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Integrated seaweed – sea cucumber farming in Tanzania

Andreas Kunzmann[1]*, Marisol Beltran-Gutierrez[2], Godfrey Fabiani[3, 6], Mary Namukose[4], Flower E. Msuya[5, 6]

[1] Leibniz Centre for Tropical Marine Research, Fahrenheitstrasse 6, 28359 Bremen, Germany

[2] Universidad Industrial de Santander, Carrera 27 con calle 9, Bucaramanga, Colombia

[3] Tanzania Fisheries Research Institute, PO Box 78850, Dar es Salaam, Tanzania

[4] National Fisheries Resources Research Institute, PO Box 343, Jinja, Uganda

[5] Zanzibar Seaweed Cluster Initiative, Mizingani Road, PO Box 3794, Zanzibar, Tanzania

[6] Institute of Marine Sciences, PO Box 668, Mizingani Road, Zanzibar

* Corresponding author: akunzmann@zmt-bremen.de

Abstract

We review piloted co-culture experiments of the sea cucumber *Holothuria scabra* with different seaweed species in existing lagoon-based seaweed farms in Tanzania during 2011-2014. Key questions were whether stocking densities would influence growth rates of both species, and whether deposit feeders would modify organic components in the sediments. From a social perspective, we investigate if local people are readily willing to become involved in sea cucumber farming as an optional livelihood. Seaweed-specific growth rates between 0.32 and 4.1 %d^{-1} were reported, showing significantly higher values for those treatments combined with sea cucumbers than for the seaweed monoculture ($F_{3,1}$=3.20, $p<0.05$) at Zanzibar sites. Sea cucumber growth rates ranged from 0.14 to 1.6 gd^{-1}, and all of the studies showed that the treatments holding *H. scabra* at a low stocking density (average of 130 gm^{-2}) presented a higher growth performance than when it was stocked at more than 200 gm^{-2}. Total organic matter in sediments increased in all treatments over the sampling periods ($p<0.05$). Some 88 percent of the surveyed local people showed willingness to participate in this type of mariculture for livelihood. The survey identified theft and lack of credit as the main hindrances for this activity. *H. scabra* is viable for lagoon co-culture with seaweed when taking into account proper stocking density, implications on total organic matter and total organic carbon in the system, and local acceptance by local people.

Keywords: *Holothuria scabra, Eucheuma, Kappaphycus*, co-culture, IMTA, growth rates, organic matter, stocking density

Introduction

Seaweed is important for Tanzania, both from social, ecological and economic points of view. From an energetics point of view, seaweeds represent the result of the most significant and most economic transfer of sunlight into sugars, energy and a number of phycocolloids (Bresinsky *et al*., 2008). The direct use of seaweeds for human consumption worldwide is in the range of 300 000 tons/year with species such as Nori (*Porphyra* spp.), *Ulva*, *Fucus* and others being produced (CEVA, 2013). About 10–12 million tons/year of seaweed are harvested from the wild and from aquaculture, and some used in the seaweed processing industry (Nayar and Bott, 2014) with a value of US$ 6 billion. The largest share (US$ 5 billion) is for human food products, while US$ 1 billion is for industrial products such as hydrocolloids, commonly used in animal feeds, bioactives and fertilizers (1 million tons). In Tanzania about 11-15 thousand tons (dry weight) of *Eucheuma* and *Kappaphycus* species are produced yearly, with a total value of 1.6 – 2.0 billion Tsh (Msuya, 2012; Msuya *et al*., 2014).

Sea cucumbers play a key role in marine ecosystems through bioturbation, burrowing and feeding on organic matter in marine sediments (Purcell *et al*., 2016). Marketed as *beche-de-mer* or *trepang*, they are highly valued because they are rich in protein, popular

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as an aphrodisiac, used in traditional Chinese medicine, and it is known that they contain significant amounts of chondroitin-sulfates for cartilage support. Recently a number of bioactive compounds such as saponins, chondroitin sulfates, glycosaminoglycan, sulfated polysaccharides, sterols, phenolics, cerberosides, lectins, peptides, glycoprotein, glycosphingolipids and essential fatty acids have been reported (Bordbar *et al.*, 2011). Unfortunately, worldwide they are severely overexploited, including in Tanzania (Eriksson *et al.*, 2013). Some 66 out of more than 400 species of sea cucumbers are commercially used (Purcell, 2010), around 41,000 tons dried tons of global wild captures annually (FAO, 2018). The percentage of these coming from global aquaculture has increased from about 1% in 2002 to around 25% in 2011 (Purcell *et al*., 2011). In Tanzania there are about 20 species of sea cucumbers commercially used (Mbaga and Mgaya, 2004), with the sandfish, *Holothuria scabra*, having the highest market value.

While mariculture is gaining popularity in many developing countries, it's development comes with potential significant environmental impacts in coastal ecosystems, including threats to habitats such as mangroves, seagrass beds and coastal lagoons. Intensive mariculture is a potential source of pollution in terms of effluents or sediment eutrophication through bio-deposition (Black, 2001; Zhang *et al.,* 2012). Chopin *et al.* (2001) showed that Integrated MultiTrophic Aquaculture (IMTA) can be considered as a mitigation approach against excess nutrients and organic matter generated by intensive mariculture activities by using waste from one species as inputs for another. In an ideal case, fed species (such as fish) are combined with extractive species (such as algae, bivalves or sea cucumbers) to make use of surplus nutrients. This leads to balanced systems for environment remediation (biomitigation), provides economic stability (improved output, lower costs, product diversification and risk reduction) and leads to better social acceptability (e.g. through better management practices and higher yields). Initial steps for IMTA include different co-culturing approaches, by combining at least two species of different trophic level such as seaweed and sea cucumbers.

The Leibniz Centre for Tropical Marine Research (ZMT) has been collaborating with Tanzania in developing seaweed-sea cucumber co-culture research since 2012. There have been studies to co-culture seaweed and sea cucumbers since 2011, when the first of such experiments was done. This was followed by three more studies: Beltran-Gutierrez (2012); Fabiani (2013); and Namukose (2014). So far there have not been studies to integrate seaweed and sea cucumber in a set-up of more than two species in Tanzania. Furthermore, these scientific studies have not been appropriately disseminated to farmers although application of such results could improve livelihoods of coastal communities in Tanzania and the western Indian Ocean in general (Purcell and Eeckhaut, 2005; Eeckhaut *et al*., 2008; Robinson and Pascal, 2009).

While searching for optimizing growth and improving potential nutrient flow synergies between species, *Eucheuma denticulatum* was deliberately included as it is a much more widespread seaweed species in Zanzibar and apparently more resistant to adverse environmental conditions than *Kappaphycus* (Hayashi *et al.* 2010; Msuya and Porter, 2014).

A wide range of stocking densities in sea cucumber aquaculture have been applied in order to better understand trade-offs and limiting capacities, as well as relation to organic matter content of sediments (Zamora *et al*., 2016). This paper reviews research in integrated seaweed-sea cucumber culture in Tanzania and fills scientific gaps that could be used to produce more information on the cultivation of these high-valued organisms. In particular, the following open questions were addressed: How do stocking densities of sea cucumber (*Holothuria scabra*) and three seaweed species (*Kappaphycus striatus, K. alvarezii* and *Eucheuma denticulatum*) influence the growth and survival of both species when co-cultured in an integrated system?; and, Are local people with/without experience in seaweed farming readily willing to become involved in sea cucumber farming as an additional source of income?

Materials and Methods

Research was conducted in the years 2012 – 2014 at three different locations in Tanzania: Muungoni and Bweleo (Menai Bay) in Zanzibar; and Pangani (Pangani District) in mainland Tanzania (Fig. 1).

Surface seawater temperature, pH, salinity and oxygen concentration were measured at the sites during the experimental periods at regular intervals during the morning hours (8:00–11:00 am), using an HQ40d multimeter and refractometer.

Experiment set-up

Cages of 0.5 m height, with a base area of 2.25 m^2 were constructed at Zanzibar sites, and 1 m^2 at the mainland Pangani site, using wooden poles, 10mm coated

wire mesh, cable ties and 4 mm nylon ropes. They were installed in the intertidal area, near local seaweed farms at each study site. The sites selected consisted of sand, sandy/muddy substrates and sea-grasses. The wire mesh of the cages was anchored into the sea sediment to a depth of 25 cm to avoid escaping of sea cucumbers according to the method described by Slater and Carton (2007).

All cages were thoroughly scrubbed with a hard nylon brush on a two-weekly basis to remove any fouling which would inhibit deposition of detritus from the seaweed to the sediment within the cage. Likewise, by scrubbing, the cages were maintained free of fouling and wrack/flotsam.

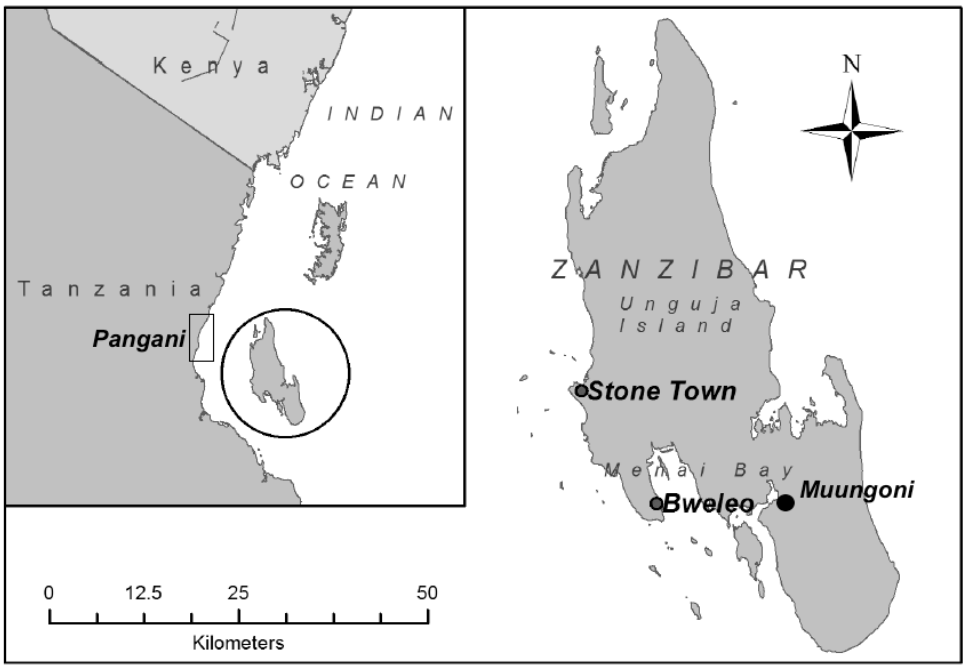


Figure 1. Location of the experimental sites in the coastal area of Muungoni and Bweleo on Unguja Island, Zanzibar (Beltran-Gutierrez, 2012; Namukose, 2014) and Pangani District on mainland Tanzania (Fabiani, 2013).

Holothuria scabra (Hamel *et al*., 2001) were collected from intertidal areas during spring low tides, weighed to the nearest 0.1 g, and allocated to cages according to specified stocking densities (Table 1). In the Zanzibar sites, sea cucumber juveniles were collected in intertidal pools at Bweleo and Unguja Ukuu (villages within Menai Bay). For the experimental trial in Muungoni, a total of 52 individuals with an average body weight of 97 ± 31g (mean ± SD) were allocated to experimental cages while 60 medium-sized individuals were allocated to experimental cages in Bweleo, with an average initial weight of 114 ± 37g. At Pangani District, younger juveniles found ranged from 29.1 to 66.6 g per animal with an average weight of 44 ± 15 g. In all trials, sea cucumbers had an acclimatization period to ensure they had not eviscerated prior to allocation into experimental cages. This period varied among the three studies consisting of 30 days at Muungoni, 14 days at Bweleo and 7 days at Pangani District. In addition, before starting the experiments, each *H. scabra* individual was photographed dorsally and ventrally, allowing characteristic markings to serve as means of recognition for individual growth and survival monitoring at every sampling event as suggested by Raj (1998), and used reliably for several sea cucumber species in previous studies (Slater and Carton, 2007; 2009).

Meanwhile, seaweed fragments purchased from local farms at each site were planted above the sea cucumber cultures using the off-bottom method, commonly practiced for seaweed farming in Zanzibar (Fröcklin *et al*., 2012), as is shown in Fig. 2. Healthy bunches of seaweed were tied to a 4 mm Ø rope using a 1 mm Ø string (*tie-tie*), maintaining a distance of 20 cm between fragments/cuttings. The culture rope lines were tightened on top of the sea cucumbers (outside the cages at Muungoni site and inside the cages in Bweleo and Pangani studies), suspended around 50 cm above the sea floor, and stretched with wooden



Figure 2a, b. Exemplary experimental plot showing seaweed fragments planted using the off-bottom method, and sea cucumber culture cages.

stakes driven into the bottom. In the Muungoni study, the seaweed species used was *Kappaphycus striatus* var. *payaka brown,* locally known as *cottoni kikarafu*, whereas *Eucheuma denticulatum* was cultured in Bweleo and *Kappaphycus alvarezii* at Pangani. Two full seaweed production cycles of 6 weeks each (from planting to harvest) were completed during each study.

Experimental designs

Across the studies, treatments were established holding different densities of seaweed and sea cucumbers (Table 1) intending to reflect low (whereby optimal growth may be observed) and high density stocking (whereby growth limitation may occur) as per the literature (Battaglene *et al.*, 1999; Pitt and Duy, 2004; Purcell and Simutoga, 2008). However, at Bweleo, Zanzibar, a medium-density treatment was added to the experimental design at which higher growth performance was expected to occur. In every study, experimental plots or cages without seaweed and sea cucumbers were added as procedural controls and each of the treatments had four replicate plots.

In Muungoni and Bweleo, the initial seaweed density was constant across treatments (ca. 500 gm^{-2}), reflecting the actual cultivation method of the seaweed farms. On the other hand, in Pangani, low and high *K. alvarezii* stocking densities of 500 g and 1000 gm^{-2}, respectively, were used as per the study by Hurtado *et al.* (2008) for stocking of seaweed.

Therefore, at Muungoni and Bweleo, there was a control treatment that held seaweed in monoculture (no sea cucumbers), another control treatment with only sea cucumbers, and experimental treatments holding sea cucumbers at low, medium (only for Bweleo trial) and high stocking densities combined with seaweed.

In the study at Pangani, eight treatments were established. First and second cage treatments were stocked with seaweed only, while the third and fourth were stocked with sea cucumbers only. These served as the controls in this experiment. The remaining plot treatments (fifth, sixth, seventh, and eighth) were stocked with both seaweed and sea cucumbers at low and high stocking densities of each species (Table 1).

Monitoring of growth of seaweed and sea cucumbers

The production cycle of seaweed took six weeks in Muungoni and Bweleo, while it consisted of eight weeks in the Pangani study. Seaweeds are usually harvested after six weeks in most parts of Tanzania, and so far only two reported studies have kept the seaweed longer than six weeks (Msuya and Salum, 2012; Msuya *et al.*, 2012). Each rope with seaweed bunches was removed from the respective cages and shaken to reduce excess water before the wet weight was taken using a digital scale.

Furthermore, caged sea cucumbers were monitored every 14 days for a two-month period. Sea cucumbers were removed from cages and brought to the surface in a 10-litre watertight container. For growth assessment, every sea cucumber was measured on an individual basis (photo-identification) at every sampling. Before measurement, the animals were given a one minute period to allow water to be expelled from the respiratory trees (Slater and Carton, 2007). They were photo-identified by their colour patterns, weighed, and returned to their respective cages. Time outside the cages did not exceed 5 minutes.

Specific growth rates (SGR) for both seaweed and sea cucumbers were calculated by using the formula according to Dawes *et al.* (1993):

$$SGR = 100 \times (\ln W2 - \ln W1)/T,$$

where SGR denotes the specific growth rate (% d^{-1}); W2 represents mean wet weight on the sampling day (g); W1 refers to initial wet weight (g); and T stands for the period of cultivation in days.

Total Organic Matter and Total Organic Carbon in sediment

Before stocking of seaweed and sea cucumbers in experimental plots at all study sites, 40 g sediment samples were taken from each plot to estimate total organic matter (TOM), and in the Bweleo study, total organic carbon (TOC) was also considered. The same procedure was repeated at the end of the experiments. This allowed a determination of the amount of organic matter available for sea cucumbers feeding by comparing cages of different densities and without sea cucumbers, to get an idea of how much organic matter was consumed by the animals.

All collected samples (before and after) were dried on tin foil in the sun for six hours, then stored at room temperature for later analysis. Sediments TOM was determined by using an ash-free analysis method. Sediment samples were dried at 60°C for two days and weighed with a digital scale to the nearest milligram. After measuring, samples were placed in a furnace and burned at a temperature of 450°C for 6 hours. After that, the furnace was allowed to cool and the samples were weighed again. Percentage of organic matter was obtained by calculating the weight loss of the sediment samples after the burning in the furnace.

Estimation of TOC was done by weighing three homogenized samples of sediment (~25–35 g) per cage using a Mettler Teledo weighing scale (precision: 0.001 g) in pre-combusted (500 °C, 3 h) silver cups. Inorganic carbon removal from the samples prior to TOC analysis followed a protocol similar to that in Kennedy *et al.* (2005), and the elemental determination for carbon was

Table 1. Experimental treatments and stocking densities (gm^{-2}) of co-culture trials combining seaweed and sea cucumber, *H. scabra* in Tanzania during study periods between 2011 and 2014 (Beltran-Gutierrez, 2012; Fabiani, 2013; Namukose, 2014).

Study site	Time period	Plots	Treatments	Stocking density (g/m2)	
				Sea cucumber	Seaweed
					Kappaphycus striatus
Muungoni	From Dec 2011 to Mar 2012	16	Control seaweed	0.0	570 ± 22
			Control sea cucumber	218 ± 21	0.0
			Low sea cucumber	124 ± 22	582 ± 6
			High sea cucumber	218 ± 16	571 ± 21
					Eucheuma denticulatum
Bweleo	From Dec 2013 to Mar 2014	20	Control seaweed	0.0	500 ± 23
			Low sea cucumber	150 ± 5	500 ± 23
			Medium sea cucumber	236 ± 24	500 ± 23
			High sea cucumber	345 ± 48	500 ± 23
					Kappaphycus alvarezii
Pangani	From Jan 2013 to Mar 2013	32	Control low seaweed	0.0	506 ± 18
			Control high seaweed	0.0	1008 ± 4
			Control low sea cucumber	109 ± 16	
			Control high sea cucumber	192 ± 14	
			Low seaweed Low sea cucumber	105 ± 11	506 ± 4
			High seaweed Low sea cucumber	124 ± 20	1015 ± 5
			Low seaweed High sea cucumber	217 ± 18	506 ± 5
			High seaweed High sea cucumber	262 ± 52	1001 ± 2

carried out using a CN Analyzer (Eurovector EA3000). Laboratory analyses were done at the Institute of Marine Sciences, Zanzibar and the ChemLab at the Leibniz Centre for Tropical Marine Research, Bremen.

Economic viability

This component of the study was done at Muungoni and Pangani sites, where the economic viability of integrated culture of seaweeds and sea cucumbers was assessed. A calculation of productivity and economic returns was carried out by using data obtained from the experiments. Analysis for long-term profit was approximated by annual projections of the costs and revenues. Factors such as the initial investment costs, the farming period of seaweed and sea cucumbers, and the labour costs, usually in terms of opportunity costs, as well as the returns from production, were taken into consideration (Troell, 2009).

Perceptions on mariculture as a livelihood option

The willingness of local communities to adopt sea cucumber farming as a livelihood activity was assessed in Pangani District in the three coastal villages Kipumbwi, Mikocheni and Mkwaja. These villages were specifically chosen due to their dependence on marine related livelihood activities. Focus group meetings and semi-structured interviews were conducted with the participants involved in the farming before and after the trial experiment (Denscombe, 2007). The discussion was concentrated on topics such as preference as a job, strategy to improve the farming and harvesting, and problems associated to mariculture activities.

Statistical analyses

To compare the effect of stocking density and seaweed on sea cucumber growth performance, linear mixed models (GLMMs) were employed using the 'lme4' package (Bates *et al*., 2012) of the statistical software R version 2.15.1 (R Development CoreTeam 2008 and 2013). The effect of stocking density on daily growth rate of sea cucumber was analyzed in a single model, with treatment and period as fixed terms, while the initial weight of individuals nested in cages was added to the model as a random term.

Also, the effect of stocking density of sea cucumbers on the survival and growth of seaweed was analyzed in two separate models for the two harvest cycles (where harvest cycle 2 was characterized by different weather conditions in the form of severe storms models), then later in a single model with treatment and harvest cycle as fixed terms, while blocks were added as random terms to the models. Negative values of seaweed data were interpreted as massive breakage loss that occurred, and hence not considered in the analysis. All interaction terms that were not significant were eliminated from the models. Where significant effects were detected, pairwise comparisons using Tukey's honest significant difference (HSD) post-hoc test was used.

For organic matter content, percentage of organic matter (% OM) was estimated by calculating the loss of weight (g) of the samples after the burning procedure. Then, a paired t-test on depended samples was applied to compare % OM in sediments between cages under the treatments sampled before and after the experiment. To analyze the effect of sea cucumber stocking density on sediment organic matter and total organic carbon, generalized linear mixed models (GLMMs) were applied.

Results

The abiotic parameters during the experimental periods did not vary much. Salinity averaged 35.1, temperature ranged from 29 to 34°C, pH was between 7.9 and 8.8, while oxygen values ranged from 6.01 to 8.15 mgL^{-1}.

Growth rates of seaweed and sea cucumbers

Seaweed growth rates

In Muungoni, Zanzibar, mean initial *K. striatus* density of 570gm^{-2} increased to 1.600gm^{-2} after one culture cycle of 41 days, reaching a specific growth rate (SGR) of 4.1%d^{-1}. This was the highest seaweed growth registered in the trial studies, which was recorded in co-culture with sea cucumbers at low stocking density. At Bweleo, Zanzibar, the highest *E. denticulatum* performance (SGR 2.3 %d^{-1}) was observed in combination with a high-density of sea cucumbers (Table 2).

In both Zanzibar studies, lower values for seaweed growth were registered in the plots without sea cucumbers (Control seaweed treatment). SGRs of *E. denticulatum* in Bweleo differed significantly among treatments ($F_{3,1}$=3.20, P=0.03; Fig. 3) and post-hoc tests revealed that mean growth rates of seaweed in the medium and high culture density treatments differed significantly from those in monoculture (P< 0.05).

In Pangani, the average wet weight of *K.alvarezii* increased from 252 to 295.4 g per 1 m of culture line. The overall mean SGR across treatments was 0.54%d^{-1}

Table 2. Growth performance of co-cultured experimental trials between 2011 and 2014 (Beltran-Gutierrez, 2012; Fabiani, 2013; Namukose, 2014).

Study site	Experimental treatments	Growth performance		
		Sea cucumber	Seaweed SGR (% day-1)	
			Kappaphycus striatus	
Muungoni		**(g d^{-1})**	**First cycle**	**Second cycle**
	Control seaweed		0.73 ±0.6	3.7 ±0.7
	Control sea cucumber	0.9 ±0.1		
	Low sea cucumber	1.6 ±0.2	1.22 ±0.5	4.1 ±0.6
	High sea cucumber	0.9 ±0.1	1.40 ±0.8	3.6 ±0.6
			Eucheuma denticulatum	
Bweleo		**(g d^{-1})**	**First cycle**	**Second cycle**
	Control seaweed		0.79 ±0.4	0.75 ±0.4
	Low sea cucumber	0.8 ±0.3	1.59 ±0.5	0.45 ±0.4
	Medium sea cucumber	0.43 ±0.2	1.87 ±0.5	1.01 ±0.3
	High sea cucumber	0.14 ±0.4	2.33 ±0.7	1.01 ±0.3
			Kappaphycus alvarezii	
		SGR (% day^{-1})	**First cycle**	**Second cycle**
Pangani	Control low seaweed		1.19 ±0.6	0.72 ± 0.7
	Control high seaweed		1.63 ±0.4	0.32 ±0.2
	Control low sea cucumber	0.99 ±0.0		
	Control high sea cucumber	0.45 ±0.1		
	Low seaweed low sea cucumber	0.32 ±0.0	1.84 ±0.8	0.37 ±0.2
	High seaweed low sea cucumber	0.89 ±0.1	1.75 ±1.1	0.32 ±0.1
	Low seaweed high sea cucumber	0.38 ±0.1	1.73 ±1.0	0.52 ±0.1
	High seaweed high sea cucumber	0.68 ±0.2	1.67± 1.2	0.56 ±0.2

±0.1 (mean±SD), reaching the highest value (1.84 %d^{-1}) in the treatment of low seaweed density combined with low sea cucumber density, as was also shown in Muungoni (Table 3). Seaweed stocked at lower density (500 gm^{-2}) had a slightly higher average growth rate of 0.63% d^{-1} compared to the high stocking density (1000 gm^{-2}), which reached 0.45% d^{-1}. Overall, in the three studies species of seaweed showed lower growth rates in monoculture treatments (seaweed control) and better performance when co-cultured with sea cucumbers (Fig. 3).

Sea cucumber performance

Survival of *H. scabra* at the Muungoni, Bweleo and Pangani trials was 85, 77 and 56% respectively. In all cases, this was not dependent on the stocking density of the treatments, but rather on uncontrollable factors attributed to the escape of animals through the mesh, given the small initial sizes of individuals. Considering sea cucumber growth in Muungoni, the average growth rate at low stocking density (1.6 gd^{-1} ±0.2) (mean±SD) was significantly higher compared to those at high stocking density (0.9 gd^{-1} ±0.1) ($P<0.01$) (Table 3). The growth rate varied significantly between measurement periods ($P<0.001$), being highest in the last time period and lowest at intermediate time periods (Fig. 4).

In Bweleo, daily growth rates of *H. scabra* also differed significantly among treatments (low, medium and high) over the sampling periods ($F_{2,5}= 5.15$, $P=0.0095$). Sea cucumbers cultured at low stocking density with seaweed had the highest average growth rate of 0.8g d^{-1} ±0.3, whereas those cultured at high stocking density had the lowest average growth rate of 0.14 gd^{-1}

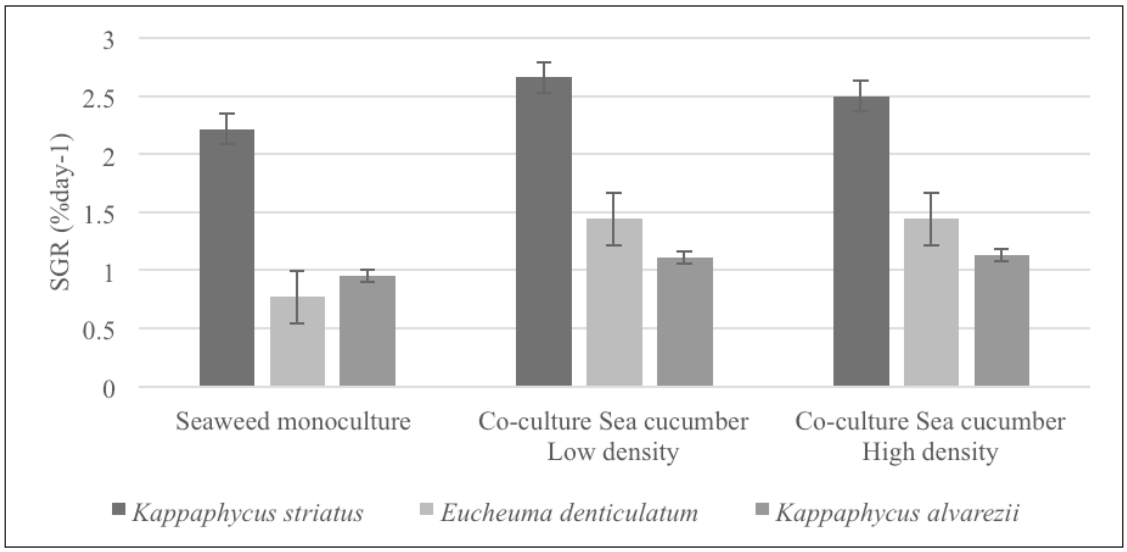


Figure 3. Average specific growth rates (SGR%day^{-1}) for the three species of seaweed *K. striatus*, *E. denticulatum* and *K. alvarezii*, each of them at 500 gm^{-2} stocking density in the following treatments: Control seaweed (monoculture), in combination with sea cucumber at low density (ca. 126g/m^2), and sea cucumber at high density (ca. 224 gm^{-2}). Error bars indicate standard error.

±0.2. Post-hoc tests revealed that mean growth rates in low and high density treatments differed significantly from each other ((Tukey's HSD test, $p<0.05$). At the end of the study, individuals cultured at low stocking density had the highest average weight (163 g ±34), while those cultured at high stocking density had the lowest value (118 g ±39).

In Pangani, the average specific growth rate (SGR) of sea cucumbers observed during the study was 0.62 %d^{-1} ±0.3 (mean±SD). In contrast to the Zanzibar studies, the lowest SGR of *H. scabra* in Pangani was recorded in the treatment with low stocking density (105 gm^{-2} of sea cucumber) combined with low seaweed density (506 gm^{-2} of *K. alvarezii*), while highest SGR was observed at low density monoculture of *H. scabra* (0.99 %day^{-1}). On average, the growth performance of sea cucumbers when co-cultured with high seaweed density was 55% higher than when combined with low seaweed density.

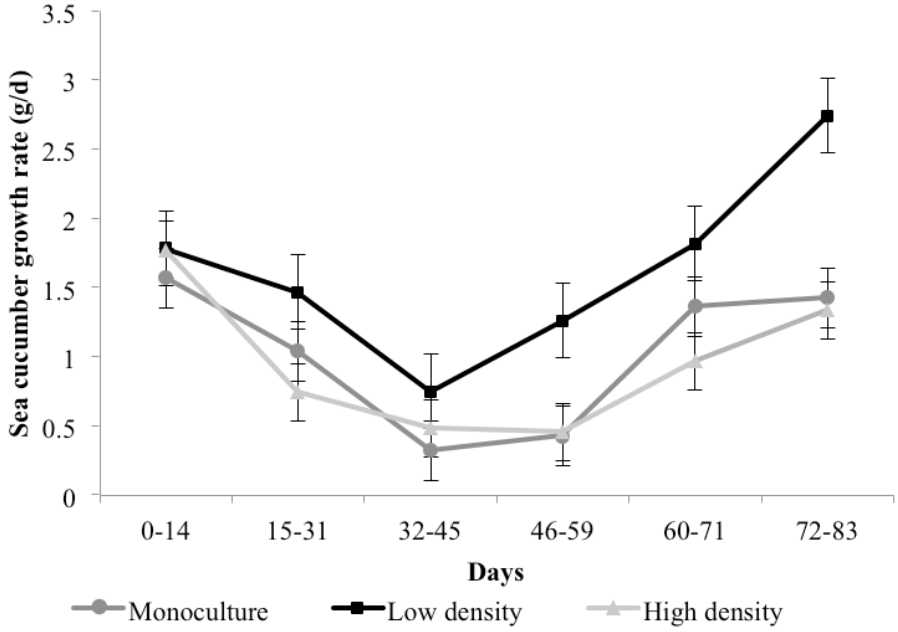


Figure 4. Mean growth rate (gd^{-1}) through sampling periods (days) of sea cucumber *H. scabra* in monoculture and co-cultured with seaweed *K. striatus* at two different sea cucumber stocking densities (low: 124 gm^{-2}, and high: 218 gm^{-2}) at Muungoni intertidal lagoons, Zanzibar. Error bars indicate standard error.

TOM and TOC in the sediment

In both the Muungoni and Bweleo trials, TOM in sediments increased generally in all treatments over the sampling periods. At Muungoni, a paired t-test showed that organic matter content percentages (OM%) of surface sediments in cages with treatment holding only sea cucumbers at a high density (without seaweed), were significantly higher after the trial time period (p=0.04). Despite the fact that OM% increased in cages with seaweed together with sea cucumbers at low and high stocking densities, differences in these plots were not significant (p=0.05355 and p=0.2284, respectively). Furthermore, TOM showed no variation in the treatment cages that held only seaweed in monoculture.

In contrast, at the Bweleo experimental site, TOM content differed significantly among treatments over the sampling periods (p=0.01). The interaction between treatment and culture period was marginally above the significance level (p=0.06, α=0.05). Generally, as in Muungoni, TOM in sediments increased in all treatments over the sampling periods, with the exception in the sea cucumber medium density treatment. TOM remained almost the same in the procedural control treatment (with neither seaweed nor sea cucumbers).

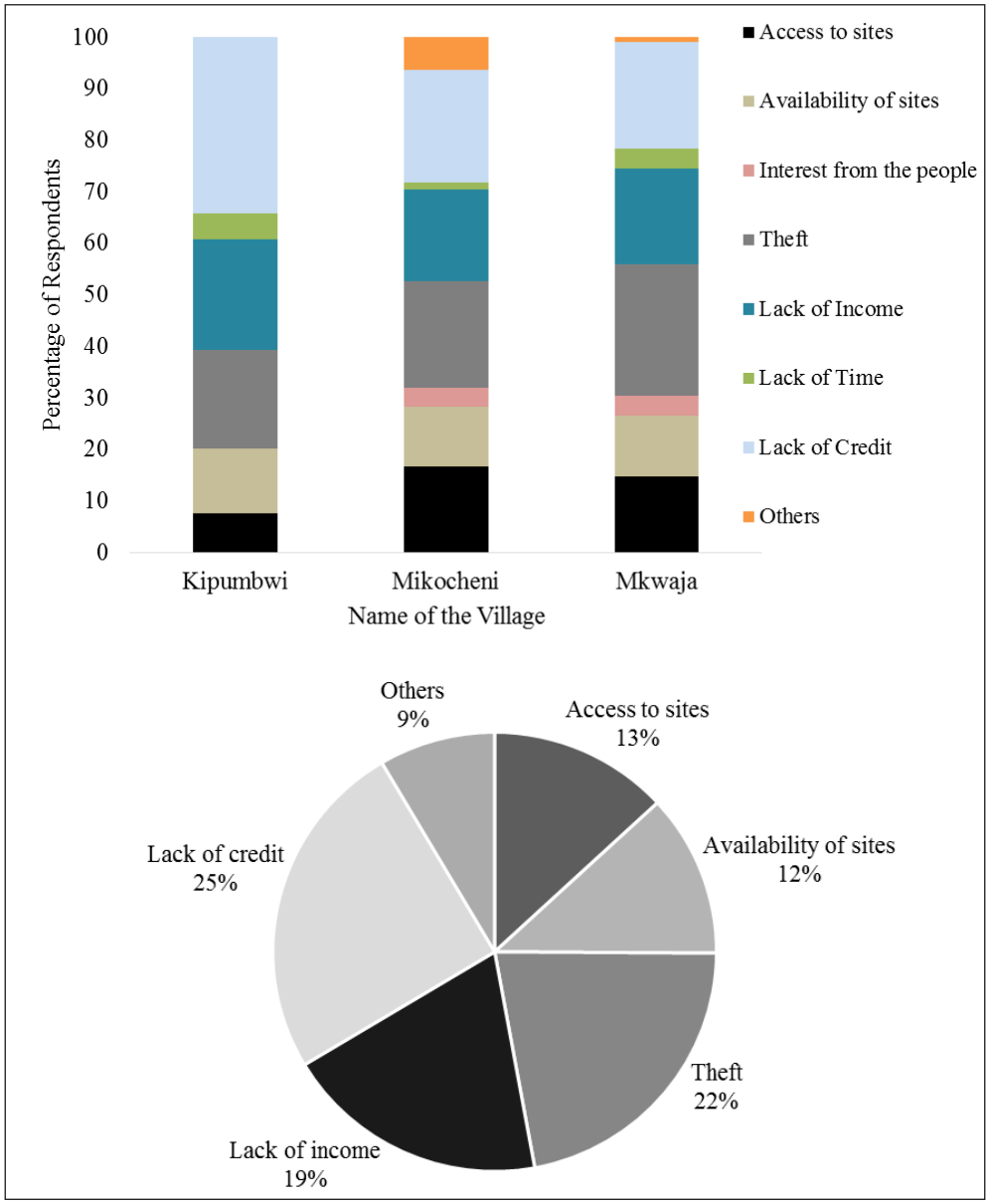


Figure 5a. Frequently mentioned problems likely to be encountered in sea cucumber farming in three villages of Pangani (n = 75).

Figure 5b. Percentage of responses to problems likely to be encountered in sea cucumber farming in Pangani, Tanzania (n = 75).

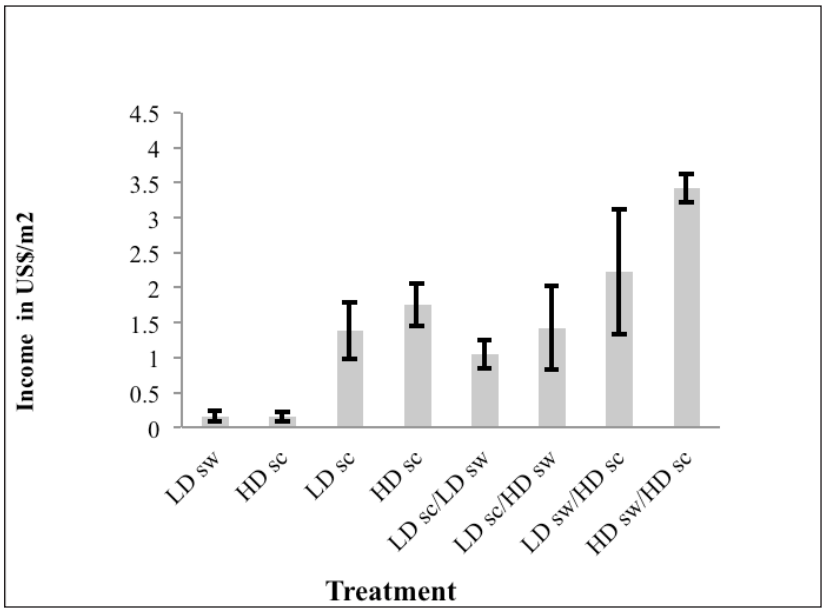


Figure 6. Income (US$m^{-2}) of *H. scabra* and *K. alvarezii*, at different low/high (LD/HD) stocking densities and combinations. Seaweed sw LD 500 gm^{-2}, sw HD 1000 gm^{-2}, sea cucumber sc LD 100 gm^{-2}, sc HD 200 gm^{-2}.

Additionally, TOC content of the sediment differed significantly among treatments over the sampling periods (p=0.03). The highest decrease in TOC was observed in the medium treatment, with the lowest overall mean value of 0.26 ±0.02% dry weight (mean ± SD) in the last sampling period. At the end of the cultivation period at Bweleo, TOM content in the guts of sea cucumbers was higher than that in the sediment.

Economic viability

Perceptions on mariculture as a livelihood activity

Respondents from the three villages were mainly involved in seaweed farming and fishing, and occasionally in other activities such as crop cultivation, food vending and rearing of animals.

The economic yield from different treatments was assessed. Overall performance in terms of returns differed substantially between both cultured species. Average yield for monoculture of sea cucumbers was US$ 1.57 ± 0.26 SD, while for seaweed it was US$ 0.16 ± 0.01 SD (Fig. 6). Across all treatments, a higher economic yield was noted in the integrated compared to the monoculture system.

The age of respondents showed a slight influence on people's willingness towards sea cucumber mariculture activities, since people between 21 and 41 years old showed high interest (93 %), compared to those between 41 and 50 years (86 %), as well as older than 51 years (80 %) (n=75). When asked whether they were willing to participate in sea cucumber mariculture to

Table 3. Cost and revenue for integrated aquaculture production at 500 g and 1000 g per m² experimental cages in Pangani with 1 m² each. Exchange rate is 1US$ = 1600Tsh.

	Integrated aquaculture production trial					Annualization		
	Investment cost per 1m² cage (US$)	Potential Production 1m² cage (Kg)	Unit Price	Income (US$)	Profit	Potential Production (kg)	Income (US$)	Profit (US$)
Seaweed	0.59	0.29	0.5	0.15	-0.44	2.03	1.02	0.43
SeSea cucumbers	18.26	0.14	12.5	1.75	-16.51	0.84	10.50	-7.76

earn more income, the majority of respondents in all three villages agreed (88 %), while only 10 respondents (11.8 %) did not show an interest.

When asked the kind of challenges they were likely to face during sea cucumber farming, most of the respondents frequently mentioned theft issues. Other problems that were given equally high attention included lack of credit and income. Difficulty in access to sites and space availability were moderately mentioned as well (Fig. 5).

Discussion

Integrating commercially valuable sea cucumbers into existing aquaculture can increase economic yields and reduce environmental impacts without increasing pressure on contested coastal spaces and resources. This review discusses piloted co-culture of the sea cucumber *H. scabra* with different seaweed species in existing lagoon-based seaweed farms in Tanzania. Survival and commercially viable growth of both algae and sea cucumbers clearly showed such a system's viability for up-scaling and commercial development.

Growth of seaweed and sea cucumbers

Stocking density showed an influence on seaweed growth. Seaweed at low stocking density grew better in these studies than those stocked at high density. These observations are in line with results reported by Hurtado *et al.* (2008) on *K. striatus*, where a lower stocking density (500 gm^{-2}) and shorter culture period (30 days) yielded a higher growth rate than a higher stocking density (1000 gm^{-2}) and longer culture period (i.e. more than 45 days). The observed specific growth rates (SGRs, expressed in % per day) of seaweed in the present studies at Bweleo are lower than those from previous studies on *E. denticulatum* in Zanzibar and other areas. Such higher growth rates reported are, notably, 3.50 in Hawaii (Glenn and Doty, 1990), 4.7 in Kenya (Wakibia *et al*., 2006), and 3–11 in Tanzania (Msuya and Salum, 2012). Msuya *et al.* (2012) reported a growth rate of 5.1 for *E. denticulatum* in Uroa, Zanzibar. However, a low rate of 1.4 $\%day^{-1}$ of this species has been reported from the southwest coast of Madagascar (Mollion and Braud, 1993) as well as minimum values of less than 1$\%day^{-1}$ at Uroa, Zanzibar (Msuya *et al*., 2012). As in the present study, lower seaweed growth rates have been attributed to the 'ice-ice' disease and severe storm events. These, in addition to epiphytism and fouling, are some of the major production challenges faced by seaweed farmers of Zanzibar and the western Indian Ocean region in general (Hayashi *et al*., 2010; Msuya, 2012; 2013; Msuya and Porter, 2014). Nevertheless, the study here presented on *K. striatus* achieved growth rates of 4.1 $\%day^{-1}$ as compared to 1.1–4.0 $\%day^{-1}$ cultured in its native area of Philippines (Hurtado *et al*., 2008).

Highest growth rates of *E. denticulatum* were achieved with stocking densities of *H. scabra* of 200 and 300 g per m^2. Similar results were obtained by Uthicke (2001) and Wolkenhauer *et al.* (2010), who observed that sea cucumbers enhance productivity of primary producers through their burrowing and nutrient recycling activities.

On the other hand, the growth rate of *H. scabra* can depend on the environmental situation and the time of the year (Agudo, 2006). Interestingly, the average growth rates of this species in the Zanzibar studies here reported, were different from 2012 (1.4 gd^{-1}) to 2014 (0.5 gd^{-1}), despite trials being performed during the same time of the year, but at different coastal lagoons (Fig. 1).

The mean growth rates from the present study are similar to peak growth rates (1.8 gd^{-1}) reported by Robinson and Pascal (2009) for *H. scabra* in commercial lagoon monoculture and exceed the 0.49–1.5 gd^{-1} reported for similar sized animals in pond culture (James 1999; Pitt and Duy, 2004; Purcell and Kirby, 2006). At Pangani District, specific growth rates (SGR) were estimated for *H. scabra* co-cultured with *K. alvarezii*, recording an average of 0.6 $\%day^{-1}$.

All of the studies showed that the treatments holding sea cucumber at a low stocking density (average of 130 gm^{-2}) presented a higher growth performance than when it was stocked at more than 200 gm^{-2}. Sea cucumber growth in co-culture was stable at densities exceeding the 300 gm^{-2} reported for commercial lagoon culture and the maximum biomass densities for pond-based culture (Battaglene *et al.,* 1999; Pitt and Duy, 2004; Purcell and Simutoga, 2008). Other results indicate, however, that biomass densities of more than 370 gm^{-2} may be achieved in co-culture. Lavitra *et al.* (2010) even report potential maximum juvenile sea cucumber biomass of up to 700 gm^{-2} in optimum sea pen areas before growth is limited.
When comparing growth rates within the current studies, it seems that *H. scabra* grows better when integrated with *K. striatus* than with *E. denticulatum* and *K. alvarezii*. This aspect requires further studies using direct comparisons of both seaweed species as co-cultivars

as there are some factors such as environmental conditions, and size and age of individuals, which could have an influence on the results (Battaglene *et al.,* 1999; Pitt *et al.,* 2004; Robinson *et al*., 2019).

TOM and TOC in sediment

Deposit-feeding sea cucumbers tend to modify their foraging behavior and digestive capabilities to optimize the intake of nutrients from the organic component in sediments (Roberts *et al*., 2000, Zamora *et al*., 2016). In the present study, an uptake of TOM through feeding by the sea cucumbers was evident in the density treatment holding c.a. 230 gm^{-2}, which showed a significant decrease in TOM and TOC over the experimental period. On the other hand, there seems to have been an accumulation of TOM in the sediments from plots without sea cucumbers. This could have been due to break-offs of seaweed thalli adding to the sediment inside the cages.

Studies on TOC utilization by *H. scabra* for comparison are limited in the literature. However, in other deposit-feeding holothurians, Michio *et al.* (2003) observed a decrease in TOC in surface sediments with sea cucumbers (*Apostichopus japonicas*) compared to sediments without sea cucumbers. Slater and Carton (2009) made a similar observation with *Australostichopus mollis* in coastal sediments impacted by mussel farm deposits. Sediment reworking and organic matter uptake by holothurians depends on individual numbers and sizes, food availability and local conditions (Dar and Ahmad, 2006). In the present study, it is evident that the stocking density was a key factor that controlled TOM and TOC utilization in the system, but it does not rule out other possible factors that were beyond the scope of this study.

Economic viability

Sea cucumber prices on the market are very attractive, which make them prone to theft. Theft issues have been reported in various places where sea cucumber farming has been operated, for instance in Madagascar (Robinson and Pascal, 2009). In the present study, when respondents were asked which problems they were likely to meet during sea cucumber farming, most of the respondents mentioned theft issues (Fig. 6). Other problems that were given equally high attention from respondents included access to sites and availability of the sites. Site selection is very important for sea cucumber farming. According to Rougier *et al.* (2013), important criteria to be considered during site selection include the presence of at least a 20 cm layer of sediments for strengthening cages, and a water depth of at least 10 cm during low spring tides. Robinson and Pascal (2009) also suggested that the site should be near a village for facilitating monitoring and necessary maintenance.

A fully functioning integrated system normally should result in better production according to Barrington *et al.* (2009). Revenues from the integrated systems in this study were calculated, and cages stocked with *H. scabra* at 200 gm^{-2} and *K. alvarezii* at 1000 gm^{-2} of seaweed (see Fabiani, 2013) had the highest potential economic yield of US$ 3.42 m^{-2} (Fig. 6) and other treatments yielded US$ 2.82 m^{-2} (Beltran-Gutierrez, 2012). The total cost of investment depends on materials used and availability of resources (e.g. in the Pangani study seaweed total costs were US$ 14.33, equivalent to US$ 0.59 per cage) (Table 3). In an estimation for the whole year, the potential yield for seaweed was around 12.39 kg for six cages, equivalent to 2.03 kg $cage^{-1}$ $year^{-1}$. According to Msuya *et al*. (2014), production of dried seaweed per meter line per harvest normally ranges between 0.17 and 0.50 kg. In this study, average production per 1 m^2 cage was 0.11 kg dry weight. Therefore, considering dying off of seaweed, which was 33%, the total potential yield was 1.77 kg dry weight for all six cages. Potential economic yield was estimated at around US$ 0.89 per production cycle (45-60 days).

The price of sea cucumbers in Zanzibar is around Tsh 20,000 (US$ 12.5) per kg. Zanzibar is currently the only market as no company or agent for buying sea cucumbers exists in mainland Tanzania due to a moratorium imposed by the government (Eriksson, 2013). Sea cucumbers can be produced all year around. By annualizing the production, potential yield was approximated at around 0.84 kg per 1 m^2 cage per year, which can bring an income of US$ 10.50. The cost for initial start-up capital, which was US$ 18.26 per 1 m^2 cage is relatively high compared to seaweed farm establishments, mainly due to the cost of wire mesh used. Fishing nets are alternatively used instead of wire mesh. For example, Beltran-Gutierrez (2012) used 1 cm^2 mesh fishing net in Zanzibar for integrated seaweed and sea cucumbers and the result was successful. The cost for initial start-up capital can be significantly reduced when using fishing nets instead of wire mesh. Also the anticipated production of sea cucumber fingerlings in a hatchery in Zanzibar by initiatives currently being supported by the Korean International Cooperation Agency (KOICA) and FAO, would significantly reduce costs.

Practical potential of integrating sea cucumbers and seaweed

This study provides useful information for future mariculture development in Zanzibar and Tanzania as a whole, however information gaps concerning mariculture of sea cucumber resources in Zanzibar still remain. Aspects like the species' absorption efficiency need to be investigated for its potential use in IMTA systems. Mariculture integration of seaweed and sea cucumbers is a potential livelihood alternative, which if adopted, can diversify livelihood portfolios of Zanzibar's coastal communities, especially of women involved in seaweed farming. Therefore, integrating sea cucumbers in seaweed farms should be promoted in Zanzibar to boost seaweed production. Significant advantages in the current co-culture model include the established and accepted nature of the culture sites and synergies in terms of husbandry and presence requirements of producers/farmers which reduces poaching and predation (Robinson and Pascal, 2009; Robinson, 2011). The piloted co-culture system, effectively integrating detritivores into existing aquaculture, allows for a significant increase in biomass production over monoculture and, given the value of sea cucumber, will result in increased income per aquaculture unit with little or no increase in resource pressure. Zanzibar seaweed farms cover approximately 1000 ha of coastal lagoon area, constituting a large established area available for co-culture of viable co-culture species (Beltran-Gutierrez *et al.,* 2016). The results of the studies reviewed here clearly demonstrate the potential of integration of commercially valuable sea cucumbers with seaweed. This review contributes to a growing body of literature establishing suitability of sea cucumbers for co-culture with existing finfish (Mills *et al*., 2012) and bivalve culture (Kang *et al.,* 2003; Slater and Carton, 2007; Paltzat *et al.* 2008; Zamora *et al.,* 2016).

Conclusions and Recommendations

In this review it was shown that high growth performance of seaweed in co-culture with sea cucumbers can be obtained in Tanzania, using high densities of seaweed (500 gm^{-2}) and low densities (200 gm^{-2}) of sea cucumbers.

Properly managed IMTA accelerates growth with no detrimental side effects on the organisms used or the environment. IMTA can increase profits and can reduce financial risks due to weather, disease and market fluctuations. Equally, co-culture offers a more efficient use of limited coastal space. The sea cucumber *H. scabra* is highly viable for lagoon co-culture with seaweed. However, care should be taken on stocking density because exceeding recommended stocking densities compromises the growth performance of sea cucumbers and may have implications on TOM and TOC budgets in the system. The appropriate adoption of an IMTA venture could increase income, acceptance, and finally create a new family business. The initial investment can be an obstacle but the use of local materials to construct culture facilities may help. In the future it is necessary also to look into secondary products (both from the seaweed and the sea cucumbers).

Integration of more organisms, with a focus on bivalves and finfish, to create real IMTA should be encouraged. For coastal environments it is necessary to consider that it is extremely difficult to convert fishermen into fish farmers. The focus should remain on smaller communities to increase the probability of success.

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