sediment treatments, the desorption loops are described by one isotherm which has the desorption coefficient (K^*_{fd}) equal to 1 and N^*_D value that is close to the average of N_D values in Fig. 3. The normalized adsorption isotherm also has the adsorption coefficient (K^*_f) equal to 1 and the N^*_S value is the same as N_S for the non-normalized Freundlich isotherm (Fig. 3 and 5). Using data for the normalized Freundlich isotherms the hysteresis index $H = N^*_D / N^*_S$ is close 0.1. This implies that the normalization scheme averages the hysteresis indices for all five loops.

The hysteresis index was also calculated based on the areas under the normalized adsorption and desorption isotherms. The hysteresis index was 77 % for low salinity (RSEL) and 66 % for high salinity (RSEH). From the H values it is evident that the low salinity sediments had more hysteresis than the high salinity sediments. What is attractive about the normalization scheme and using the areas under the adsorption and desorption isotherms to calculate the hysteresis index is that both adsorption parameters (K_f and N_S) and desorption parameters (K_{fd}, and N_D) are incorporated into the normalized isotherms.

The normalization scheme was also carried out by using the Langmuir isotherm for desorption and the Freundlich isotherm for adsorption (Fig. 6). All five desorption isotherms coalesced into one desorption loop which had S^*_{max} = 1 for both RSEL and RSEH (Table 2). The calculated hysteresis index using areas under the adsorption and desorption normalized isotherms was 73 % for low salinity and 59 % for high salinity sediment treatments. It is believed that the difference in the calculated H indices using the normalized Freundlich and the Langmuir desorption isotherms is because the Freundlich model is not appropriate for desorption data. This can be seen in Fig. 5 in which the Freundlich isotherms abruptly go to $S^* = 0$ at normalized sorption concentration (S^*) of about 0.7. This abrupt approach to $C^* = 0$ over- estimates the area under the normalized desorption Freundlich isotherms which leads to an increase in the calculated *H* since the area under the normalized adsorption isotherm remains the same when the Freundlich or the Langmuir model is used. However, regardless of the model used to describe the normalized desorption isotherms the low salinity sediment had more hysteresis than the high salinity sediment. Based on these hysteresis data the normalized Langmuir isotherm is recommended for describing desorption isotherms and for calculating the hysteresis index.

Hysteresis is one of several manifestations of non-ideal adsorption behavior that challenge the assumptions associated with the application of adsorption models to the interaction of hydrophobic organic chemicals with adsorbent (Huang *et al*., 1998). The adsorption-desorption behavior of chlorpyrifos at

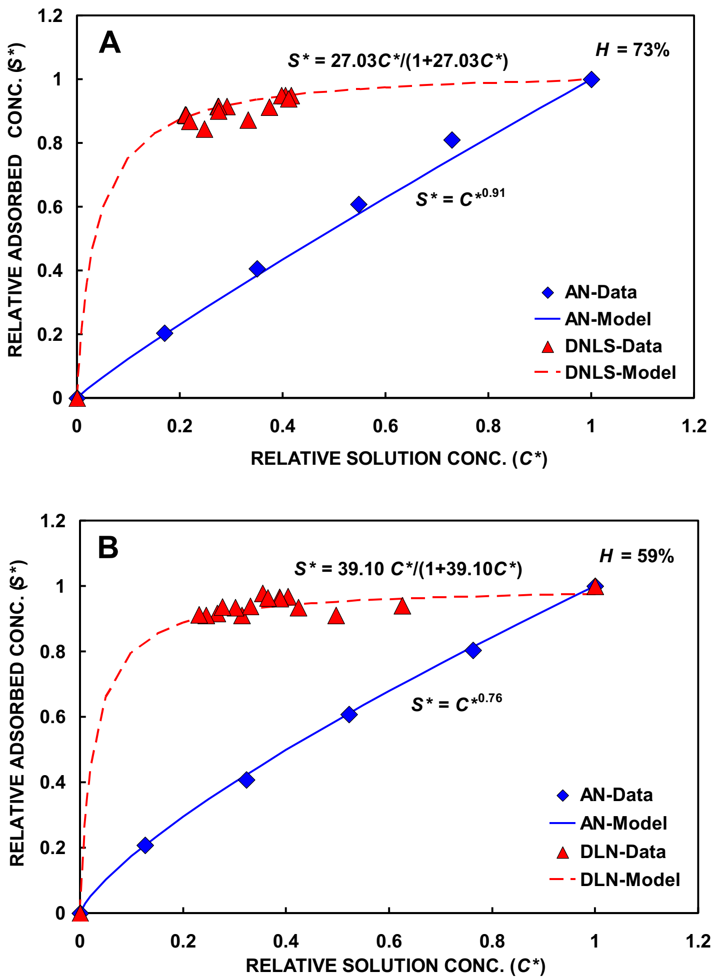

Figure 6. Normalized isotherms for Ruaruke sediment. A=Low salinity, adsorption-Freundlich and desorption-Langmuir isotherms; B=High salinity, adsorption-Freundlich and desorption-Langmuir isotherms.

both high and low salinity exhibited hysteresis indicating that the adsorption interactions are not truly reversible (Fig. 3 and 4). The amount of chlorpyrifos desorbed from the sediments was less than the amount adsorbed. This phenomenon may be caused by several factors including changes in solution composition and irreversible binding of chlorpyrifos to the sediments. Not attaining equilibrium during the desorption process could also contribute to hysteresis as the rate of desorption is slow (Mersie and Seybold, 1996; Amankwah, 2003; Kleineidam *et al.*, 2004) and it has been shown that both hysteresis and non-linear adsorption are enhanced by cross-linking with aluminum ions (Al^{3+}) in the sorbent material (Lu and Pignatello, 2004). The difference between the adsorption and desorption processes is expressed in the hysteresis index values (*H*) summarized in Table 2. On average, the *H* decreased with increasing salinity, indicating that sediments in fresh water are better at sequestering chlorpyrifos than sediments in a saline water environment.

It is clear that the methods used to calculate sorption coefficients are very critical when discussing adsorption and desorption data. If the isotherm is nonlinear, using the sorption coefficient from the linear isotherm model can yield erroneous conclusions. For example, in Table 2, the K_D value for the high salinity sediment is larger than that for the low salinity sediment. However, using the linearized K_{D2}, the low salinity sediment adsorbed chlorpyrifos more strongly than the high salinity sediment. This leads to the over-estimation of K_{OC} when the linear isotherm model is used (Table 2). Similarly, using the Freundlich isotherm model for desorption showed that there was no difference in hysteresis between RSEL and RSEH if the hysteresis index is calculated based on N values for adsorption and desorption. Therefore, the index $H = N_D/N_S$ might not be appropriate because this method does not include the adsorption and desorption coefficients. A better index of hysteresis is one that considers areas under the normalized adsorption and desorption isotherms, provided the desorption isotherm is described by the normalized Langmuir isotherm. This method of calculating H incorporates all adsorption (K_f and N) and desorption (S_{max}, and k) parameters. Based on the normalized Langmuir desorption isotherm and the Freundlich normalized adsorption isotherm, the low salinity sediments exhibited more hysteresis than the high salinity sediment (Table 2).

Concluding remarks

The results from this study show that chlorpyrifos was strongly adsorbed in sediments and soils from the Rufiji Delta and therefore adsorption and settling of sediments are among the major removal pathways of the chemical from the water column. The adsorption process was found to be nonlinear, and, contrary to what was expected, the organic carbon content was not the only adsorbent parameter that influenced chlorpyrifos adsorption, suggesting that other adsorbent components such as clay content were also responsible for adsorption of chlorpyrifos. When calculating K_{OC} values a correct model for describing adsorption isotherms must be used. If the isotherm is nonlinear then the linear isotherm model should not be used. However, for a nonlinear isotherm a justifiable linearization method is one that calculates the average K_D within the range of solution concentration (0 to *C*). The value of *C* has been taken to be $C = 1$ µg/ml by many researchers. This leads to using K_f in Eq. 7 to calculate

K_{OC}. Adsorption-desorption hysteresis was observed in sediments under both low and high salinity conditions. The extent of chlorpyrifos adsorption on the sorbents tested, as well as hysteresis calculated in different methods, decreased with salinity, implying that under freshwater conditions, sediments play a more important role in trapping chlorpyrifos than in saline water sediments. The finding that chlorpyrifos adsorbs more at low than high salinity is puzzling. A salting out effect that lowers the solubility of the compound with higher salt concentration would have been plausible (Means, 1995). The explanation may lie in competition for adsorptive sites between chlorpyrifos and ions at higher cation exchange capacity (CEC). Additional studies are needed to confirm these findings.

Acknowledgments

Anna Hellström and Lutufyo Mwamtobe gave technical assistance. This work was carried out with grants from the International Programmes in Chemical Sciences (IPICS), Uppsala University, Sweden, and the Western Indian Ocean Marine Science Association (WIOMSA). Soil analyses and scintillation counting were performed at the Department of Soil Sciences, Swedish University of Agricultural Sciences.

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Calculations

Concentration of Chlorpyrifos in analysed supernantant (Cw, µg/ml) was calculated using the following formula:

$$Cw = \frac{\text{Net radioactivity reading of supernatant X Conc. of original solution}}{\text{radioactivity reading of original solution}}$$

$$Cw = \frac{(A\ B)\ X\ Co}{Ro}$$

Original Mass of chlorpyrifos (Mo) = Co x volume of Solution (V)

Mo = Co x V

Mass of chlorpyrifos in the supernatant (Mw) = Cw x volume of Solution (V)

Mw = Cw x V

Mass of chlorpyrifos in the adsorbed in soil/sediment (Ms) = Mo - Mw

$$\text{Concentration of chlorpyrifos (Cs , µg/g = mg/kg)} = \frac{\text{Mass of chlorpyrifos in soil/sediment (Ms)}}{\textit{Mass of soil/sediment}}$$

$$\text{Cs (µg/g = mg/kg)} = \frac{Ms}{ms}$$

Data from adsorption experiment using Ruaruke Soil (RSO) , Matosa Soil (MSO) and Ruaruke Sediments (RSE)

Sorbate (ms = 2g)	Sample	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
		Sample (A)	Blank (B)	Net (A-B)	Original Solution (Ro)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
RSO	C1A	860.53	51.15	809.38	11106.36	10	0.055942	0.55942	0.004077	0.040768	0.518652	0.259326
	C1B	961.03	51.15	909.88	11106.36	10	0.055942	0.55942	0.004583	0.04583	0.513589	0.256795
	C2A	1755.57	51.15	1704.42	22212.71	10	0.111884	1.118839	0.008585	0.08585	1.032989	0.516494
	C2B	1753.51	51.15	1702.36	22212.71	10	0.111884	1.118839	0.008575	0.085747	1.033092	0.516546
	C3A	2975	51.15	2923.85	33319.07	10	0.167826	1.678259	0.014727	0.147272	1.530986	0.765493
	C3B	3033.82	51.15	2982.67	33319.07	10	0.167826	1.678259	0.015024	0.150235	1.528024	0.764012
MSO	C1A	369.82	79.35	290.47	13556.24	10	0.068282	0.682818	0.001463	0.014631	0.668188	0.334094
	C1B	388.64	79.35	309.29	13556.24	10	0.068282	0.682818	0.001558	0.015579	0.66724	0.33362
	C2A	818.53	79.35	739.18	27112.47	10	0.136564	1.365637	0.003723	0.037232	1.328405	0.664202
	C2B	855.5	79.35	776.15	27112.47	10	0.136564	1.365637	0.003909	0.039094	1.326542	0.663271
	C3A	1280.94	79.35	1201.59	40668.71	10	0.204845	2.048455	0.006052	0.060523	1.987932	0.993966
	C3B	1271.36	79.35	1192.01	40668.71	10	0.204845	2.048455	0.006004	0.060041	1.988414	0.994207
RSE	C1A	1473.29	80.06	1393.23	11203.22	10	0.05643	0.564298	0.007018	0.070176	0.494122	0.247061
	C1B	1191.19	80.06	1111.13	11203.22	10	0.05643	0.564298	0.005597	0.055967	0.508331	0.254166
	C2A	3270.86	80.06	3190.8	22406.43	10	0.11286	1.128597	0.016072	0.160718	0.967878	0.483939
	C2B	3280.08	80.06	3200.02	22406.43	10	0.11286	1.128597	0.016118	0.161183	0.967414	0.483707
	C3A	5379.82	80.06	5299.76	33609.65	10	0.169289	1.692895	0.026695	0.266945	1.42595	0.712975
	C3B	5467.65	80.06	5387.59	33609.65	10	0.169289	1.692895	0.027137	0.271369	1.421526	0.710763

Sorption-desorption experiment

A: Data from adsorption-desorption experiment using Ruaruke Sediments (RSE, ms = 2g) at low salinity conditions.

Sorption Day zero	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
Sample	Supernatant (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	1480.42	97.2	1383.22	8558.83	10	0.04311	0.431102	0.006967	0.069672	0.361431	0.180715
1CA2	**983.59**	97.2	886.39	8558.83	10	0.04311	0.431102	0.004465	0.044647	0.386456	0.193228
1CB1	1000.44	97.2	903.24	8558.83	10	0.04311	0.431102	0.00455	0.045496	0.385607	0.192803
1CB2	**1527.99**	97.2	1430.79	8558.83	10	0.04311	0.431102	0.007207	0.072068	0.359035	0.179517
2CA1	1900.54	97.2	1803.34	17117.66	10	0.08622	0.862205	0.009083	0.090833	0.771372	0.385686
2CA2	1946.43	97.2	1849.23	17117.66	10	0.08622	0.862205	0.009314	0.093144	0.76906	0.38453
2CB1	1908.76	97.2	1811.56	17117.66	10	0.08622	0.862205	0.009125	0.091247	0.770958	0.385479
2CB2	1984.43	97.2	1887.23	17117.66	10	0.08622	0.862205	0.009506	0.095058	0.767146	0.383573
3CA1	3005.15	97.2	2907.95	25676.49	10	0.129331	1.293307	0.014647	0.146471	1.146836	0.573418
3CA2	3026.08	97.2	2928.88	25676.49	10	0.129331	1.293307	0.014753	0.147526	1.145782	0.572891
3CB1	2973.68	97.2	2876.48	25676.49	10	0.129331	1.293307	0.014489	0.144886	1.148421	0.57421
3CB2	2894.71	97.2	2797.51	25676.49	10	0.129331	1.293307	0.014091	0.140909	1.152399	0.576199
4CA1	4021.70	97.2	3924.5	34235.32	10	0.172441	1.72441	0.019767	0.197674	1.526735	0.763368
4CA2	4065.00	97.2	3967.8	34235.32	10	0.172441	1.72441	0.019986	0.199855	1.524554	0.762277
4CB1	3832.20	97.2	3735	34235.32	10	0.172441	1.72441	0.018813	0.188129	1.53628	0.76814
4CB2	3776.57	97.2	3679.37	34235.32	10	0.172441	1.72441	0.018533	0.185327	1.539082	0.769541
5CA1	5384.15	97.2	5286.95	42794.15	10	0.215551	2.155512	0.02663	0.2663	1.889212	0.944606
5CA2	5315.37	97.2	5218.17	42794.15	10	0.215551	2.155512	0.026284	0.262836	1.892676	0.946338
5CB1	5637.80	97.2	5540.6	42794.15	10	0.215551	2.155512	0.027908	0.279076	1.876436	0.938218
5CB2	5650.21	97.2	5553.01	42794.15	10	0.215551	2.155512	0.02797	0.279701	1.875811	0.937905

Desorption Day 1	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
Sample	Supernatant (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	497.56	160.77	336.79	15559.73	10	0.078373	0.361431	0.001696	0.016964	0.344467	0.172233
1CA2	496.53	160.77	335.76	15559.73	10	0.078373	0.386456	0.001691	0.016912	0.369544	0.184772
1CB1	502.80	160.77	342.03	15559.73	10	0.078373	0.385607	0.001723	0.017228	0.368379	0.18419
1CB2	808.56	160.77	647.79	15559.73	10	0.078373	0.359035	0.003263	0.032629	0.326406	0.163203
2CA1	888.18	160.77	727.41	15559.73	10	0.078373	0.771372	0.003664	0.036639	0.734733	0.367366
2CA2	927.25	160.77	766.48	15559.73	10	0.078373	0.76906	0.003861	0.038607	0.730453	0.365227
2CB1	947.14	160.77	786.37	15559.73	10	0.078373	0.770958	0.003961	0.039609	0.731349	0.365674
2CB2	943.87	160.77	783.1	15559.73	10	0.078373	0.767146	0.003944	0.039444	0.727702	0.363851
3CA1	1353.75	160.77	1192.98	15559.73	10	0.078373	1.146836	0.006009	0.06009	1.086746	0.543373
3CA2	1378.09	160.77	1217.32	15559.73	10	0.078373	1.145782	0.006132	0.061316	1.084466	0.542233
3CB1	1277.03	160.77	1116.26	15559.73	10	0.078373	1.148421	0.005623	0.056225	1.092196	0.546098
3CB2	1294.72	160.77	1133.95	15559.73	10	0.078373	1.152399	0.005712	0.057116	1.095282	0.547641
4CA1	1688.97	160.77	1528.2	15559.73	10	0.078373	1.526735	0.007697	0.076974	1.449761	0.72488
4CA2	1742.75	160.77	1581.98	15559.73	10	0.078373	1.524554	0.007968	0.079683	1.444871	0.722436
4CB1	1637.56	160.77	1476.79	15559.73	10	0.078373	1.53628	0.007438	0.074385	1.461895	0.730948
4CB2	1666.83	160.77	1506.06	15559.73	10	0.078373	1.539082	0.007586	0.075859	1.463223	0.731612
5CA1	2228.79	160.77	2068.02	15559.73	10	0.078373	1.889212	0.010416	0.104165	1.785047	0.892524
5CA2	2245.24	160.77	2084.47	15559.73	10	0.078373	1.892676	0.010499	0.104993	1.787683	0.893842
5CB1	2414.97	160.77	2254.2	15559.73	10	0.078373	1.876436	0.011354	0.113543	1.762893	0.881447
5CB2	2387.61	160.77	2226.84	15559.73	10	0.078373	1.875811	0.011216	0.112164	1.763646	0.881823

Desorption Day 2	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
Sample	Supernatant (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	379.82	70.29	309.53	15042.31	10	0.075767	0.344467	0.001559	0.015591	0.328876	0.164438
1CA2	367.87	70.29	297.58	15042.31	10	0.075767	0.369544	0.001499	0.014989	0.354555	0.177277
1CB1	356.49	70.29	286.2	15042.31	10	0.075767	0.368379	0.001442	0.014416	0.353963	0.176982
1CB2	366.01	70.29	295.72	15042.31	10	0.075767	0.326406	0.00149	0.014895	0.311511	0.155755
2CA1	582.36	70.29	512.07	15042.31	10	0.075767	0.734733	0.002579	0.025793	0.70894	0.35447
2CA2	573.93	70.29	503.64	15042.31	10	0.075767	0.730453	0.002537	0.025368	0.705085	0.352543
2CB1	632.80	70.29	562.51	15042.31	10	0.075767	0.731349	0.002833	0.028333	0.703016	0.351508
2CB2	632.80	70.29	562.51	15042.31	10	0.075767	0.727702	0.002833	0.028333	0.699369	0.349684
3CA1	862.85	70.29	792.56	15042.31	10	0.075767	1.086746	0.003992	0.039921	1.046826	0.523413
3CA2	872.80	70.29	802.51	15042.31	10	0.075767	1.084466	0.004042	0.040422	1.044044	0.522022
3CB1	852.49	70.29	782.2	15042.31	10	0.075767	1.092196	0.00394	0.039399	1.052797	0.526398
3CB2	841.99	70.29	771.7	15042.31	10	0.075767	1.095282	0.003887	0.03887	1.056412	0.528206
4CA1	1141.35	70.29	1071.06	15042.31	10	0.075767	1.449761	0.005395	0.053949	1.395812	0.697906
4CA2	1118.08	70.29	1047.79	15042.31	10	0.075767	1.444871	0.005278	0.052776	1.392095	0.696047
4CB1	1110.87	70.29	1040.58	15042.31	10	0.075767	1.461895	0.005241	0.052413	1.409482	0.704741
4CB2	1118.56	70.29	1048.27	15042.31	10	0.075767	1.463223	0.00528	0.052801	1.410423	0.705211
5CA1	1470.30	70.29	1400.01	15042.31	10	0.075767	1.785047	0.007052	0.070518	1.71453	0.857265
5CA2	1467.28	70.29	1396.99	15042.31	10	0.075767	1.787683	0.007037	0.070365	1.717318	0.858659
5CB1	1560.41	70.29	1490.12	15042.31	10	0.075767	1.762893	0.007506	0.075056	1.687837	0.843919
5CB2	1569.45	70.29	1499.16	15042.31	10	0.075767	1.763646	0.007551	0.075512	1.688135	0.844067

Desorption Day 3	**Radioactivity Readings disintegration per minute (dpm)**				**Volume**	**Original Conc**	**Original Mass**	**Conc. supernatant**	**Mass in supernatant**	**Mass adsorbed**	**Conc adsorbed**
Sample	**Supernatant** (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	299.12	103.53	195.59	14579.71	10	0.073437	0.328876	0.000985	0.009852	0.319024	0.159512
1CA2	327.97	103.53	224.44	14579.71	10	0.073437	0.354555	0.00113	0.011305	0.34325	0.171625
1CB1	370.2	103.53	266.67	14579.71	10	0.073437	0.353963	0.001343	0.013432	0.340531	0.170266
1CB2	300.81	103.53	197.28	14579.71	10	0.073437	0.311511	0.000994	0.009937	0.301574	0.150787
2CA1	455.53	103.53	352	14579.71	10	0.073437	0.70894	0.001773	0.01773	0.69121	0.345605
2CA2	448.19	103.53	344.66	14579.71	10	0.073437	0.705085	0.001736	0.01736	0.687725	0.343863
2CB1	518.76	103.53	415.23	14579.71	10	0.073437	0.703016	0.002091	0.020915	0.682101	0.34105
2CB2	533.06	103.53	429.53	14579.71	10	0.073437	0.699369	0.002164	0.021635	0.677734	0.338867
3CA1	727.64	103.53	624.11	14579.71	10	0.073437	1.046826	0.003144	0.031436	1.01539	0.507695
3CA2	737.53	103.53	634	14579.71	10	0.073437	1.044044	0.003193	0.031934	1.01211	0.506055
3CB1	693.39	103.53	589.86	14579.71	10	0.073437	1.052797	0.002971	0.029711	1.023086	0.511543
3CB2	702.97	103.53	599.44	14579.71	10	0.073437	1.056412	0.003019	0.030193	1.026219	0.513109
4CA1	928.71	103.53	825.18	14579.71	10	0.073437	1.395812	0.004156	0.041564	1.354249	0.677124
4CA2	908.46	103.53	804.93	14579.71	10	0.073437	1.392095	0.004054	0.040544	1.351551	0.675775
4CB1	908.35	103.53	804.82	14579.71	10	0.073437	1.409482	0.004054	0.040538	1.368944	0.684472
4CB2	911.2	103.53	807.67	14579.71	10	0.073437	1.410423	0.004068	0.040682	1.369741	0.68487
5CA1	1208.36	103.53	1104.83	14579.71	10	0.073437	1.71453	0.005565	0.05565	1.65888	0.82944
5CA2	1207.92	103.53	1104.39	14579.71	10	0.073437	1.717318	0.005563	0.055627	1.66169	0.830845
5CB1	1293.03	103.53	1189.5	14579.71	10	0.073437	1.687837	0.005991	0.059914	1.627923	0.813961
5CB2	1291.66	103.53	1188.13	14579.71	10	0.073437	1.688135	0.005985	0.059845	1.628289	0.814145

B: Data from adsorption-desorption experiment using Ruaruke Sediments (RSE, ms = 2g) at high salinity conditions.

Day zero Sorption	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
Sample	Supernatant (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	591.87	102.4	489.47	8943.075	10	0.045046	0.450457	0.002465	0.024654	0.425802	0.212901
1CA2	594.09	102.4	491.69	8943.075	10	0.045046	0.450457	0.002477	0.024766	0.425691	0.212845
1CB1	664.51	102.4	562.11	8943.075	10	0.045046	0.450457	0.002831	0.028313	0.422143	0.211072
1CB2	**593.26**	102.4	490.86	8943.075	10	0.045046	0.450457	0.002472	0.024724	0.425732	0.212866
2CA1	1420.45	102.4	1318.05	17886.15	10	0.090091	0.900913	0.006639	0.066389	0.834524	0.417262
2CA2	1412.84	102.4	1310.44	17886.15	10	0.090091	0.900913	0.006601	0.066006	0.834907	0.417454
2CB1	1384.16	102.4	1281.76	17886.15	10	0.090091	0.900913	0.006456	0.064561	0.836352	0.418176
2CB2	1427.06	102.4	1324.66	17886.15	10	0.090091	0.900913	0.006672	0.066722	0.834191	0.417095
3CA1	2250.95	102.4	2148.55	26829.23	10	0.135137	1.35137	0.010822	0.108221	1.243149	0.621574
3CA2	2228.47	102.4	2126.07	26829.23	10	0.135137	1.35137	0.010709	0.107089	1.244281	0.622141
3CB1	2197.58	102.4	2095.18	26829.23	10	0.135137	1.35137	0.010553	0.105533	1.245837	0.622918
3CB2	2191.65	102.4	2089.25	26829.23	10	0.135137	1.35137	0.010523	0.105234	1.246136	0.623068
4CA1	3104.02	102.4	3001.62	35772.3	10	0.180183	1.801826	0.015119	0.15119	1.650637	0.825318
4CA2	3119.76	102.4	3017.36	35772.3	10	0.180183	1.801826	0.015198	0.151982	1.649844	0.824922
4CB1	3244.19	102.4	3141.79	35772.3	10	0.180183	1.801826	0.015825	0.15825	1.643577	0.821788
4CB2	3296.84	102.4	3194.44	35772.3	10	0.180183	1.801826	0.01609	0.160902	1.640925	0.820462
5CA1	4178.35	102.4	4075.95	44715.38	10	0.225228	2.252283	0.02053	0.205303	2.04698	1.02349
5CA2	4126.11	102.4	4023.71	44715.38	10	0.225228	2.252283	0.020267	0.202672	2.049611	1.024806
5CB1	4128.64	102.4	4026.24	44715.38	10	0.225228	2.252283	0.02028	0.202799	2.049484	1.024742
5CB2	4176.75	102.4	4074.35	44715.38	10	0.225228	2.252283	0.020522	0.205222	2.047061	1.02353

Day 1 Desorption	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
Sample	Supernatant (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	449.82	234.35	215.47	17299.09	10	0.087134	0.425802	0.001085	0.010853	0.414949	0.207475
1CA2	**415.00**	234.35	180.65	17299.09	10	0.087134	0.425691	0.00091	0.009099	0.416591	0.208296
1CB1	390.92	234.35	156.57	17299.09	10	0.087134	0.422143	0.000789	0.007886	0.414257	0.207129
1CB2	402.10	234.35	167.75	17299.09	10	0.087134	0.425732	0.000845	0.008449	0.417283	0.208641
2CA1	774.30	234.35	539.95	17299.09	10	0.087134	0.834524	0.00272	0.027197	0.807327	0.403663
2CA2	768.35	234.35	534	17299.09	10	0.087134	0.834907	0.00269	0.026897	0.80801	0.404005
2CB1	735.33	234.35	500.98	17299.09	10	0.087134	0.836352	0.002523	0.025234	0.811118	0.405559
2CB2	770.41	234.35	536.06	17299.09	10	0.087134	0.834191	0.0027	0.027001	0.80719	0.403595
3CA1	1035.61	234.35	801.26	17299.09	10	0.087134	1.243149	0.004036	0.040359	1.20279	0.601395
3CA2	**1061.01**	234.35	826.66	17299.09	10	0.087134	1.244281	0.004164	0.041638	1.202643	0.601321
3CB1	1050.93	234.35	816.58	17299.09	10	0.087134	1.245837	0.004113	0.041131	1.204706	0.602353
3CB2	1061.29	234.35	826.94	17299.09	10	0.087134	1.246136	0.004165	0.041652	1.204483	0.602242
4CA1	1421.21	234.35	1186.86	17299.09	10	0.087134	1.650637	0.005978	0.059781	1.590855	0.795428
4CA2	1451.75	234.35	1217.4	17299.09	10	0.087134	1.649844	0.006132	0.06132	1.588524	0.794262
4CB1	1441.75	234.35	1207.4	17299.09	10	0.087134	1.643577	0.006082	0.060816	1.582761	0.79138
4CB2	1427.15	234.35	1192.8	17299.09	10	0.087134	1.640925	0.006008	0.060081	1.580844	0.790422
5CA1	1711.95	234.35	1477.6	17299.09	10	0.087134	2.046980	0.007443	0.074426	1.972554	0.986277
5CA2	1709.79	234.35	1475.44	17299.09	10	0.087134	2.049611	0.007432	0.074317	1.975295	0.987647
5CB1	1719.54	234.35	1485.19	17299.09	10	0.087134	2.049484	0.007481	0.074808	1.974676	0.987338
5CB2	1702.66	234.35	1468.31	17299.09	10	0.087134	2.047060	0.007396	0.073958	1.973103	0.986551

Desorption Day 2	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
Sample	Supernatant (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	331.11	86.69	244.42	15497.15	10	0.078058	0.414949	0.001231	0.012311	0.402638	0.201319
1CA2	431.10	86.69	344.41	15497.15	10	0.078058	0.416591	0.001735	0.017348	0.399244	0.199622
1CB1	327.49	86.69	240.80	15497.15	10	0.078058	0.414257	0.001213	0.012129	0.402128	0.201064
1CB2	529.54	86.69	442.85	15497.15	10	0.078058	0.417283	0.002231	0.022306	0.394977	0.197488
2CA1	839.40	86.69	752.71	15497.15	10	0.078058	0.807327	0.003791	0.037913	0.769413	0.384707
2CA2	578.18	86.69	491.49	15497.15	10	0.078058	0.808010	0.002476	0.024756	0.783254	0.391627
2CB1	581.35	86.69	494.66	15497.15	10	0.078058	0.811118	0.002492	0.024916	0.786202	0.393101
2CB2	562.40	86.69	475.71	15497.15	10	0.078058	0.807190	0.002396	0.023961	0.783229	0.391614
3CA1	780.61	86.69	693.92	15497.15	10	0.078058	1.202790	0.003495	0.034952	1.167838	0.583919
3CA2	762.24	86.69	675.55	15497.15	10	0.078058	1.202643	0.003403	0.034027	1.168616	0.584308
3CB1	781.29	86.69	694.60	15497.15	10	0.078058	1.204706	0.003499	0.034987	1.16972	0.58486
3CB2	820.20	86.69	733.51	15497.15	10	0.078058	1.204483	0.003695	0.036946	1.167537	0.583768
4CA1	1003.74	86.69	917.05	15497.15	10	0.078058	1.590855	0.004619	0.046191	1.544664	0.772332
4CA2	992.18	86.69	905.49	15497.15	10	0.078058	1.588524	0.004561	0.045609	1.542915	0.771458
4CB1	1022.18	86.69	935.49	15497.15	10	0.078058	1.582761	0.004712	0.04712	1.535641	0.76782
4CB2	1045.42	86.69	958.73	15497.15	10	0.078058	1.580844	0.004829	0.048291	1.532553	0.766277
5CA1	1223.66	86.69	1136.97	15497.15	10	0.078058	1.972554	0.005727	0.057268	1.915286	0.957643
5CA2	1201.09	86.69	1114.40	15497.15	10	0.078058	1.975295	0.005613	0.056132	1.919163	0.959581
5CB1	1218.55	86.69	1131.86	15497.15	10	0.078058	1.974676	0.005701	0.057011	1.917665	0.958832
5CB2	1181.67	86.69	1094.98	15497.15	10	0.078058	1.973103	0.005515	0.055153	1.91795	0.958975

Desorption Day 3	Radioactivity Readings disintegration per minute (dpm)				Volume	Original Conc	Original Mass	Conc. supernatant	Mass in supernatant	Mass adsorbed	Conc adsorbed
Sample	Supernatant (A)	V(mls)	Co (µg/ml)	(Mo) VCo(µg)	Cw	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)	Mw CwV	Ms (Mo - Mw)	Cs (Ms/ms)
1CA1	353.72	81.37	272.35	14544.95	10	0.073262	0.402638	0.001372	0.013718	0.38892	0.19446
1CA2	303.17	81.37	221.80	14544.95	10	0.073262	0.399244	0.001117	0.011172	0.388072	0.194036
1CB1	273.59	81.37	192.22	14544.95	10	0.073262	0.402128	0.000968	0.009682	0.392446	0.196223
1CB2	405.77	81.37	324.40	14544.95	10	0.073262	0.394977	0.001634	0.01634	0.378637	0.189318
2CA1	511.96	81.37	430.59	14544.95	10	0.073262	0.769413	0.002169	0.021689	0.747725	0.373862
2CA2	502.54	81.37	421.17	14544.95	10	0.073262	0.783254	0.002121	0.021214	0.76204	0.38102
2CB1	479.19	81.37	397.82	14544.95	10	0.073262	0.786202	0.002004	0.020038	0.766164	0.383082
2CB2	475.14	81.37	393.77	14544.95	10	0.073262	0.783229	0.001983	0.019834	0.763395	0.381697
3CA1	665.9	81.37	584.53	14544.95	10	0.073262	1.167838	0.002944	0.029442	1.138395	0.569198
3CA2	647.07	81.37	565.70	14544.95	10	0.073262	1.168616	0.002849	0.028494	1.140122	0.570061
3CB1	619.12	81.37	537.75	14544.95	10	0.073262	1.16972	0.002709	0.027086	1.142634	0.571317
3CB2	640.47	81.37	559.10	14544.95	10	0.073262	1.167537	0.002816	0.028161	1.139375	0.569688
4CA1	831.7	81.37	750.33	14544.95	10	0.073262	1.544664	0.003779	0.037794	1.506871	0.753435
4CA2	819.55	81.37	738.18	14544.95	10	0.073262	1.542915	0.003718	0.037182	1.505734	0.752867
4CB1	843.04	81.37	761.67	14544.95	10	0.073262	1.535641	0.003836	0.038365	1.497276	0.748638
4CB2	845.58	81.37	764.21	14544.95	10	0.073262	1.532553	0.003849	0.038493	1.494061	0.74703
5CA1	1001.24	81.37	919.87	14544.95	10	0.073262	1.915286	0.004633	0.046333	1.868953	0.934476
5CA2	989.41	81.37	908.04	14544.95	10	0.073262	1.919163	0.004574	0.045737	1.873426	0.936713
5CB1	1029	81.37	947.63	14544.95	10	0.073262	1.917665	0.004773	0.047731	1.869933	0.934967
5CB2	1037.42	81.37	956.05	14544.95	10	0.073262	1.91795	0.004816	0.048156	1.869794	0.934897

Determinants of sustainability for community based water projects: the case of *Hazina ya Maendeleo ya Pwani* in coastal Kenya

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Abstract
Sustainability of development projects is considered essential for the continued delivery of services to beneficiary communities beyond external financing. However, various factors cause community projects to fail the sustainability test. This study investigated the determinants of sustainability for community-based water projects implemented through World Bank and Kenya Government financing known as *Hazina ya Maendeleo ya Pwani*. Research was conducted using sustainability criteria comprising social, organizational, technical and financial aspects that were selected based on literature review and community perceptions. The research was conducted in Kenya's coastal region using data collected from 285 respondents. Frequencies, means and percentages were used to describe data while the Structural Equation Modeling technique determined factors influencing sustainability. Results illustrated that all the four indicators assessed predict sustainability. However, only the technical and financial indicators influence sustainability significantly. In conclusion, while it is important to incorporate all the four indicators during planning and designing of community-based water projects, special attention must focus on financial and technical aspects. The study recommends that building the capacity of Community Based Organizations in terms of technical competence and financial resources to support operation and maintenance is a requirement, rather than a choice, for sustainability of community-based water projects.

Keywords: Community Participation; Water Projects; *Hazina ya Maendeleo ya Pwani*; Sustainability; Kenya Coast

Introduction
Sustainability of development projects occupies a significant proportion of contemporary discourse on development. Of specific interest is the sustainability of donor-supported community projects that has captured the attention of researchers (Komives *et al.*, 2008; Akinbile *et al.*, 2006). The concept of sustainability is understood intuitively, and not easily expressed in concrete operational terms (Briassoulis, 2001). Originating from the term "Sustainable Development", it is essentially not a methodology but a thinking dimension (Jaafari, 2007). According to Blewitt (2008) all the definitions have to do with: (a) living within limits; (b) understanding interaction among economy, society and environment; and (c) equitable distribution of resources. The World Commission on Environment and Development (WCED, 1987) views sustainable development as the ability to make development continuous by ensuring that it meets the needs of the present community without compromising the ability of future generations to meet their own needs. The International Fund for Agricultural Development Strategic Framework (IFAD, 2007) defines project sustainability as the ability to ensure that the institutions supported through projects and the benefits realized are maintained and continue after the end of the project's external funding. Dale and Newman (2010) define sustainable development as a process that takes care of the ecological, social and economic imperatives of the local communities, while ensuring equitable access to resources under each facet of development. As such, a project is considered sustainable if the beneficiaries are capable on their own, without the

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assistance of outside development partners, to continue producing results for their benefit for as long as their problem still exists (Luvenga *et al.*, 2015). In this study we operationalize sustainability as the capacity of a development project to continue delivering the expected services to the targeted beneficiaries beyond the termination of external financing.

Significant amounts of government and donor funds have been channeled towards implementing development projects with a view to provide benefits and services to targeted communities. A large number of the development projects however, tend to experience difficulties with sustainability, and it is estimated that over 40% of all community-managed projects in Africa are not functional (Padawangi, 2010; Ademiluyi and Odugbesan, 2008). Besides, the manner in which projects are managed, measured and reported does not reflect the different aspects of sustainability that can be derived from the concepts of sustainable development (Goedknegt, 2012). Interestingly, while the connection between sustainability and projects was established by the WCED (1987), decades later the standards for project management still "fail to seriously address the sustainability agenda" (Eid, 2009). Worse still, the alignment between sustainability and project management is very rare (Grevelman and Kluiwstra, 2009) and the concept of sustainability has only recently been linked to project management (Gareis *et al.*, 2009; Silvius *et al.*, 2009). Consequently, poor sustainability of development projects deprives the targeted beneficiaries of the intended benefits and expected returns from these investments (Luvenga *et al.*, 2015). Within this context, it therefore becomes necessary to incorporate sustainability mechanisms into projects to ensure continuity of services beyond project timelines.

A number of factors have been considered to be essential for sustainability of development projects in the literature. One of the main factors is community participation. Major development organizations including multi-lateral agencies like the World Bank (WB) and the International Monetary Fund (IMF) have arrived at a near consensus that projects cannot be sustainable and long-lasting unless the community's participation is made central to the planning and management of those projects (Kumar, 2002). Various scholars recognize that when local communities participate directly in planning their own water supply systems, such systems are more likely to be sustainable than those imposed by the government or donor organizations (Barnes and Ashbolt, 2010). For sustainable development to be realized, the community must participate in project planning, budgeting, resource identification, procurement and allocation of resources through project implementation committees (Mulwa, 2008). Development experts at times treat communities as passive-recipient objects in quick fixing of pressing needs without directly involving them in decision-making (Mulwa, 2010). This has led to poor maintenance of community projects and misuse of public resources that threaten the achievement of development goals (Ibrahim, 2017). Development literature acknowledges that community participation in all phases of project planning is important in yielding community responsibility for operation and maintenance of community projects (Schouten and Moriarty, 2003; Sobsey, 2006).

Besides community participation, there are other factors that influence project sustainability. These include poor leadership, limited management capacity (Rutatora *et al.*, 2008) and lack of follow up of micro projects by the community (Ngailo, 2010). The limited sustainability of community-managed projects has been attributed to community management deficiencies such as weak cost-recovery mechanisms, inadequately trained project managers and technicians at grassroots level, and weak local institutions (Spaling *et al.*, 2014; Morris and Hieu, 2008; Datta, 2007). In addition, failure by individual community members to contribute maintenance fees usually leads to disillusionment among project committee members and often affects community cohesion that is critical for project sustainability (Kaunda *et al.*, 2012; Fonchingong, 2005). Communities may not always have the technical capacity on their own for extensive system repairs and maintenance (Kleemeier, 2000). Therefore, external technical support needs to be available to help communities maintain and monitor system performance (Lockwood, 2004). A number of studies suggest that unless communities are able to lobby for continued support for marginal inputs and training, their ability to sustain such projects may be limited (Mansuri and Rao, 2003).

Therefore, this study sought to investigate the sustainability of community-based water projects (CBWPs) implemented through the *Hazina Ya Maendeleo ya Pwani* (HMP) programme in the coastal region of Kenya. HMP is a community development initiative implemented under the auspices of the Kenya Coastal Development Project (KCDP). KCDP was a World Bank (WB) funded project in which coastal communities were fully engaged in the entire process of identifying, developing and implementing projects of their choice (Aura *et al.*, 2015). HMP adopted a Community Driven Development (CDD) approach in the delivery of the community projects (Hassan *et al.*, 2018). CDD is a typology of participatory approaches popularly defined as a methodology that emphasizes handing over of planning decisions and investment resources directly to community groups and the local government (Wong, 2012). The focus on CBWPs was informed by the fact that Kenya is a water scarce nation and therefore access to water is a challenge to many people. A significant proportion of coastal residents (Government of Kenya, 2008) are especially vulnerable to water shortages (Government of Kenya, 2013a; 2013b; 2013c; 2013d; 2013e; 2013f). Additionally, in many rural households of Kenya (57%), women, who are already overburdened by multiple domestic chores, assume the responsibility of collecting water for the household (Mumma *et al*. 2011). Hence they spend much of their valuable time trekking for long distances in search of water. In the present context, understanding determinants of sustainability of CBWPs will inform strategies that will ensure continuous availability and reliability of water supply.

Ways of measuring project sustainability have been suggested by various authors in the literature. A "Sustainability Checklist" incorporating economic, environmental and social aspects was developed to assist in integrating sustainability into projects and project management (Silvius *et al.*, 2010). In their paper "A Maturity Model for the Incorporation of Sustainability in Projects and Project Management", Silvius and Schipper (2010) presented a practical model for the assessment and integration of the concepts of sustainability into projects and project management. Founded on the basis of the sustainability checklist, the model focuses on project resources, processes and products. In this context the model seeks to ensure that project resources provide the same functionality but are less harmful to the environment, and finally take into consideration the way the products or services are delivered in a sustainable manner. Ibrahim

Table 1. Multidimensional indicators for measuring sustainability of projects.

Indicators	Sub Indicators
Technical	Reliability
	Quality
	Accessibility
	Design and site suitability
	Functionality of the system
Social	Inclusivity
	Equity
	Public benefits
	Community participation in operation and maintenance
Financial	Payment for services rendered
	Fees collection system
	Book recording system
Organizational	Regular Community Based Organisation (CBO) meetings
	CBO functionality
	Existence of a trained project manager/operator
	Cooperation with external agencies
	Support from local authorities

Source: Modified from Ibrahim (2017)

(2017) designed a sustainability framework using a set of multidimensional indicators comprising technical, social, environmental, financial and organizational parameters to monitor community-based water supply management in Sudan (Table 1). With minor modifications, this study adopted this framework to assess the determinants of sustainability in the community projects implemented through HMP.

Materials and Methods

Study Area

Figure 1 shows a map of the Kenya coast indicating where the CBWPs and other HMP projects were located and implemented in all the counties.

The study was conducted in the six coastal counties of Kenya; namely Kwale, Taita Taveta, Mombasa, Tana River, Lamu and Kilifi (Fig. 1). The region covers an area of 83,603 km^2 constituting about 11.5% of the total area of the Republic of Kenya that has a coastline of approximately 600 km long (Government of Kenya, 2008; 2013a; 2013b; 2013c; 2013d; 2013e; 2013f).

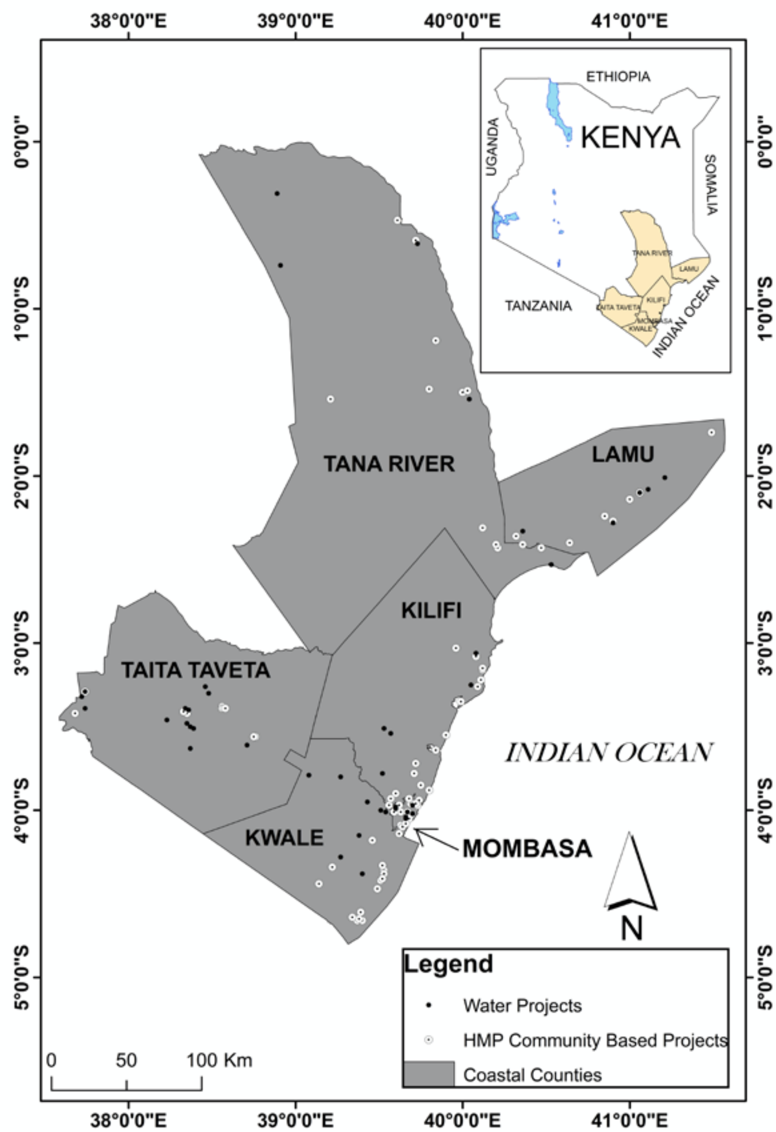

Figure 1. Map of the coastal region of Kenya showing the counties, locations of CBWPs and other HMP projects implemented under KCDP.

To assess the determinants of sustainability of CBWPs, their performance was rated using a set of qualitative indicators corresponding to technical, social, financial and organizational aspects of the project.

It is inhabited by a culturally heterogeneous population with the *Mijikenda* being the largest ethnic group. The region also hosts a large migrant population of different ethnic and racial origins (Government of Kenya, 2008). The region is endowed with a variety of resources that support livelihoods and economic development regionally and nationally in addition to maintaining the health and function of marine and coastal ecosystems (Ongoma and Onyango, 2014). The key economic activities and livelihoods in the region are small-scale fisheries, tourism, mariculture, agriculture and forestry, energy sector, ports and coastal transport and coastal mining (Hoorweg *et al.*, 2000).

The population growth rate of Kenya's coastal region reduced from 3.0 to 2.7% between 2009 and 2019 and the population currently stands at 4.3 million people, with each county population estimated as follows: Mombasa 1,208,333; Kwale 866,820; Kilifi 1,453,787; Tana River 315,943; Lamu 143,920 and Taita Taveta 340,671 (Government of Kenya, 2010; KNBS, 2019). The population is characterized by high poverty rates with about 69.7% of the coastal population living below the poverty line (Government of Kenya, 2008). Besides increasing poverty levels, the majority of the coastal residents have limited access to basic social services. The region is also characterized by significant disparity in literacy between men and women; with that of women being much lower in the counties of Kilifi, Tana River and Kwale (Government of Kenya, 2008; Hoorweg *et al.*, 2000).

Case Study

The study investigated the determinants of sustainability of different CBWPs distributed over the six coastal counties and implemented through HMP. Since 2013, a total of 58 community service projects covering sectors such as education, water, conservation, health and sanitation were implemented. Out of the 58 projects 38 were CBWPs implemented with the objective of improving access to water. This study therefore assessed the sustainability of the 38 CBWPs. The rationale for selecting the CBWPs was guided by the fact that access to water is one of the major challenges affecting Kenya's coastal communities. It was therefore not unexpected that water projects were implemented in all the six coastal counties. In addition, choosing projects from one sector, in this case water, makes it possible to apply uniform criteria for assessing determinants of sustainability.

Study population

The target study population comprised communities living in coastal Kenya. The accessible population included 1,392 community members drawn from the 38 CBOs that participated in the implementation of CBWPs and were beneficiaries of the same.

Sample Size

A sample size of 301 persons was computed using Ross *et al.* (2002) as illustrated in the Equation below. Simple random sampling techniques were used to obtain the study respondents using a sampling frame obtained from records of the HMP Manual (Aura *et al.,* 2015).

Equation: Computation of study sample

$$n = \frac{NZ^2 \text{ X } 0.25}{(d^2 \text{x } (N\text{-}1) + (Z^2 \text{ x } 0.25)}$$

Where: n = sample size required
N = Total population size (known or estimated)
d = precision level (usually 0.05 or 0.10)
Z = number of selected standard deviation units of the sampling distribution corresponding to the desired confidence level

To compute the study sample the following formula was used:

$$n = \frac{1{,}392 \text{ x } 1.96^2 \text{ x } 0.25}{(0.05^2 \text{ x } (1{,}392 \text{ -}1) + (1.96^2 \text{ x } 0.25)}$$

Therefore n = 301

Data Collection

Primary data was collected using semi-structured questionnaires that had two sections. The first section requested demographic information of the participants while the second was used to assess the sustainability of the community projects. Enumerators were engaged to administer the questionnaires in order to improve the response rate and also avoid the possibility of bias. Desktop review of previous published and unpublished research that also included internet materials was used to obtain secondary data pertaining to the research topics.

Data Analysis

The Structural Equation Modeling (SEM) technique was used to analyze the data through R Statistical Software. The choice of the SEM technique was informed by its suitability for measuring latent constructs using observable indicators. In this model, the latent variables were sustainability and the multi-dimensional indicators used for measuring sustainability comprising of technical, social, financial and organizational aspects. The general model syntax in as follows:

- *latent variable* =~ *indicator*1 + *indicator*2 + *indicator*3 + *indicator*4

For example, to measure technical sustainability the following model was used.

- *Technical* =~ *quality* + *realiability* + *accessibility* + *funtionality* + *design*

The other latent variables comprising social, financial and organizational aspects were modeled in the same way. Descriptive statistics were used to report on the demographic characteristics of the respondents while SEM was used to examine the determinants of sustainability of CBWPs implemented through HMP.

Results and Discussion

Demographic characteristics of respondents

The majority of the respondents (n = 211, 74%) were female, while 26% were male (Table 2). This indicates that unlike men, women are more likely to participate in CBWPs, probably because they are the most affected when there is no water in the household as many house chores depend on the availability of water. Most of the respondents (n = 191, 67%) were in the age range of 31 to 50 years, while 28% were over 50 years and 5% were 20 to 30 years.

A negligible percentage of the respondents were below 20 years of age. As for educational level, most of the respondents (n = 256, 90%) had primary education, while 6% had high school education. College

Table 2. Socio-economic characteristics of respondents.

Variables	Frequency	Percentage %
Gender		
Male	74	26.0
Female	211	74.0
Age		
<20 Years	1	0
20 - 30 Years	14	5
31 - 50 Years	191	67
>50 Years	79	28
Level of Education		
Primary School	256	90
High School	18	6
College	8	3
University	3	1
Household Size		
1-5	115	40
6-10	157	55
10-15	11	4
Over 15	2	1
Economic Activity		
Farming	239	84
Fishing	1	0
Trading	35	12
Employment	8	3
Other	2	1

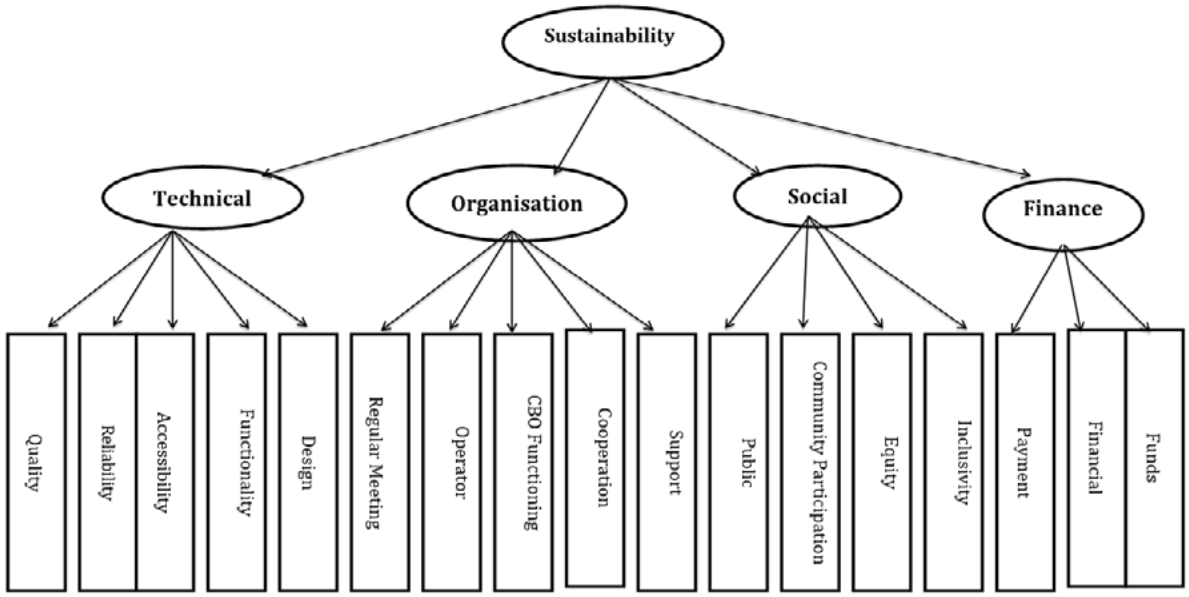

Figure 2. Relationship between the latent variables and measured parameters.

and university education comprised 3% and 1% respectively. The majority of the respondents (n = 157, 55%) had a household size of 6 - 10 persons followed closely (n = 115, 40%) by a household size of 1-5 persons. Very few respondents had household sizes of 10 - 15 (4%) and above 15 (1%) persons. With respect to occupation, the majority (n = 239, 84%) of the respondents were farmers, while 12% were traders, 3% were formally employed, and a negligible percentage were fishermen.

Sustainability of community projects

Using a SEM technique, the study assessed the sustainability of CBWPs implemented through HMP. Figure 2 shows an output from the SEM (Table 3) depicting the relationship between the latent variables and the measured parameters.

Table 3 shows the output of the SEM model from the relationship between latent variables and measured parameters presented in Figure 2. The study results revealed that the quality of service and functionality of the CBWPs seemed to impact positively on this technical indicator of sustainability with β_1 =1.000, β_4 = 0.013. On the contrary however, parameters comprising reliability, accessibility of service and design of the CBWPs seemed to negatively impact on the Technical aspects of the water project, with β_2 = −0.058, β_3 = −0.073, β_5 = −0.023. The implication of this finding is that the quality of service and functionality of the water systems contributed positively to the technical indicator of the CBWPs. On the flipside however, parameters such as accessibility, reliability and design of the water system negatively influenced the technical sustainability of the CBWPs and therefore need to be carefully checked and corrected during project implementation. During focus group discussion sessions, most of the respondents pointed to the fact that there were still issues around reliability and accessibility of the water service. Instances where communities could remain for weeks without water were reported in the counties of Taita Taveta, Kwale and Tana River. This is especially in cases where the CBWPs rely on supply of water from County-managed water service companies. It was also reported by some of the respondents that insufficient consultation was carried out regarding the choice of the water supply technology. This led to choices such as investing in a water pan or boreholes that ended up drying during the dry season, therefore undermining the sustainability of the water projects. Such cases were mostly reported in the counties of Lamu, Kilifi and Tana River. The study results agree with those of U-Dominic *et al.* (2015) who recommended that for sustainability to be achieved, successful community participation needs to go beyond mere consultation, and should include dialogue on technology options.

The social indicators of sustainability were measured in terms of inclusivity, equity and public benefit. The study results revealed that public benefits had a positive impact with β_1 =1.000. The remaining parameters comprising community participation in operation and maintenance, equity and inclusivity, seemed to have a negative impact on the social construct with

Table 3. Output of the SEM Model.

Optimization method	**NLMINB**
Number of free parameters	36
Number of observations	285
Estimator	ML
Model Fit Test Statistic	171.640
Degrees of freedom	117
P-value (Chi-square)	0.001

Parameter Estimates:

Information	Expected
Information saturated (h1) model	Structured
Standard Errors	Standard

Latent Variables:

	Estimate	Std.Err	z-value	P(>|z|)
Technical =~				
quality	1.000			
reliability	-0.058	0.088	-0.655	0.512
accessibility	-0.073	0.094	-0.773	0.439
functionality	0.013	0.094	0.143	0.886
design	-0.023	0.092	-0.248	0.804
Organisational =~				
regular	1.000			
operator	0.109	0.078	1.402	0.161
cbo	-0.016	0.058	-0.284	0.777
cooperation	0.038	0.083	0.455	0.649
support	0.005	0.084	0.063	0.950
Social =~				
public	1.000			
com.participtn	-0.010	0.279	-0.037	0.970
equity	-2.340	1.681	-1.392	0.164
inclusitivity	-1.212	0.594	-2.041	0.041
Finance =~				
payment	1.000			
financial	-0.023	0.245	-0.094	0.925
funds	-0.363	0.569	-0.639	0.523
sustain =~				
Social	1.000			
Technical	2.999	3.005	0.998	0.318
Organisational	0.557	1.499	0.372	0.710
Finance	4.434	5.537	0.801	0.423

Variances:

	Estimate	Std.Err	z-value	P(>|z|)
Social	-0.108	0.087	-1.244	0.213
Technical	1.000			
Organisational	1.000			
Finance	0.151	0.560	0.269	0.788
.quality	0.569	0.167	3.408	0.001
.reliability	1.575	0.132	11.923	0.000
.accessibility	1.781	0.149	11.917	0.000
.functionality	1.795	0.150	11.937	0.000
.design	1.734	0.145	11.935	0.000
.regular	0.243	0.105	2.316	0.021
.operator	1.372	0.115	11.912	0.000
.cbo	0.776	0.065	11.936	0.000
.cooperation	1.584	0.133	11.935	0.000
.support	1.641	0.137	11.937	0.000
.public	1.551	0.158	9.817	0.000
.com.participtn	1.675	0.140	11.937	0.000
.equity	2.068	0.495	4.180	0.000
.inclusitivity	1.574	0.184	8.574	0.000
.payment	0.947	0.551	1.719	0.086
.financial	1.714	0.144	11.935	0.000
.funds	1.767	0.165	10.732	0.000
sustain	0.009	0.015	0.610	0.542

$\beta_2 = -0.0100$, $\beta_3 = -2.340$, $\beta_4 = -1.212$, respectively. The study findings imply that when the community is able to receive benefits from a community project, its social sustainability is likely to be enhanced. However, keen attention needs to be paid to parameters such as community participation in operation and maintenance, equity and inclusivity, which have a potential to undermine the social sustainability indicator, and by extension the overall sustainability of CBWPs. Adequate training of community members to enhance their preparedness in operation and maintenance of CBWPs is therefore necessary for sustainability. This corroborates the findings of Ademiluyi and Odugbesan (2008) who noted that lack of community training is one of the important factors that could lead to breakdown and non-sustainability of water supply projects in developing countries. The study findings correlate with those of Whittington *et al.* (2009) who reported that for community-managed water projects to be sustainable, they require meaningful community participation in all stages of the project cycle and ongoing external support long after project commissioning. Similar results were reported by Olori and Okide (2014) who identified factors constraining sustainability of community development projects in Rivers State, Nigeria. These factors included a lack of transparency and accountability among community leaders, especially on funds made available for development projects, poor leadership, poor involvement of community members in development projects, corruption and a lack of maintenance culture. Results from the present study however contradict those of Barnes *et al.* (2011) and Spaling *et al.* (2014). Barnes *et al.* (2011) cautioned that participatory approaches do not automatically produce sustainable solutions because decisions made by a community are influenced by the community's perception of the issues involved. For example, Spaling *et al.* (2014) reported that local knowledge may conclude that there is ample water supply without awareness of aquifer drawdown or the effect of catchment deforestation on stream recharge, and as a result the sustainability of the water project becomes questionable.

Table 4 summarizes the results of the SEM model output by highlighting the impact of each sub indicator on the four main indicators of sustainability.

Table 4. Summary of the impacts of sub indicators on main indicators of sustainability.

Indicators	Sub Indicator	Impact
Technical	Reliability	-
	Quality	+
	Accessibility	-
	Design and site suitability	-
	Functionality of the system	+
Social	Inclusivity	-
	Equity	-
	Public benefits	+
	Community participation in operation and maintenance	-
Financial	Payment for services rendered	+
	Fees collection system	-
	Book recording system	-
Organizational	Regular CBO meetings	+
	CBO functionality	-
	Existence of a trained project manager/operator	+
	Cooperation with external agencies	+
	Support from local authorities	+

Using financial parameters as a lens to measure sustainability, the study found that payment for services rendered positively impacted) the financial construct. Sound management of financial records and availability of funds for undertaking operation and maintenance of the CBWPs negatively impacted the financial sustainability indicator with $\beta_2 = -0.023$ and $\beta_3 = -0.363$. This implies that in order to enhance financial sustainability of CBWPs, more attention needs to be paid to these two parameters. These results concur with the findings of Ngopa (2012) who demonstrated that lack of financial resources led to poor implementation of CBWPs approaches in some parts of Tanzania.

In terms of organizational indicators, parameters measured comprised regularity of meetings held by the CBO, general functionality of the CBO, existence of a project manager to provide the requisite leadership, cooperation with external agencies, and support from local authorities. Of these parameters, regularity of CBO meetings, existence of a project manager, cooperation with external agencies and support from local authorities had a positive impact on the organizational construct with $\beta_1 = 1.000$, $\beta_2 = 0.109$, $\beta_4 = 0.038$ and $\beta_5 = 0.005$. The implication of this finding is that these parameters need to be strengthened further for purposes of enhancing sustainability of the CBWPs. An interesting observation made during the focus group discussions was that throughout most of the CBWPs, the operators were basically volunteers and did not receive any payment for the work, which in many cases appeared demanding in terms of time and level of attention. While most CBOs did not have a problem with this status, a few of the operators felt that if a small stipend was offered to them as a token of appreciation, it would boost their level of motivation. This finding is similar to those of Moriarty *et al.* (2013) who observed that under community based management, paying those individuals carrying out non-technical duties critical for sustainable management of water supply facilities may need to be considered, because voluntarism may only work to a certain extent. General functionality of the CBO (comprising aspects such as quality and timely communication among CBO members, attendance of CBO activities, and making contributions where required) scored

β_1 = –0.016 implying a potential negative impact on the organizational indicators of the CBWPs. The implication of this finding is that investing in building the capacity of the CBO to improve its functionality may positively enhance the organizational sustainability of the CBWPs. This finding corroborates those of Rico *et al.* (2009) who argued that communication within the CBO team can be a factor that influences team management and overall cohesiveness.

Sustainability of CBWPs

In the present study, sustainability of CBWPs was measured from the latent variables comprising technical, organizational, social and financial aspects. The model used is shown below:

Sustainality =~ Technical + Organisational + Social + Financial + funtionality + design

On this basis, the full model taking into account the covariance between the latent variables was:

Organisational =~ regular + operator + cooperation + support
Social =~ public + com.participation + equity + inclusivity
Finance =~ payment + financial + funds
Social ~~ Social
Technical ~~ Technical
Organisational ~~ Organisational
Finance ~~ Finance
sustain =~Social + Technical + Organisational + Finance

The study used the Maximum Likelihood estimator and from the results the model was statistically significant at the 5% level of significance (χ^2 = 171.640, degrees of freedom = 117, p – value = 0.001). All the four constructs, namely Social, Technical, Organizational and Financial, had a positive influence on sustainability since the standard estimates were all positive with β_1 = 1.000, β_2 = 2.999, β_3 = 0.557, β_4 = 4.434 respectively. Finance and Technical indicators however seemed to impact heavily on sustainability (β_2 = 2.999, β_4 = 4.434). The implication of this finding is that while social and organizational aspects are important, more attention needs to be focused on financial and technical aspects as these two factors have a relatively stronger influence on the overall sustainability of CBWPs. The study findings are similar to those of Spaling *et al.* (2014) and Binder (2008). Spaling *et al.* (2014) reported that water projects established under community management should not need heavy financial investments during operation and maintenance. If the operation costs are higher than the community's capacity to meet, then such water projects can easily stall. On the same note Binder (2008) observed that the financing process that involves raising and maintaining adequate funding for water facilities is of critical importance for sustainability of CBWPs. Similar observations were made by Campos (2008) who argued that training on issues like operation and maintenance empower communities to take care of water supply systems, thus aiding sustainability.

Conclusions

This study has demonstrated that all the four indicators comprising Social, Technical, Organizational and Financial aspects have a positive influence on sustainability, which means that they are essential determinants of the sustainability of CBWPs. However, the study also revealed that among the four indicators, technical and financial aspects have a stronger influence on the sustainability of CBWPs. The study concludes that while it is important to ensure that all the four criteria are well taken care of during the planning and designing of CBWPs, special attention should be given to their financial and technical aspects. In this context, the study recommends that building the capacity of the CBO in terms of having adequate technical competence and reliable financial resources to support operation and maintenance of the CBO is not a choice but a requirement for sustainability of CBWPs.

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Size-distribution and length-weight relationship of a deep-water population of *Holothuria scabra* (Jaeger, 1833) in Zanzibar, Tanzania

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Abstract
A study was carried out on the size distribution, length-weight relationship and condition factor of a deep-water population of the commercially important tropical sea cucumber *Holothuria scabra* in Zanzibar, Tanzania. Samples were collected from fishers and supplementary information gathered. The deep water (15-20 m) population of *H. scabra* is dominated by large sized individuals that have already attained maturity. There was no significant difference in size between male and female individuals (p>0.05). The sex ratio in this population significantly differed from 1:1 in favour of male individuals (p=0.01). The results showed significant correlation between length and weight for male, female, indeterminate individuals, and pooled data, with r values of 0.681, 0.794, 0.821 and 0.680, respectively. Moreover, the b-value for male, female, indeterminate individuals and pooled data was 1.288, 1.439, 1.686 and 1.407 respectively, which revealed that individuals of deep-water *H. scabra* exhibit negative allometric growth. The mean condition factor (K) value when all data were pooled together was 4.213±0.106 indicating that individuals were in good condition and came from a healthy environment. This study fills a key information gap that is relevant to the management of the *H. scabra* fishery in the country.

Keywords: *Holothuria scabra*, Size distribution, Length-weight relationship, Condition factor, Allometric growth, Zanzibar

Introduction
Sea cucumbers constitute an important part of marine fisheries in Tanzania (Semesi *et al.,* 1998) and have provided a source of income to individual collectors as well as revenue at a national level through export (Eriksson *et al.,* 2010). However, as in other producing countries across the region, the resource has already dwindled in Tanzania as evidenced by catch reduction, dominance of small size individuals (Jiddawi, 1997; Mgaya and Mmbaga, 2007; Mmbaga, 2013) and a decrease in the number of exporters (Marshall *et al.,* 2001).

Despite the crucial role played by sea cucumbers both economically and ecologically, the status of wild stocks of commercially important species is unknown and has not yet been quantified in Tanzania (Mmbaga and Mgaya, 2004), even though the resource could be at high risk. Unlike in mainland Tanzania where a total moratorium on sea cucumber fishing has been implemented for more than a decade (Eriksson *et al.*, 2010) (though its enforcement is still questionable), the situation is much worse in Zanzibar, where the fishery is still operating despite a directive aimed at prohibiting it.

As shallow water (near shore) sea cucumbers have already been depleted in Zanzibar, sea cucumber collectors are now moving further off-shore (Eriksson *et al.*, 2010); a common practice along the whole west coast of Unguja Island. This represents a significant threat to the sea cucumber population, ecosystem (Uthicke, 1999) as well as the safety of fishers (Eriksson *et al.*, 2010).

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Holothuria scabra, commonly known as sandfish, is one of the more commercially important tropical species and contributes a significant portion of the total sea cucumber catch in Tanzania (Mmbaga and Mgaya, 2004). It is a deposit-feeding species found in low-energy environments behind fringing reefs up to 20 metres deep or within protected bays and shores of the tropics (Hamel *et al.,* 2001). The deep-water populations (>10 m depth) (Ram *et al.,* 2016) are the last potential group of breeders that the ecosystem relies on to repopulate the dwindling shallow water population of *H. scabra*. However, they are at high risk of being overfished due to the existing fishing pressure which is influenced by high prices obtained for the species by collectors. With existing fishing pressure on the deep-water *H. scabra* population, it is most likely the species will disappear in the near future, unless appropriate and effective management measures are taken.

Knowledge on the size composition of harvested individuals and their length-weight relationships is crucial in fisheries management (King, 2007; Ahmed *et al.,* 2018) as they provide information about the impact of harvesting on the population and distribution of different-sized individuals both temporally and spatially (Montgomery, 1995; Natan *et al.,* 2015). The length-weight relationship is the standard method used in fisheries biology to estimate average weight of an animal at a given length group or class (Froese, 2006; Gerritsen and McGrath, 2007). Moreover, this can also be used to determine condition factor which in turn determines the well-being

Figure 1. The study site (Fuji-Kama fishing ground) in Unguja Island, Zanzibar, Tanzania.

or relative fatness of an organism and the health of its environment (Natan *et al.,* 2015; Aydin, 2016; Ram *et al.,* 2016). However, this information is missing for the *H. scabra* population in Zanzibar and Tanzania as a whole, especially for those found in deeper waters, which presents a key information gap that is relevant to their management. The present study aimed to determine the size distribution, length-weight relationship and condition factor (K) of deeper water *H. scabra* along the coast of Zanzibar, Tanzania.

Methodology

Study site and sample collection

This study was conducted at the Fuji-Kama fishing ground located on the west coast of Unguja Island, Zanzibar between 6°2′30″S to 6°7′30″E, 4 km off the coastline (Fig. 1). The water depth of the fishing ground is between 15-20 m and the sea floor is characterized by muddy-sandy sediment with no seagrasses. The sea cucumber population in the fishing ground is dominated by *H. scabra*. Sea cucumber samples were collected directly from the fisherman who fish within the studied fishing ground. Prior to the study, the fishermen were requested to collect all *H. scabra* encountered, regardless of size.

Measurements

Upon the arrival of fishers at the landing site, sea cucumbers were transferred from drums to trays filled with sea water to allow them to relax for five minutes. When they were fully relaxed, total length was measured from the mouth to the anus using a ruler to the nearest 0.5 cm. The total body weight of each individual was measured, followed by dissection and removal of all internal organs (guts, respiratory trees and reproductive system), after which the body wall weight was measured to the nearest 0.1 g. Gonad samples were taken from each individual and stored in a plastic container for microscopic examination and determination of their sex (presence of eggs or sperm). Unsexed individuals which had no sperm and eggs in their gonad were recorded as indeterminate.

Length-weight relationship

Length-weight relationship was estimated using the power function (Pauly, 1984)

$$W = a L^b$$

Where W = Weight in g, L = Length in cm, a = Intercept, b = Slope

The value of b from the power function equation was tested and used to determine growth patterns of the sea cucumber (i.e. isometric growth (b=3) or allometric growth (b≠3)) by using the Students t-test (after Pauly, 1984). The coefficient of determination (R^2), that is, the degree of relation between the length and weight, was computed by linear regression analysis.

Condition factor (K)

Fulton's condition factor (K) was analysed according to Pauly (1984)

$$K = 100W/L^3$$

Where K = Condition factor, W = weight in g, L = Length in cm

Statistical analysis

All data were tested for normality and homogeneity of variances using Shapiro-Wilk and Levene's test, respectively. Chi-square was used to test whether the sex ratio significantly deviated from 1:1. The mean differences in body weight, total length and condition factor (K) between male, female and indeterminate *H. scabra* were tested using a one-way ANOVA.

Results and discussion

Sex ratio

A total of 179 individuals of *H. scabra* were collected between August and September, 2019. The number of samples collected per sampling day is presented in Table 1. There were significantly more male than female *H. scabra* in this population during the study period, with 104 (58.1%) males, 70 (39.1%) females and 5 (2.8%) sexually undifferentiated (indeterminate) individuals. The chi-square test results show that the sex ratio significantly deviated from 1:1 (x^2 = 6.644, df=1, p=0.01).

A male-biased sex ratio for *H. scabra* has been also reported by Conand (1993), Mercier *et al.* (2000), Al-Rashdi *et al.* (2007) and Muthiga *et al.* (2009) from New Caledonia, Solomon Islands, Sultanate of Oman, and Kenya, respectively. However, their sex ratio values were not significantly different from 1:1. Muthiga *et al.* (2009), from data collected in three different years, reported a shift in sex ratio from precisely 1:1 in the first year towards significantly more males than females in the last year of their study. The same result was also reported by Natan *et al.* (2015) from Indonesia which is comparable to the findings of the present study.

Table 1. Study period and the number of samples collected on each sampling date, and their sex distribution.

Date	Number of Sample	Male	Female	Indeterminate
24/08/2019	23	13	10	-
27/08/2019	10	4	6	-
29/08/2019	29	13	16	-
01/09/2019	17	9	8	-
05/09/2019	40	30	9	1
09/09/2019	34	18	12	4
15/09/2019	26	17	9	-
Total	179	104	70	5

Hasan (2005) has pointed out that a population with more male than female individuals may be an indication of increase in fishing pressure, which is also possible in the current study. As shallow water sea cucumber populations are already depleted locally, fishermen are now shifting their efforts toward deep-water populations. Other authors have interpreted this phenomenon in different ways, for example: this might be due to high mortality of larvae, juveniles and adults of female individuals (Hoareau and Conand, 2001); or limited dispersal ability of female larvae as reported for other holothurians species (Uthicke and Benzie, 1999).

Size distribution

The overall size of all collected individuals expressed as body weight (BW), body wall weight (BWW) and total length (TL) ranged from 410 to 1957.8 g (1077.63±20.75 g (SE)), 220 to 960.6 g (579.42±9.44 g (SE)), and 20 to 42 cm (29.83±0.29 cm (SE)), respectively. There was no significant difference in average size between male and female individuals (Table. 2). However, female individuals were slightly longer and heavier than males. Indeterminate individuals had significantly lower body weight, body wall weight and total length ($p<0.05$) compared to sexed individuals (Table 2). The size distributions (total length, body weight and body wall weight) of collected individuals are shown in Fig. 2A, 2B and 2C respectively. More than 85% (153) of all collected individuals from this population had a length between 25 and 35 cm, 9.5% (17) were below 25 cm, 5% were above 35 cm, with no individuals smaller than 20 cm (Fig. 2).

Size at first sexual maturity for *H. scabra* in Tanzania has been found to be 16.8 cm (Kithakeni and Ndaro, 2004) from samples collected in Dar es Salaam, mainland Tanzania. Therefore, it can be concluded that all individuals collected in the present study had already reached maturity as they were all greater than 20 cm. Even if it is assumed that the size at first maturity is 25 cm, which is the highest ever recorded for *H. scabra* (India and Northern Australia) (Lee *et al.*, 2018), the majority (>90%) of all individuals collected in the present study would have already attained maturity. The presence of indeterminate individuals in this population does not signify that these individuals had not reached maturity, but rather that their gonads were in a resting stage during their collection. Individuals

Table 2. Mean size comparison between male, female and indeterminate individuals. Values on the same row with different superscripts indicate significant differences.

	Mean Values (±SE)		
	Male	Female	Indeterminate
Total Length (cm)	29.548 ± 0.381^{a}	30.586 ± 0.451^{a}	25.00 ± 1.342^{b}
Total Body Weight (g)	1068.438 ± 27.580^{a}	1118.691 ± 30.705^{a}	694.08 ± 87.336^{b}
Body Wall Weight (g)	575.965 ± 12.691^{a}	599.965 ± 13.176^{a}	363.92 ± 27.598^{b}

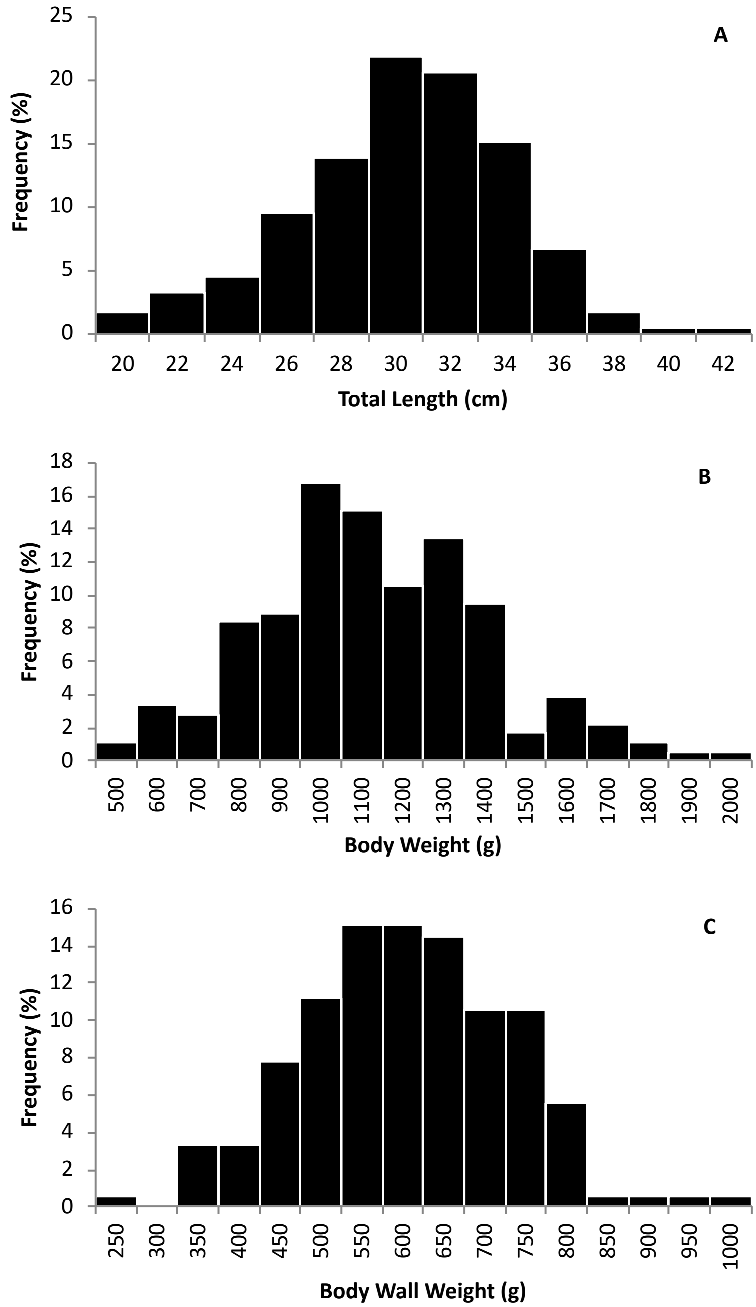

Figure 2. Size distribution of collected *Holothuria* scabra from the deep-water population. (A): Length, (B): Body weight and (C): Body wall weight.

with gonads at different maturation stages have been reported to occur throughout the year in Tanzania (Kithakeni and Ndaro, 2002).

The present findings add to the number of studies that support the fact that large sized individuals are found in deeper waters, probably migrating from the intertidal zone as they grow bigger (Mercier *et al.*, 2000). For instance, in the Solomon Islands, individuals >25 cm were mainly located in the deep water zone and small size individuals (4-15 cm) were found in shallow (intertidal) waters (Mercier *et al.*, 2000). However, James (1994) reported individuals of 30-35 cm in 5-10 m depth in India which is contrary to other studies. Murphy *et al.* (2011) suggests that it may be difficult to find small size sea cucumbers as they burrow during the day and become active at night.

The size frequency distribution of sea cucumber populations can either be unimodal, bimodal or plurimodal (Hamel *et al.*, 2001) depending on the population. In this study, the size (length) frequency distribution was unimodal with 12.3% of all individuals having a length of 32 cm (Fig. 2A). Conand (1994) and Natan *et al.* (2015) reported a plurimodal length frequency distribution with poorly defined modes in New Caledonia and Indonesia respectively. However, Basker (1994), Uthicke and Benzie (1999), and Al-Rashdi *et al.* (2007) recorded a unimodal length frequency distribution from India, Australia and the Sultanate of Oman, which is comparable to the present study. However, their modal value was smaller (23 and 26.9 cm) than the value recorded in the present study.

Based on published records, the maximum length and body weight of *H. scabra* ever recorded was 70 cm in China and 2 kg in India, respectively (Hamel *et al.*, 2001). The maximum length and body weight recorded in the present study is smaller than this, but average body weight was higher than other reported values, for example: 300 g (Papua New Guinea, Sultanate of Oman, India), 335 g (Australia), 500 g (Egypt) and 580 g (New Caledonia) (Purcell *et al.*, 2012).

Moreover, the average length recorded in the present study is quite high, exceeded only by 37 cm mean length in Egypt (Purcell *et al.*, 2012). The values from other countries such as Australia, New Caledonia, Papua New Guinea and India ranged from 19 to 25 cm (Purcell *et al.*, 2012). The difference in size of *H. scabra* from different populations or countries could be attributed to differences in environmental factors (Uthicke and Benzie, 1999) such as food availability (Morgan, 2001; Pitt, 2001), fishing pressure (Uthicke and Benzie, 1999; Hasan, 2005) and the depth where the samples were collected (Kithakeni and Ndaro, 2002) in addition to the actual biological differences of individuals between populations. Furthermore, it could be due to inconsistency of measurement methods between studies since body length and weight of sea cucumber are highly variable (Hamel *et al.*, 2001).

Length-weight relationship

The calculated correlation coefficient (r) values for male, female, indeterminate and pooled data ranged from 0.680 to 0.821 while the respective tabulated

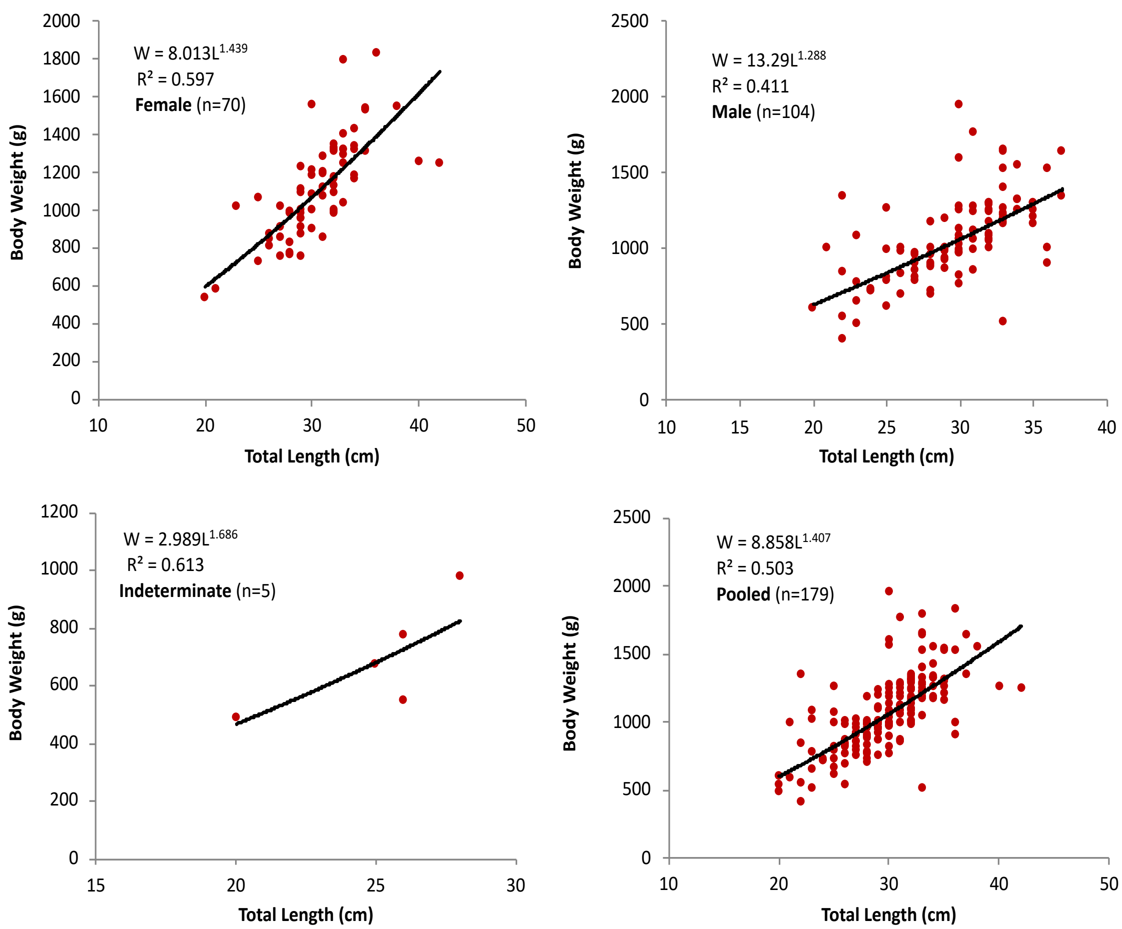

Figure 3. Length-weight relationship of *Holothuria scabra* collected from deep water.

Table 3. Length-weight relationship of *Holothuria scabra* collected from deep water.

Sex	n	W=a L^b	Log W = Log a + b x Log L	r calc	r table (p=0.01)	t calc	t table (p=0.01)	K
Female	70	W=8.013L$^{1.439}$	Log W=0.903+1.44LogL	0.794*	0.295	10.890*	2.66	4.018
Male	104	W = 13.29L$^{1.288}$	Log W=1.123+1.28LogL	0.681*	0.295	11.218*	2.62	4.331
Indeterminate	5	W=2.989L$^{1.686}$	Log W=0.475+1.69LogL	0.821*	0.805	1.700*	1.638	4.491
Pooled	179	W=8.858L$^{1.407}$	Log W=0.947+1.41LogL	0.680*	0.114	15.155*	2.626	4.213

* Denoted significant difference

r values ranged from 0.114 to 0.805 (Table 3). The calculated r was found to be larger than critical r which indicates highly significant correlation between length and weight for male, female, indeterminate and pooled data. Moreover, the coefficient of determination (R^2) value which shows the percentage contribution of the independent variable to the dependent variable ranged from 0.411 to 0.613 (Fig. 3). The R^2 value in this study is smaller than that recorded by Lee *et al.*, (2018) (R^2=0.90), Al-Rashdi *et al.* (2007) (R^2=0.80) and Natan *et al*. (2015) (R^2=0.43-0.68) from Fiji, Sultanate of Oman and Indonesia, respectively.

The length-weight relationship results (Table 3 and Fig. 3) also show that the b values for male, female, indeterminate and pooled data ranged from 1.288 to 1.686. The b value was significantly less than 3, so it can be concluded that the growth pattern of deep-water *H. scabra* is negatively allometric. Such growth patterns have also been reported elsewhere, for example in Indonesia (b=1.264 to 2.127; Natan *et al*., 2015), Sultanate of Oman (b=2.18; Al-Rashdi *et al.,* 2007), Vietnam (b=2.84; Pitt and Duy, 2004), and New Caledonia (b=2.28; Conand, 1990; b=1.26; Purcell *et al.,* 2009). This indicates that at a given length, the individuals collected from deep water in Zanzibar are leaner than in these other locations, except for those collected in the Purcell *et al.* (2009) study. The value of b in length-weight relationships is always changing depending on the animal's habitat, physiological condition, maturity stage and food availability (Froese, 1998; Natan *et al.,* 2015). Moreover, the differences could be attributed to the actual differences existing between individuals in relation to the environmental conditions around them, or the inconsistency in procedures used to estimate length and weight between studies (Al-Rashdi *et al.,* 2007).

Condition factor (K)

The mean K value for *H. scabra* from this population was 4.213±0.106 when all data were pooled together. One-way ANOVA results show no significant differences in K values between male, female and indeterminate individuals (F=0.607, df=177, p=0.799). However, male individuals have a slightly higher mean K value than female individuals. The overall mean K value reported in this study is high which indicates that *H. scabra* from this population are in good physical condition and come from a healthy environment (Pauly, 1984).

Conclusions

It can be concluded that the deep-water population of *H. scabra* on the west coast of Unguja Island, Zanzibar mainly consists of large sized mature individuals. The sex ratio in this population is significantly different from 1:1 in favour of males, indicating high fishing pressure. Like other sea cucumber species, *H. scabra* from this study shows negative allometric growth, i.e. length increment is faster than weight increment. The condition factor (K) recorded reveals that the individuals were in good condition and that they came from a healthy environment. This study provides baseline information on the overall condition of the deep-water population of *H. scabra* in the coastal waters of Zanzibar, hence contributing towards better management of the species. Since this group of individuals consist mainly of potential breeders which are expected to repopulate dwindling shallow water populations, management measures such as temporal (seasonal) closure or total prohibition should be enforced to minimize fishing pressure on deep water populations. However, more studies are needed on the reproductive biology, spawning pattern and stock status of the species across the Zanzibar Islands and Tanzania as a whole.

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A review of soft corals (Octocorallia: Alcyonacea) and their symbionts: Distribution of clades and functionality

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Abstract

Even though soft corals are an integral part of the coral reef ecosystem, very little research has focused on their endosymbiotic association with the zooxanthellae (Symbiodiniaceae). Symbiotic algae appear in soft corals from both the tropical seas as well as temperate regions across the world. The present study provides a list of soft corals along with their associated zooxanthellae using published data. By combining all the data, 52 soft coral species belonging to 21 genera were identified and their corresponding specific Symbiodiniaceae genera were analysed. It was important to initially compare soft corals and distinguish zooxanthellae at clade level to find any host specificity. The vast majority (75 %) of soft corals predominantly hosted the genus *Cladocopium* (Clade C) and therefore the focus of this study was to evaluate its geographical distribution. The genus *Cladocopium* consists of many species which are classified as subclades in this study, exhibiting high intra-clade diversity. For 40 of the 52 soft corals reviewed, 18 % had the same clade type C1 (considered as generalists and ancestral) and 13 % contained the clades C15, C64 and C1:3a, respectively. Analysis showed that some clades (C71a, C15b and C64) were confined to specific geographical regions while clade C1 was distributed worldwide. Understanding the distribution of endosymbionts may enable predictions of which symbioses will survive and exist under future climate change scenarios.

Keywords: soft corals, zooxanthellae, symbiodiniaceae, endosymbiosis, *Cladocopium*

Introduction

Global coral communities have been severely damaged as a result of natural and anthropogenic disasters (Dar *et al.*, 2012), and soft corals which occupy up to 25 % of the primary space (Benayahu, 1995) have been equally affected. About 107 species of soft corals have been reported in Brazilian waters (Almeida *et al.*, 2014), 80 species in the inshore zone of the Red Sea (Dar *et al.*, 2012), and 70 species in Taiwanese reefs (Banayahu *et al.*, 2004). They may also be found in many colder regions such as Antarctica, southern Africa, the Pacific Northwest coast of North America, and the North Atlantic (Haverkort-Yeh *et al.*, 2013). Sesoko Island, Japan, is best known for soft coral coverage of as high as 34.4 % (Loya *et al.*, 2001). The presence of octocorals in most benthic habitats under the influence of various environmental factors, indicates the adaptive nature of this taxonomic group (van de Water *et al.*, 2018).

The most conspicuous feature of soft corals is the polyps which contain eight tentacles (hence octocorals) that are invariably pinnate (Janes and Lee, 2007). For some genera, the tentacles contain sensory cells which are filled with zooxanthellae, unicellular photosynthetic microalgae belonging to the Symbiodiniaceae (Order Suessiales, Class Dinophyceae) (Fournier, 2013).

These symbiotic types of soft corals have a tendency to be found in shallow tropical and subtropical waters (Cooper *et al.*, 2014). The host and the symbiont hold a mutualistic relationship, where the symbiont receives inorganic nutrients from the host and in-turn provides translocated photosynthetic products necessary for host functions (Muscatine, 1990) such as calcification and reproduction (Farag *et al.*, 2018). Farag *et al.* (2018) further stated that the formation of the modern

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coral reef ecosystem and the contributions to global carbon and biogeochemical cycles is due to the mutualistic exchange of metabolites between the host, the zooxanthellae and their associated microbial assemblages. Unlike hard corals, soft corals exhibit mostly a mixotrophic nature (Fabricius and Klumpp, 1995; Slattery *et al.,* 2019). Depending on symbiont diversity, the host trophic mode can be autotrophic or heterotrophic (Baker *et al.,* 2015). Similar to scleractinian corals, heterotrophic feeding in soft corals is also increased by the energy provided by the Symbiodiniaceae (Slattery *et al.,* 2019) and allow corals to thrive in oceanic deserts (nutrient-poor environments) (Houlbrèque and Ferrier-Pagès, 2009). Both hard and soft corals acquire their symbionts by vertical and horizontal transfer. The diversity of symbionts is higher in hard corals but at the same time the association of Symbiodiniacea in soft corals is more stable than that of the hard corals (Poland and Coffroth, 2016). Compared to zooxanthellate octocorals, azooxanthellate (absence of dinoflagellates) octocorals populate deep and dark environment where they rely solely on heterotrophic feeding (Fabricius and Klumpp, 1995).

Research on different soft corals such as the genera *Sarcophyton, Sinularia, Xenia* and *Lobophytum* has demonstrated that a similar endosymbiotic relationship exists between the zooxanthellae and the soft coral hosts (Sammarco and Strychar, 2013). Extensive studies over the past 60 years on the physiological contribution of the zooxanthellae to symbiosis unveiled their major role in the nutrition of the host (Santos *et al.,* 2002). Furthermore, some reviews highlighted that depending on the local environment as well as the microhabitats within a host, some adult coral species can couple with different dinoflagellates from the genera of Symbiodiniaceae (Little *et al.*, 2004). In tropical reefs, an increase in the diversity of symbiotic Symbiodiniaceae may improve the adaptability of coral to climate change (Qin *et al.,* 2019). This particular form of association, termed polymorphic, implies that corals from the same species may not be physiologically similar and the presence of a particular zooxanthellae may play a role in determining the physiology of the host-symbiont endosymbiosis association (Toller *et al.* 2001). The ability of the host to acquire multiple symbiont phylotypes depends also on the host age (Poland and Coffroth, 2016). The work carried out by Poland and Coffroth (2016) has shown that the octocoral *Briareum asbestinum* can easily harbour up to 11 symbiont phylotypes, with single polyps capable of harbouring at least 6 phylotypes simultaneously in its juvenile state of life, while the adult colonies are in symbiotic association with only 1 or 2 symbiont phylotypes.

Rowan and Powers (1992), who spearheaded phylogenetic work on *Symbiodinium*, used nuclear ribosomal small subunit (nr18s) sequences to obtain 3 key clades (A-C). Various nuclear ribosomal large subunit (nr28s) sequences were assigned to different host taxa as well as larger geographic parameters (Santos *et al.*, 2002) to ultimately obtain 9 *Symbiodinium* lineages, with suggestions that many more genetic variations exist within the clades (Davis *et al.*, 2017). Some questions have been raised on the phylogenetic techniques used in the study of zooxanthellae. Rowan *et al*. (1996) addressed, and Santos *et al*. (2001) questioned, the un-established culture techniques used for zooxanthellae and the dilemma of excluding un-culturable microalgae. This exclusion led to a lack of crucial data and a limited sample size for the phylogenetic studies. Additionally, Rowan (1998) mentioned that some of the members of the zooxanthellae still remain uncultured and lack description. The presence of many morphological characters and the lack of sexual reproduction in this algal group has not allowed the evolutionary groups within the zooxanthellae to be adequately described (Wilcox, 1998). Consequently, it has been suggested that these techniques have limited use in phylogenetics (Schoenberg and Trench, 1980). Despite the comprehensive body of physiological knowledge, the understanding on the phylogenetics of zooxanthellae remains unresolved.

Previously, researchers assumed that all zooxanthellae were associated with a single accepted species, *Symbiodinium microdriaticum* (Freudenthal) (Taylor, 1974). The heterogeneity of zooxanthellae in response to different hosts was addressed by various researchers (eg. Santos *et al.*, 2002; Trench, 1993; Rowan, 1998; Schoenberg and Trench, 1980). The existence of a single genus comprising of hundreds of both closely and distantly related species is most likely to generate confusion (LaJeunesse *et al.*, 2018). Interestingly, recent in-depth research by LaJeunesse *et al.* (2018) explained the evolutionary divergence of *Symbiodinium,* previously referred as to as ‘clades’, as being analogous to the genera in the family Symbiodiniaceae. Systematic revision was needed due to low transcript similarity (<20 % orthologous gene loci) between the Symbiodiniaceae clade recognized by Bayer *et al.* (2012). Moreover, high species diversity among Symbiodiniaceae distributed across highly diverse marine organisms, and ecologically diverge lineages, increased the importance for a systematic revision (LaJeunesse *et al.,* 2018). LaJeunesse *et al.* (2018) redefined the genus *Symbiodinium sensu strictu* to Clade A and also defined several new genera: B as *Brevidum*, C as *Cladocopium*, D as *Durusdinium*, E as *Effrenium*, F as *Fugacium* and G as *Gerakladium*. Additionally, the lineage encompasses multiple distinct genetic types which are highly variable (LaJeunesse *et al.,* 2018).

Increase in temperature and loss of Symbiodiniaceae in soft corals: a reality or a myth?

It is no more a myth that worldwide coral bleaching, due to loss of zooxanthellae, is a heat stress response to an increase of sea surface temperature above the mean yearly maximum or elevated above 30 °C (Brown, 1990). Several reports have documented that corals are affected by long term temperature exposure above 30 °C and that they usually condition themselves to global heat stress (Strychar *et al.*, 2005). Adaptive bleaching hypothesis (Fautin and Buddemeier, 2004) proposed that bleaching provides an opportunity for corals to change their algal communities to acquire more heat-resistant algal species. High mortality rates due to bleaching episodes have been reported and there is now good evidence to show that in response, zooxanthellae communities may change following bleaching in at least a few coral species. The soft coral host and the zooxanthellae display different degrees of adaptation to rising sea surface water temperature (Sammarco and Strychar, 2013). Barshis *et al.* (2014) explained how the host usually has a stronger transcriptional response to stress changes, while the Symbiodiniaceae is deprived of this transcriptional response. Lack of transcriptional responses was identified in Symbiodiniaceae D2 and C3k when exposed to heat stress, which differ generally from the transcriptional shifts in coral hosts (Barshis *et al.,* 2014). Fitt *et al.* (2000) monitored the growth rate of several Symbiodiniaceae and found that temperature plays a vital role in their optimal growth and photosynthetic rate. Moreover, zooxanthellae can display optimal growth rates at temperatures between 26 °C – 32 °C, with some growing best at 26 °C with death occurring at 32 °C (Fitt *et al.,* 2000). Yet exceptions exist, such as in the Persian Gulf where some zooxanthellae (mainly the thermotolerant lineage *S. thermophilium*) have adapted to temperatures as low as 13 °C and as high as 38 °C (Sammarco and Strychar, 2013). The density of zooxanthellae in soft corals usually varies seasonally (Fitt *et al.,* 2000), but after abnormal seasonal change, it is vital that they become re-established within a few days or weeks to prevent the corals from dying (Sammarco and Strychar, 2013). The re-establishment of zooxanthellae is time dependant and this process can be hindered by factors such as salinity, pollution, ocean acidification and diseases. The 'layered cell' hypothesis describes how the Symbiodiniaceae population increases within the layers of soft corals, with the outer layer having a higher zooxanthellae density than the inner layers. The cells located deeper within the soft corals are exposed to lower light intensity and are less adapted to resist thermal and UV fluctuation than the resistant cells located in the upper layers. When loss of upper layer zooxanthellae cells occurs due to a rise in temperature above the tolerant value, the less-resistant inner layer cells are exposed to temperature and UV differences, making them more vulnerable and causing dissociation from the soft corals. This explains the concept of the 'two large bursts' of Symbiodiniaceae loss in soft corals elucidated by Strychar *et al.* (2005). Corals in general, and mainly octocorals, have an obligate association with the zooxanthellae, which even after an overproduction of reactive oxygen species (ROS), do not expel the symbionts, which instead migrate to the stolon (Parrin *et al.*, 2016). The symbionts still possess photosynthesis power after full migration to the stolons (van de Water *et al.,* 2018).

Extreme storm events as reported by Emanuel (2013) can cause serious damage to coral reefs, and ocean acidification undoubtedly affects physiological processes in corals (Doney *et al.,* 2009). The drop in pH limits the capacity to produce calcium carbonate structures and limits algal photosynthetic productivity (Sogin *et al.,* 2016). The work by Farag *et al.* (2018) clearly demonstrated that an increase in CO_2 levels results in a change in both polar and non-polar metabolism in soft corals. However, the change in metabolic reaction varies depending on the species. Interestingly, when exposed to an increase in CO_2, nicotinic acid was released from *S. glaucum* but not from *S. ehrenbergi* (Farag *et al.,* 2018). Farag *et al.* (2018) suggested that the release of nicotinic acid may account for the increased stress resistance of *S. glaucum* compared to *S. ehrenbergi*, however no further published records are available. Alteration of metabolites (amino acids, polyamines, nitrogenous compounds) can act as biomarkers for predicting the impact of stress.

The objective of this review is to understand the distribution of different type of endosymbionts in soft corals (Octocorallia:Alcyonacea). The soft corals and their associated symbionts were listed demonstrating that the majority of the soft corals form an endosymbiotic association with *Cladocopium.* The specificity of the genus *Cladocopium* and its geographical distribution was also reviewed.

Methods

Data from various reports were compiled into one large data set. The Symbiodiniaceae data were taken from field-collected soft corals and not from zooxanthellae culture due to the probability of overlooking non-culturable Symbiodiniaceae (Goulet and Coffroth, 1997; Santos *et al.,* 2001; LaJeunesse, 2002). Most reports identified zooxanthellae at the genus level, with some reporting within-clades resolution. If a soft coral was not identified to the species level, the genus was noted with a 'sp.' notation. To be more explicit, each genus level (soft corals) was treated as a different species. Such an approach diminishes misinterpreting the species hosting a single Symbiodiniaceae. Furthermore, the latest systematic revision of the zooxanthellae (LaJeunesse *et al.,* 2018) was taken into account while pooling the various data on soft corals and their particular endosymbionts. Using the compiled data set, a dendrogram was generated using the SPSS statistics 20 programme. Particularly, Average Linkage (between groups) was used to generate the phylogenetic tree based on the Symbiodiniaceae possessed by the soft corals. Less emphasis was given to the collection depth of the soft corals while constructing the dendrogram. A combined data set of soft corals with the specific genus *Cladocopium* type from various geographic locations was evaluated.

Results

Soft corals and their associated zooxanthellae

Fifty-two soft coral species belonging to 21 genera from the families Alcyoniidae, Nephteidae and Xeniidae obtained from various research works as well as their corresponding Symbiodiniaceae genera were studied. The depth from which the soft corals were collected ranged from 1 m to a maximum depth of 40 m. Moreover, 60 % of the soft corals were from Australia (Great Barrier Reef and Lizard Island), while the rest were from the Red Sea, Hawaii, Fiji, Guam and China. Most reports identified the soft corals up to species level, yet some were limited to genus level. The Symbiodiniaceae genera reported in the soft corals were *Symbiodinium* (Clade A), *Breviolum* (Clade B), *Cladocopium* (Clade C), *Durusdinium* (Clade D) and *Gerakladium* (Clade G) (Table 1). Interestingly, it can be inferred that the majority of the soft corals form an endosymbiotic association with *Cladocopium* (Clade C) (Fig. 1). Soft corals in multiple sites from the Great Barrier Reef (GBR), Guam, Fiji, Japan, Red Sea and Hawaii hosted predominantly clade C zooxanthellae (Table 1). Genus *Symbiodinium* was found in soft corals sampled from Hawaii, Israel, and the GBR, while *Breviolum, Durusdinium* and *Gerakladium* were only found in GBR.

The results from the dendrogram (Fig. 2) clearly show that all soft corals hosting the genus *Cladocopium* clustered together, irrespective of the depth from where they were collected. Similar results were obtained for soft corals hosting the genus *Durusdinium* and *Symbiodinium*. *Nephthea* sp. from the family Nephtheidae were found in the different clusters due to the presence of distinct zooxanthellae. They hosted different zooxanthella clades at different geographic locations (LaJeunesse and Trench, 2000); namely genus *Cladocopium* from Israel, *Durusdinium* and *Breviolum* from Australia, and *Symbiodinium* from the Red Sea. It can also be inferred that cladal specificity does not occur at the family level of soft corals. In the family Alcyoniidae, all 20 species host genus *Cladocopium*, with two species also hosting genus *Durusdinium* and genus *Symbiodinium*. In the 15 Nephtheidae species, 7 hosted the genus *Cladocopium,* 2 hosted genus *Durusdinium,* 3 hosted genus *Symbiodinium,* 1 hosted the genera *Breviolum* and *Gerakladium*, and one hosted multiple zooxanthella (A, C). The greater diversity of zooxanthellae clades was observed in the family Nephtheidae. In the family Xenidae, 12 species hosted genus *Cladocopium*, and 1 hosted the genera *Durusdinium* and *Symbiodinium,* respectively. Furthermore, specific zooxanthellae genera were distributed globally while others exhibited a restricted distribution. Genus *Cladocopium* was globally distributed while genus *Symbiodinium* was very common in soft coral species in Australia, the Red Sea and Hawaii., based on data that are available. Interestingly, the genera *Durusdinium, Breviolum* and *Gerakladium* were restricted in soft corals from Australia. Aside from geographical location, the depth the soft corals were sampled from also defines the cladal specificity. The majority of the soft corals hosting the genus *Cladocopium* were obtained from a wide depth range from 1 m to 40 m (*Sarcophyton* sp. - 1.5 m; *Sinularia polydactyla* – 2-6 m, *Sinularia lochmodes* - 7-10 m, *Klyxum* sp. – 10-17 m, *Rhytisma fulvum fulvum* - 3-40 m) while the genera *Durusdinium, Symbiodinium* and *Gerakladium* were mostly found in soft corals at a depth of <20 m. The genus *Breviolum* was collected from soft corals at a depth of 3 m.

Table 1. List of soft corals and their associated Symbiodiniaceae genera from tropical and temperate regions. GBR: Great Barrier Reef, NA: Not available.

Family	Genus	Species	Location	Reported depth range/m	Symbiodi-niaceae genera	Citation
Alcyoniidae	*Sarcophyton*	*ehrenbergi*	GBR Australia	7-10	C	Sammarco and Strychar, 2013
		glaucum	Australia	NA	A	Carlos *et al.*, 1999
		sp.	Lizard Island Australia	1.5	C	van Oppen *et al.*, 2005
		sp.	South China Sea	5	C	Gong *et al.*, 2018
		trocheliophorum	Eilat's reef Red sea	<20	C	Barneah *et al.*, 2004
	Sinularia	*lochmodes*	GBR Australia	7-10	C	Sammarco and Strychar, 2013
		gardinen	Eilat's reef Red sea	<20	C	Barneah *et al.*, 2004
		querciformis	Eilat's reef Red sea	<20	C	Barneah *et al.*, 2004
		polydactyla	Australia	2-6	C	Goulet *et al.*, 2008
		abrupta	Hawaii	2-6	C	Goulet *et al.*, 2008
		erecta	Fiji	2-6	C	Goulet *et al.*, 2008
		flexibilis	Australia	2-6	C	Goulet *et al.*, 2008
		gyrosa	Fiji	2-6	C	Goulet *et al.*, 2008
		maxima	Guam	2-6	C	Goulet *et al.*, 2008
	Lobophytum	sp.	Lizard Island Australia	1.5	C	van Oppen *et al.*, 2005
		compactum	Australia	2-6	C	Goulet *et al.*, 2008
	Cladiella	*pachyclados*	Eilat's reef Red sea	<20	C	Barneah *et al.*, 2004
		tuberculoides	Israel	<20	C	Barneah *et al*, 2004
		sp.	Australia	2-6	C	Goulet *et al.*, 2008
		sp.	Australia	<18	D	van Oppen *et al.*, 2005
	Rhytisma	*fulvum fulvum*	Australia Israel	3-40	C	Barneah *et al.*, 2004
	Klyxum	sp.	Australia	10-17	C	LaJeunesse *et al.*, 2004 ; van Oppen *et al.*, 2005
		sp.	Australia	<18	D	van Oppen *et al.*, 2005

Family	Genus	Species	Location	Reported depth range/m	Symbiodi-niaceae genera	Citation
Nephtheidae	*Capnella*	*lacerthliensis*	Northern GBR Australia	2-6	C	Goulet *et al.*, 2008
		sp.	Northern GBR Australia	<18	A,C	van Oppen *et al.*, 2005
		sp.	GBR Australia	<15	D	van Oppen *et al.*, 2005
	Lemnalia	sp.	Australia	<15	C	Goulet *et al.*, 2008; van Oppen *et al.*, 2005
	Litophyton	*arboreum*	Australia Israel	<20	A	Goulet *et al.*, 2008; Barneah *et al.*, 2004
	Nephthea	sp.	Eilat's reef Red sea	<20	A	Barneah *et al.*, 2004
		sp.	Israel	<20	C	Goulet *et al.*, 2008
		sp.	Australia	3	B	LaJeunesse *et al.*, 2003
		sp.	Australia	>3	D	LaJeunesse *et al.*, 2003
	Paralemnalia	*thyrsoides*	Red sea	<20	C	Barneah *et al.*, 2004; Goulet *et al.*, 2008
		digitiformis	Australia	2-6	C	Goulet *et al.*, 2008
		eburnea	Australia	<20	C	Barneah *et al.*, 2004
	Stereonephth-ya	*cundabiluensis*	Red sea	<20	A	Barneah *et al.*, 2004
		sp.	Australia	<15	G	van Oppen *et al.*, 2005
		sp.	Fiji	2-6	C	Goulet *et al.*, 2008
Xenidae	*Anthelia*	*edmondsoni*	Hawaii	2-6	A	Goulet *et al.*, 2008
		glauca	Israel	<20	C	Barneah *et al.*, 2004
	Asterospicularia	*laurae*	Australia	2-6	C	Goulet *et al.*, 2008
	Bayerxenia	sp.	Lizard Island Australia	1.5	C	Ziegler *et al.*, 2018

Family	Genus	Species	Location	Reported depth range/m	Symbiodi-niaceae genera	Citation
Xenidae (continued)	Cespitularia	sp.	Australia	<15	C	van Oppen *et al.*, 2005
	Efflatounaria	sp.	Australia	2-6	C	Goulet *et al.*, 2008
	Heteroxenia	*fuscescens*	Israel	2-6	C	Behayahu, 1991; Goulet *et al.*, 2008
		sp.	Australia	<10	C	LaJeunesse *et al.*, 2004
	Sarcothelia	sp.	Hawaii	<10	C	LaJeunesse *et al.*, 2004
	Sympodium	sp.	Australia	<15	D	van Oppen *et al.*, 2005
	Xenia	*macrospiculata*	Israel	<20	C	Barneah *et al.*, 2004
		umbellata	Israel	<20	C	Barneah *et al.*, 2004 Behayahu, 1991
		elongata	GBR Australia	7-10	C	Sammarco & Strychar, 2013
		farauensis	Eilat's reef Red sea	<20	C	Barneah *et al.*, 2004

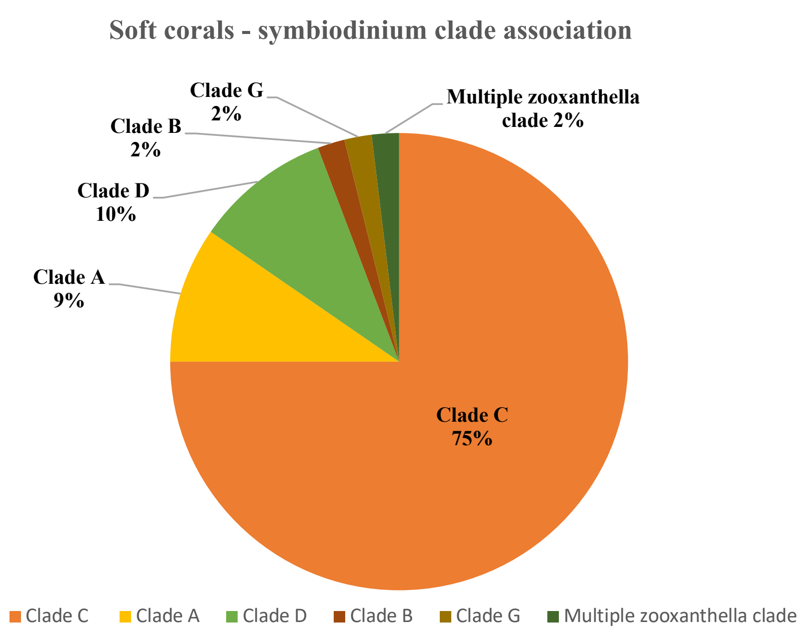

Figure 1. Frequency of each symbiodiniacea genus in the soft corals from the regions mentioned above (Table 1). The species were classified as hosting multiple genera when occurring in either the same or different colonies.

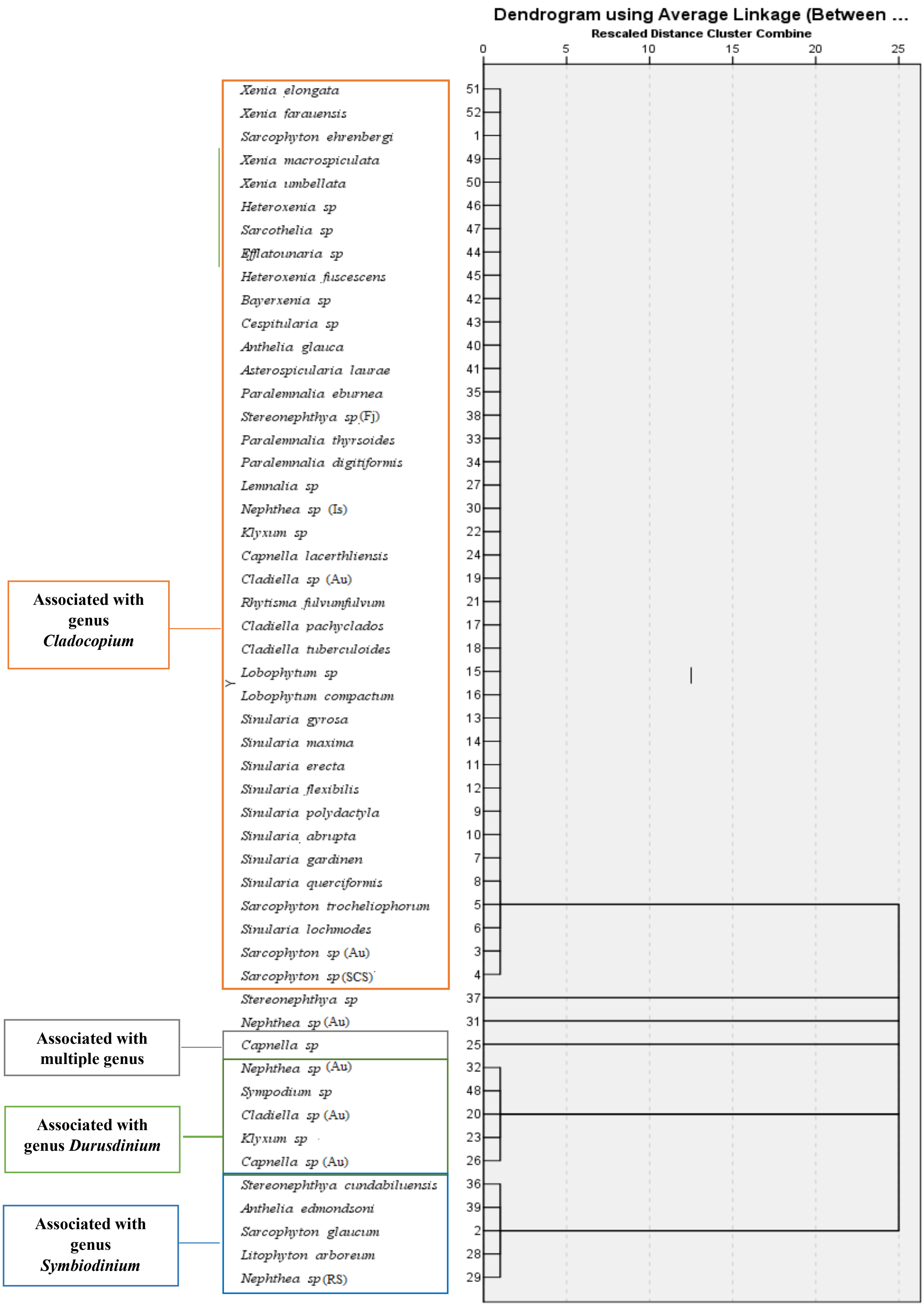

Figure 2. Dendrogram based on the average linkage (between group) method using the different Symbiodiniaceae associated with the different soft corals. Au: Australia; SCS: South China Sea; Fj: Fiji; RS: Red Sea

Soft corals and genus *Cladocopium* (clade C) specificity

Forty out of the 52 soft corals reviewed were found to be associated with *Cladocopium* (clade C). The results from Table 2 summarise how different soft corals have the ability to host multiple *Cladocopium* subclades at different collection depths. For example, *Paralemnalia digitiformis* from Australia has been found to harbour C1:2 and C64, and *Heteroxenia* sp. from Australia is associated with C15, C15e and C64 (Table 2). The data showed that the all the genus *Cladocopium* subclade was obtained from soft corals sampled from a depth of less than 20 m. Furthermore, Fig. 3, constructed from 40 soft corals, illustrates that 18 % have the same type C1 (considered as generalists and ancestral), 13 % contain the C15, C64 and C1:3a respectively, 8 % harbour C3j and C1:2, 5 % have C1c and C65, and finally 3 % contain C3, C1:1, C71a, C1k, C15e, C1q, C15b and C84a, respectively.

The results shown in Fig. 4 illustrate the global distribution of genus *Cladocopium* type in soft corals. Specialized symbionts (such as C71a, C1:2, C15b, C15, C1z) displayed limited ranges in geographic distribution. C71a is dominant in soft corals in the region of Japan and C15b only in Hawaii. Soft corals from the tropical zone are more likely to host a wide variety of Clade C type. Australia, being partially in the sub-tropical zone, hosts various Clade C types (C1, C64, C1:3a, C1c, C1q, and many more). C1 (generalist) is known to be distributed worldwide in various hosts, but due to limited research having been conducted on soft corals and their symbionts, it is difficult to show the generalist nature of C1. From Fig. 4, it can be seen that C1 was present in various soft coral species from Australia and New Zealand.

Table 2. List of soft corals and their associated Clade C subclade.

Soft corals Host	Clade C subclade	Location	Reported depth range/m	Citation
Klyxum sp.	C1	Australia	<18	van Oppen *et al*, 2005
	C64	Australia	10-17	LaJeunesse *et al.*, 2004a
Lobophytum compactum	C1:3a	Australia	2-6	Goulet *et al.*, 2008
Lobophytum sp.	C1	Australia	<17	LaJeunesse *et al.*, 2004a
	C3j	Australia	2-4	LaJeunesse *et al.*, 2003
Rhytisma sp.	C1	Australia	<18	van Oppen *et al.*, 2005
	C1:1	Australia	2-6	Goulet *et al.*, 2008
Sarcophyton sp.	C1	Australia	<17	LaJeunesse *et al.*, 2004a
	C65	Australia	<17	LaJeunesse *et al.*, 2004a
	C71a	Japan	<10	LaJeunesse *et al.*, 2004a
	C1:3a	Australia	2-6	Goulet *et al.*, 2008
	C3j	Australia	<10	LaJeunesse *et al.*, 2003
Sinularia flexibilis	C1:3a	Australia	2-6	Goulet *et al.*, 2008
Sinularia polydactyla	C1:3a	Australia	2-6	Goulet *et al.*, 2008

Soft corals Host	Clade C subclade	Location	Reported depth range/m	Citation
Sinularia sp.	C1c	Australia	5	LaJeunesse *et al.*, 2003
	C65	Australia	10-17	Goulet *et al.*, 2008
	C1	New Zealand	10	Wicks *et al.*, 2010
	C3	New Zealand	10	
	C3j	Australia	<10	
	C1z	New Zealand	5-10	
Nephthea sp.	C1 C1:2	Australia	2-6	Goulet *et al.*, 2008
Paralemnalia digitiformis	C1:2 C64	Australia	2-6	Goulet *et al.*, 2008
Paralemnalia thyrsoidea	C1:2	Australia/ Israel	2-6	Goulet *et al.*, 2008
Stereonephthya sp.	C15	Australia/ Fiji	2-6	Goulet *et al.*, 2008
Anthelia sp.	C64	Australia	10-17	LaJeunesse *et al.*, 2004a
	C84a	Australia	2-6	Goulet *et al*, 2008
Sarcothelia sp.	C15b	Hawaii	10-20	LaJeunesse *et al.*. 2004b
Asterospicularia laurae	C15	Australia	2-6	Goulet *et al.*, 2008
Cespitularia sp.	C15 C1q C1	Australia	<15	van Oppen *et al.*, 2005 Goulet *et al.*, 2008
Efflatounaria sp.	C1c C1:3a	Australia	2-6	Goulet *et al.*, 2008
Heteroxenia sp.	C15 C15e C64	Australia	10-17 1-17	LaJeunesse *et al.*, 2004a
Xenia sp.	C1	Australia	<18	van Oppen *et al.*, 2005
	C1k C64	Australia	15 3-17	LaJeunesse *et al.*, 2003
	C15	Israel	2-6	Goulet *et al.*, 2008

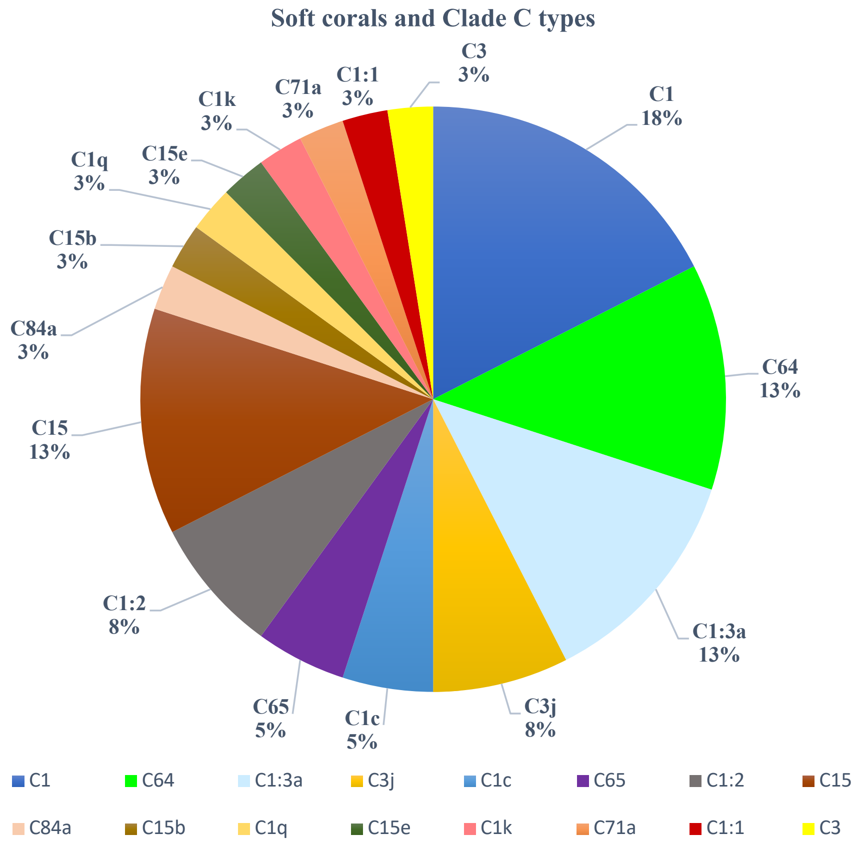

Figure 3. Frequency of each Clade C (*Cladocopium*) subclade in the soft corals mentioned above in Table 2.

Discussion

Soft corals form an integral part of the coral reef community worldwide, yet very little research has focused on the Symbiodiniacea genera they possess (Goulet *et al.*, 2008; Barneah *et al.*, 2004; van Oppen *et al.*, 2005). The data compiled in this study revealed the array of Symbiodiniacea associated with tropical and temperate soft coral species. Three main factors were reported to play a role in the specificity of Symbiodiniaceae; namely the ability to host multiple clades (Goulet *et al.,* 2008), the mode of acquisition of zooxanthellae (Barneah *et al.,* 2004), and finally geographical location / bathymetric distribution (Iglesias-Prieto *et al.*, 2004).

Specificity of Symbiodiniaceae clades hosted by soft corals

The diversity and complexity of the Symbiodiniacea genera has prompted researchers to explore cladal specificity. The specificity of the host and associated symbionts can explain the difference in coral physiology (growth rate, photophysiology, thermal stress resistance, bleaching and disease susceptibility) (Stat *et al.*, 2009). Several hypotheses have been proposed to explain the degree of specificity of Symbiodiniacea genera.

Ability to host single/multiple zooxanthellae and zooxanthellae density

One of the proposed theories holds that the specificity of a Symbiodiniacea genus is defined by the ability of some soft corals (eg. *Sinularia* sp., *Lobophytum* sp. and *Xenia* sp.) to host a single zooxanthellae clade at a time (Goulet *et al.,* 2008). These types of soft corals may not change their symbionts even if a change in environmental condition occurs (Gaulet, 2006). A change such as a rise in sea surface temperature will cause bleaching and eventually death of the corals if they fail to acquire the same symbionts again in a specific time period (Sammarco and Strychar, 2013). However, octocorals hosting a single clade are found to be more stable over time and space when subjected to different thermal stresses as compared to the scleractinian corals (Tamar and Marie Alice, 2003).

It is interesting to note that some soft corals such as the *Capnella sp.* may host more than one zooxanthellae

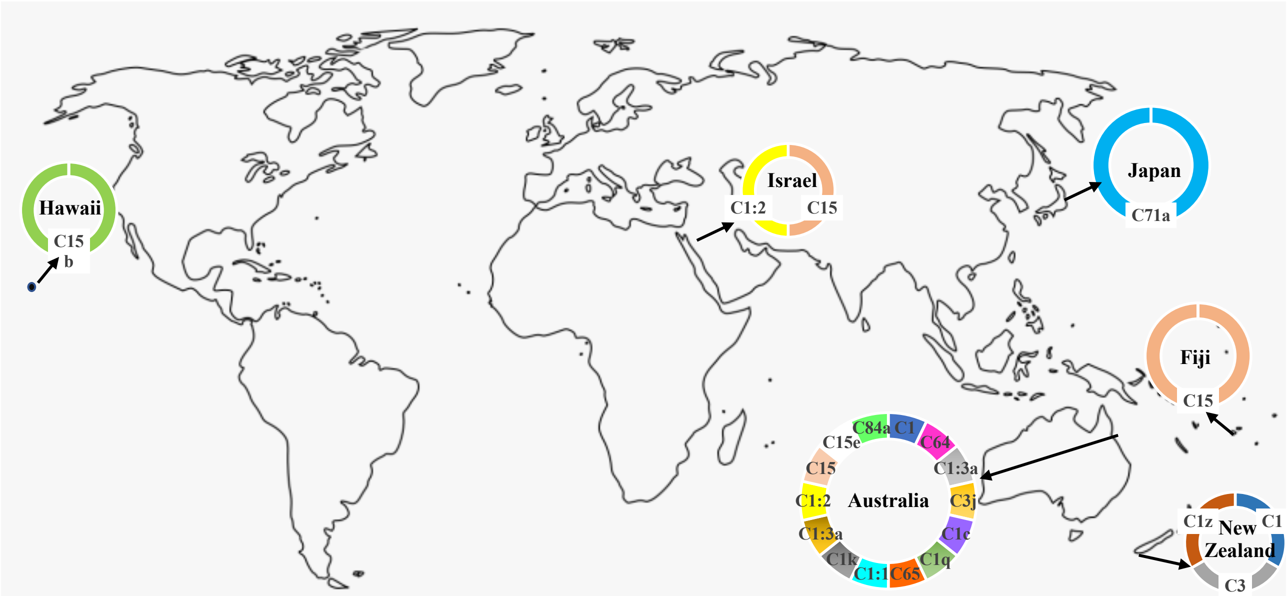

Figure 4. Global distribution of genus *Cladocopium* type in soft corals. Pie charts represent the percentage of each genus *Cladocopium* type at each geographic location.

genus at a time (van Oppen *et al.,* 2005). One possible explanation is that before one of the genera gets outcompeted, a change in the climatic condition may result in a change in the dominancy of a particular zooxanthellae genus (Carlos *et al.,* 2000). Intraspecific zooxanthellae diversity on a single host is not confined to soft corals communities, and has also been found in scleractinian corals (Baker, 1999, 2001; Baker *et al.*, 1997; Glynn *et al.*, 2001; LaJeunesse, 2001, 2002; LaJeunesse *et al.*, 2003; Pawlowski *et al.*, 2001; Pochon *et al.*, 2001; Santos *et al.,* 2001; Van Oppen, 2001, Howells *et al.,* 2013), foraminiferans (Pawlowski *et al.*, 2001; Pochon *et al.*, 2001), gorgonians (Coffroth *et al.*, 2001; Santos *et al.*, 2003; Goulet and Coffroth, 1999, 2003a, b), hydrocorals (Baker, 1999; LaJeunesse 2002) and anemones (Santos *et al.,* 2003). Scleractinian corals hosting multiple symbionts have been known for decades. For example, Baker and Romanski (2007) reported that 38 of 59 (64 %) of hard corals surveyed contained multiple symbionts.

Contrarily, the type and ability to host different/single clades defines the potential of a coral to withstand thermal stress, but zooxanthellae density (ZD) in the host also plays an important role (Xu *et al.*, 2016). For example, hard corals such as massive *Favia* and *Porites* with high ZDs are less vulnerable to thermal bleaching as compared to branching *Acropora* corals with a low ZD (Li *et al.*, 2008; Li *et al.*, 2011). Further research and evidence is needed to confirm the effect of zooxanthellae density on the host and thermal tolerance (Qin *et al.,* 2019).

Mode of acquisition

Barneah *et al.* (2004) worked on cladal specificity and explained how this to some extent depends on the mode of acquisition of zooxanthellae. Soft corals hosting the genus *Cladocopium* 'clade C' mainly acquire their symbionts through horizontal acquisition from the environment, while those hosting the genus *Symbiodinium* acquire theirs directly from their parents (Barneah *et al.,* 2004). Horizontal transmission patterns are advantageous for both hard and soft corals to form associations with Symbiodiniaceae which are heat-tolerant (Boulotte *et al.*, 2016). The mode of acquisition may not always explain the distinct Symbiodiniacea genera in soft corals as exemplified by *Stereonephthya* sp. belonging to the family Nephtheidae (Goulet *et al.*, 2008). Van Oppen *et al.* (2005) stated that the symbionts associated with *Stereonephthya* are facultative as most members of that particular group are azooxanthellate. Several studies (Barneah *et al.,* 2004; Goulet *et al.,* 2008; van Oppen *et al.,* 2005) showed that *Stereonephthya* sp. form an endosymbiotic association with different zooxanthellae in distinct environments. *Stereonephthya cundabiluensis* from the Red Sea (Barneah *et al.,* 2004) host the genus *Symbiodinium*, while the other *Stereonephthya* sp. from Australia (van Oppen *et al.,* 2005) and Fiji (Goulet *et al.,* 2008) host the genus *Gerakladium* and *Cladocopium,* respectively. Barneah *et al.* (2004) mentioned that the reason for *Stereonephthya cundabiluensis* hosting *Symbiodinium* is due to the fact that the symbionts are obtained vertically. It is currently unclear as to how the other

Stereonephthya sp. have a variety of symbionts. Poor correlation between transmission mode and zooxanthellae type was also observed in the scleractinian corals *Montipora* sp. and *Acropora* sp. (van Oppen, 2004).

Geographical location/bathymetric distribution

Geographical location plays a role in clade distribution within the soft corals. Van de Water *et al.* (2018) emphasized the dominancy of some genera based on their geographical location. Red Sea and Pacific Ocean octocorals are dominated by *Cladocopium,* Mediterranean octocorals by *Symbiodinium*, while those in the Caribbean are dominated by *Breviolum.* However, the lack of high resolution spatial and temporal biological and environmental data has resulted in many fundamental gaps in the understanding of zooxanthellae biogeography (Cooper *et al.,* 2011). Latitudinal variations in coral-algal symbiosis have been reported by Baker (2003). Studies on scleractinian corals have documented that *Symbiodinium*, *Breviolum* and *Fugacium* are more common at higher latitudes, while *Cladocopium* tends to be more common in the tropics (Rodriguez-Lanetty *et al.,* 2001, 2002; Savage *et al*., 2002; reviewed in Baker, 2003). However, all these studies concluded that the clade distributions which vary worldwide are governed by temperature and light factors (Rowan and Knowlton, 1995; Baker, 2003; Toller *et al*., 2001; Ulstrup and van Oppen, 2003; Fabricius *et al.,* 2004; Rowan, 2004).

Another factor that determines the clade specificity is location (i.e. depth). Light intensity is directly proportional to depth, and soft corals will likely host distinct genotypes or species of zooxanthellae dependant on depth (Iglesias-Prieto *et al.*, 2004). In the case of *Nephthea* sp. in Australia (LaJeunesse *et al.,* 2003) specimens collected from a depth of 3 m harboured the genus *Breviolum* while those collected at a depth of >3 m hosted the genus *Durusdinium.* However, the evidence for this is not conclusive as LaJeunesse *et al.* (2018) indicated that the genus *Breviolum* occurs in hosts found at depths ranging from 5-30 m. Moreover, soft corals hosting the genus *Cladocopium* were obtained from a wide depth ranging from 1 m to 40 m. LaJeunesse *et al.* (2018) identified this particular genus as being symbiotic with soft corals across depths ranging from the intertidal to the mesophotic zone. Additionally, the genus *Symbiodinium* are adapted to high light intensity (LaJeunesse *et al.,* 2018) explaining why most soft corals harbouring this genus were all from a depth of less than 20 m. In addition, the genus *Durusdinium* reported from marginal reef environments can tolerate stressful environments and are resistant to coral bleaching, thus explaining their presence in soft corals at depths of less than 18 m (Table 1). Furthermore, the genus *Durusdinium* has been reported to occur in areas where turbidity is high (Chen *et al.,* 2003).

Increasingly frequent and harsh episodes of coral bleaching and mortality have been reported in recent decades. An increase of sea surface temperature above 30°C (Brown, 1990) (usually occurring at 20 m below the sea surface) causes the soft corals to dissociate from their symbionts, and the specificity of particular zooxanthellae genera defines the degree to which bleaching takes place. Soft corals hosting genus *Durusdinium* (extremophile) are more likely to increase the thermal tolerance of the coral (Ulstrup and van Oppen, 2003) compared to those hosting genus *Cladocopium*. Hosts harbouring genus *Symbiodinium* and *Breviolum* are considered more susceptible to bleaching compared to the other genera (Baker *et al.,* 1997). Therefore, it can be concluded that corals hosting unique or multiple symbiotic Symbiodiniaceae have varying abilities to deal with environmental stress (Sampayo *et al.*, 2008; Silverstein *et al.*, 2015).

Specificity of genus Cladocopium in soft corals

From 40 soft corals sampled, association was highest with the genus *Cladocopium* (Clade C). Similarly, the work by Leveque *et al.* (2019) showed *Cladocopium* as being the most abundant endosymbiont identified in all the Merulinidae corals, accounting for 78.2 % of sequences retained. Clade C strains exhibited more within-clade diversity as compared to the other functional clades (Lesser *et al.,* 2013). Savage *et al.* (2002) mentioned that the comparison of zooxanthellae physiology within a clade from various hosts revealed as much variability within a clade as between clades. The phenomenon of specificity, where the symbiont type forms a partnership with individual hosts with some degree of selectivity (depending on the depth and geographical location) is important for the understanding of the symbiotic association (LaJeunesse, 2001). Host species that are in symbiosis with a sole zooxanthella clade may host several types within that clade (Gaulet, 2006). For example, a single colony of *Heteroxenia* sp. hosts C15 and C64 (Table 2) (LaJeunesse *et al.,* 2004). Numerous host-specific, regionally endemic and/or rare types have radiated from the ancestral Types C1 and C3 symbionts (LaJeunesse *et al.,* 2004). As per the data collected, C1 was the most prevalent symbiont among soft corals. Similarly, type C1 has been reported to be common in many hard corals. For example, *A. cytherea, A. nasuta, Pavona* sp., *Lepttastrea* sp., *Fungi* sp. and *Pocillopora* sp. have all been reported to be associated with type C1 (Stat *et al.,* 2009). Additionally, types C15, C64 and C1:3a were among the most common symbionts. Specialized symbionts (such as C71a, C1:2, C15b, C15, C1z) displayed limited ranges in geographic distribution as shown in Fig. 4. C71a is dominant in soft corals in the region of Japan and C15b in Hawaii, and both are from the temperate zone. Soft corals from the tropical zone are more likely to host a wide variety of Clade C type. Australia being partially in the sub-tropical zone, hosts various Clade C type (C1, C64, C1:3a, C1c, C1q and many more). The work of LaJeunesse *et al.* (2004) confirmed that specific/rare forms of symbionts tend to have narrow geographic ranges and express endemicity. Similarly, biogeographic patterns in symbiont type was reported in scleractinian corals (Stat *et al.,* 2009). According to Stat *et al.* (2008), *Acropora cytherea* in Hawaii associates with C1, C3 and C3b while *A. cytherea* from the GBR harbours C3 only (LaJeunesse *et al.,* 2003). However, it is also possible that a rare symbiont specialized to live in a particular host in a specific region displayed more generalized associations at another geographical location (LaJeunesse *et al.,* 2003).

Apart from the presence of a variety of Symbiodiniaceae species, the type of endosymbionts present in the host can change in response to environmental conditions. Jones *et al.* (2008) reported that after a bleaching event, the hard coral *Acropora millepora*, which predominantly hosted *Cladocopium* C3, acquired more C1 or *Durusdinium* endosymbionts. Furthermore, shuffling of symbionts in *A. millepora* from C1 to C2 due to temporal change has been documented by Cooper *et al.* (2011).

Symbionts that are acquired from the environment are usually dependant on the particular environment and latitude where they occur which affects the dominancy of certain zooxanthellae (LaJeunesse *et al.,* 2004). Some more specialist subclades such as C15 (present in soft corals from Australia, Fiji and Israel) can survive in different waters at different depths and are thus considered resistant to thermal stress. The variance in thermal tolerance highlights the fact that the genus *Cladocopium* type is ecologically and physiologically distinct and the sequence divergence is low (LaJeunesse *et al.,* 2003).

The complex nature of Clade C type has been explored by various researchers. From the data collected, it can be inferred that some specific symbionts are limited to specific host tissues (LaJeunesse *et al.,* 2003), while others are diversely present irrespective of the soft coral family. C64 was found in soft corals from the 3 different families; namely *Klyxum* sp. (Alcyoniidae), *Paralemnalia digitiformis* (Nephtheidae), and *Anthelia* sp. (Xenidae), while C3j was mostly associated with the alcyonacian soft corals (*Lobphytum* sp., *Sinularia* sp. and *Sarcophyton* sp.) (LaJeunesse *et al.,* 2003). This evidence confirms that certain host tissues act as an individual habitat that is specialised to host a specific type of zooxanthellae (LaJeunesse, 2002). Similar data was found for scleractinian corals where specific symbionts were limited to specific hosts, and sometimes to a specific genus. *Porites lobota* was found to associate solely with C15 irrespective of the biogeographical location (Hawaii and Japan) and the type of molecular marker used (ITS2 sequence and chloroplast 23S sequence) (Stat *et al.,* 2009). In addition, from Table 2 it can be seen that no particular trend was observed in the genus *Cladocopium* type composition based on the different collection depths. Most of the genus *Cladocopium* subclade was obtained from soft corals sampled from a depth of less than 20 m. However, some aspects remain unclear, as shown in the work by LaJeunesse *et al.* (2003) who showed that some zooxanthellae types are associated selectively with a specific host, at times at certain depths, and are adapted to that host's intracellular environment.

These specific zooxanthellae are functionally different from others that share almost identical rDNA-ITS sequences. Increasing knowledge on the full ecological significance of symbiont diversity, host-symbiont specificity, and soft coral physiology, is crucial for predicting how endosymbiotic association may respond to environmental changes in different geographical regions (LaJeunesse *et al.*, 2003).

Conclusions

Using the data available, this review summarises the existing symbionts associated with soft corals in the temperate and tropical regions around the globe. The majority of soft coral species host a single zooxanthella clade. Soft corals associate with 5 different zooxanthellae genera; namely *Symbiodinium*, *Breviolum, Cladocopium, Durusdinium* and *Gerakladium*. The host-symbiont specificity and diversity are influenced by factors such as the geographical location, sea depth as well as the ability of the symbionts to survive in particular environments. The most prevalent endosymbiotic association was noted between soft corals and the genus *Cladocopium*. Additionally, more within-clade diversity was observed in the genus *Cladocopium* as compared to the other functional clades. Deciphering similarities and differences between the soft corals hosting the different symbionts may aid in predicting soft coral survivorship in the face of global climate change. Furthermore, from the research reviewed, it is apparent that no data are available on the different soft corals and their associated symbionts from the Indian Ocean tropical islands such as Mauritius, Rodrigues and the Maldives, which are known to have extensive coral reefs. Thus, research work involving these small islands is of high priority.

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