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Co-culture of sea cucumber *Holothuria scabra* and red seaweed *Kappaphycus striatum*

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Abstract

Commercially valuable sea cucumbers are potential co-culture species in tropical lagoon environments, where they may be integrated into established aquaculture areas used for seaweed farming. In the current study, wild-caught juvenile sea cucumbers, *Holothuria scabra*, and red seaweed *Kappaphycus striatum* were co-cultured on Zanzibar, United Republic of Tanzania. Sea cucumbers (97 g ± 31 SD, $n = 52$) were cultured in mesh enclosures at initial cage stocking densities of 124 ± 21 SD and 218 ± 16 SD g m^{-2} under seaweed culture lines. Over 83 days, individual growth rate (1.6 g d^{-1} ± 0.2 SD) of sea cucumbers at low stocking density was significantly higher ($\chi^2 = 8.292$, d.f. = 1, $P = 0.004$) than at high-stocking density (0.9 g d^{-1} ± 0.1 SD). Seaweed individual growth rates [6.27 (±0.3 SE) g d^{-1}] were highest in co-culture with sea cucumber at low density but did not differ significantly from high sea cucumber density or seaweed monoculture treatments ($\chi^2 = 3.0885$, d.f. = 2, $P = 0.2135$). Seaweed growth varied significantly ($\chi^2 = 35.6$, d.f. = 2, $P < 0.0001$) with sampling period, with the final sampling period resulting in the highest growth rate. Growth performance for seaweed and sea cucumbers ($\chi^2 = 3.089$, d.f. = 2, $P = 0.21$ and $\chi^2 = 0.08$, d.f. = 1, $P = 0.777$ respectively), did not differ significantly between monoculture and co-culture treatments, yet growth in co-culture was comparable with that reported for existing commercial monoculture. Results indicate *H. scabra* is a highly viable candidate species for lagoon co-culture with seaweed. Co-culture offers a more efficient use of limited coastal space over monoculture and is recommended as a potential coastal livelihood option for lagoon farmers in tropical regions.

Keywords: sandfish, co-culture, lagoon, seaweed farming, Zanzibar

Introduction

Expanding aquaculture is increasingly competing for limited available coastal space in areas facing high resource-user pressure. To sustain this growth, the aquaculture industry must use the limited available space more efficiently in order to optimize production yields. For instance, macroalgae or seaweed aquaculture occurs primarily in developing nations, such as Tanzania, with generally low returns to primary producers (Hayashi, Hurtado, Msuya, Bleicher-Lhonneur & Critchley 2010). Despite seaweed production accounting for 35% of the global mariculture biomass produced, it only represents 7% of the total aquaculture harvest value (FAO 2010). Therefore, integrating alternative and commercially valuable aquaculture species into existing sites for low-value seaweed production may increase space efficiency and yields, benefiting farmers and other coastal resource users.

In Zanzibar, Tanzania, significant areas of lagoon space, estimated at approximately 1000 ha, are dedicated to seaweed production (Olafsson, Johnstone & Ndaro 1995), making Tanzania the leading producer in Africa with 5% of the total global supply of the commercially valuable red seaweeds (FAO 2010; Hayashi *et al.* 2010). Seaweed farmers in Tanzania practise a low-technology off-bottom cultivation method, and earn US $50–500 per month during spring tides (Hayashi *et al.* 2010). Despite poor economic returns, lagoon-based seaweed farming is the most important marine economic activity on Zanzibar after artisanal near-shore fisheries (Lange & Jiddawi 2009). Recently, tourism development has placed increasing demand on coastal areas, leading to spatial conflicts with artisanal activities such as seaweed farming (Masalu 2000). Hence, space is a limiting resource for the further development of mariculture. This limitation may be overcome by integrating co-culture of commercially valuable species into existing mariculture areas.

Unlike seaweed, sea cucumbers are high-valued marine products exported to established international markets in Asia and North America (Ferdouse 2004; Eriksson, de la Torre-Castro & Olsson 2012; Purcell 2014). Sea cucumber stocks throughout Tanzania are severely overexploited, due to attempts to supply this strong demand, with a ban on the fishery in place in most of the country since 2006 (Mgaya & Mmbaga 2007; Eriksson, de la Torre-Castro, Eklöf & Jiddawi 2010). The multi-species and selective sea cucumber fishery in Zanzibar (Mkenda 2011) reports an annual catch of 32.5 dry tonnes (Department of Fisheries & Marine Resources of Zanzibar 2010) and represents an important income generating activity in the intertidal areas along the coast (MACEMP 2009).

Commercially valuable sea cucumbers as *Holothuria scabra*, commonly known as sandfish, offer a potential complimentary crop which could be integrated into dedicated areas to increase production and income per unit area while reducing pressure on coastal resources and benefitting from production and labour cost synergies. Deposit-feeding sea cucumbers recycle nutrients in co-culture and natural benthic ecosystems, with recycled nutrients positively impacting benthic primary productivity (Uthicke & Klumpp 1998; Uthicke 2001). Deposit-feeding sea cucumbers reduce organic content in sediments impacted by other aquaculture species by assimilation of bacteria, microalgae and dead organic matter including dead an decaying macroalgae (Feng, Gao, Dong, Sun & Zhang 2014); bioturbation through the displacement and mixing of the bottom substrate; and solubilization of nutrients to near-sediment water (Hamel, Conand, Pawson & Mercier 2001; Purcell 2004; Slater & Carton 2009). This solubilization of benthic nutrients can positively influence growth of associated seagrasses under certain conditions and potentially, macrophytes (Wolkenhauer, Uthicke, Burridge, Skewes & Pitcher 2010). The nutrient release from decaying seaweed has been poorly studied; however, Eklöf, de la Torre-Castro, Adelskold, Jiddawi and Kautsky (2005), Eklöf, de la Torre-Castro, Nilsson and Ronnback (2006) report increased sediment organic content and increased grazer presence at seaweed farms. Macroalgae has also been shown to be a partially digestible and useful diet component for tropical and temperate sea cucumber species (Xia, Zhao, Chen, Li, Liu, Zhang & Yang 2012; Orozco, Sumbing, Lebata-Ramos & Watanabe 2014). Hence, in a co-culture combining sea cucumbers with lagoon-based seaweed aquaculture, nutrient release from seaweed breakages, sloughed epiphytes, seaweed grazers and epifauna may offer a diet source to sea cucumbers while sea cucumbers may directly recycle limiting nutrients from the sediment to support seaweed growth (Titlyanov & Titlyanova 2010; MacTavish, Stenton-Dozey, Vopel & Savage 2012; Feng *et al.* 2014).

In the current study, sea cucumbers (*Holothuria scabra*) – organic extractive organisms – are combined with inorganic extractive organisms (seaweed) at established aquaculture sites to form a co-culture. Successful hatchery and husbandry methods exist for sandfish and it is successfully farmed in monoculture in a number of tropical nations in the Pacific and Indian oceans (Purcell, Hair & Mills 2012). Without access to a suitable hatchery juvenile supply, we, however, utilize wild-caught juvenile sea cucumbers in our experimental work and examine the growth performance and survival of both seaweed and sea cucumbers at different stocking densities in lagoon-based co-culture. The study aims to determine the viability of integrating sea cucumber aquaculture into an established seaweed farm.

Materials and methods

Fieldwork was conducted from December 2011 to March 2012 at an established seaweed farm in the coastal shallow-water lagoon zone of Muungoni, in southwest Unguja Island, Zanzibar (Fig. 1).

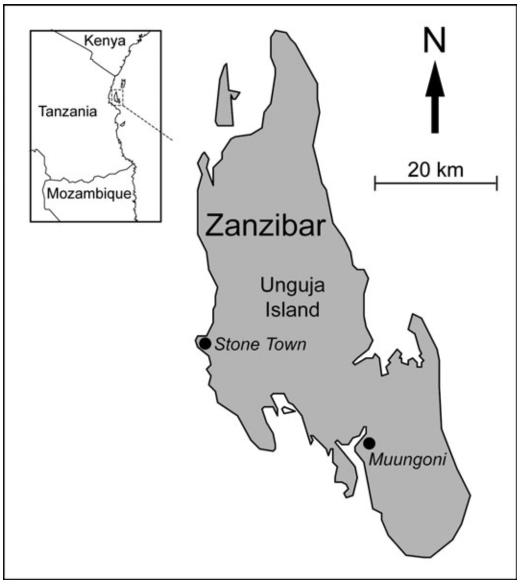

Figure 1 Location of experimental aquaculture site within Muungoni coastal area (S06°19′12.7″ E039°24′43.3″) on Unguja Island, Zanzibar, Tanzania.

Figure 2 Experimental cage for the co-culture trial enclosing sandfish juveniles with seaweed fragments planted on top. Cages measured 1.5 m × 1.5 m × 0.50 m (L × W × H = base area 2.25 m^2).

Lowest water level at the site at low spring tide was 30 cm. Surface seawater temperature, pH, salinity and oxygen concentration were measured at the site during the experimental period on days 1, 41, 58, 71, and 82 during morning hours (8:00–11:00 hours) at low spring tides, using a Hach Lange (HACH LANGE GmbH, Düsseldorf, Germany) HQ40d multimeter and a refractometer.

Sixteen fully enclosed ground-fixed net-cages (1.5 m × 1.5 m × 0.50 m – L × W × H) were constructed using 11-mm polyethylene mesh and 4-mm nylon rope to form cage edges/structure (Fig. 2). Mesh cages were tensioned to 1.5 m length wooden stakes driven into the sediment. The cage base was held at 0.25 m below the sediment surface allowing the animals to bury and avoid direct contact with the mesh at the base. One stake secured each corner and one stake secured the middle of each side (Davis, Stead, Jiddawi, Abdulaziz & Slater 2011). Sand removed during cage placement was filled back into each cage. A tie-able opening was made at the top of each cage, allowing access to caged animals. To minimize hydrodynamic disturbance the distance between cages was 5 m (Wolkenhauer *et al.* 2010). 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 seabed within the cage. The majority of dislodged fouling was removed (also by water movement) but unquantified amounts of dislodged fouling may have been available to sea cucumbers in the cages if it remained settled in the cages. Cages were maintained free of fouling and free of wrack/flotsam by this method also.

Seaweed stocking

In a system mirroring the 'tie-tie' off-bottom farming method whereby seaweed fragments are secured to an anchored main backbone rope with small lengths of string for culture (Foscarini & Prakash 1990), healthy 10 cm fragments of *Kappaphycus striatum* var. *payaka brown* were tied to a 4 mm Ø rope with 1 mm Ø string (tie-tie), maintaining a distance of 20 cm between fragments. Three culture rope lines each holding seven fragments were suspended above each experimental cage (approximately 50 cm above the sea floor) with wooden stakes driven into the sediment (Fig. 2). Two full seaweed production cycles (planting to harvest) were completed during the full study.

Sea cucumber stocking

Juvenile *Holothuria scabra* were collected from intertidal areas of Unguja Island during spring tides. Animals were collected in buckets, ensuring constant water exchange to avoid stress, transported by car and placed in holding cages with sediment access to acclimatize to the study site.

Average acclimatization period was 30 days at a density of approximately 300 g m^{-2} prior to allocation to experimental cages.

A total of 52 juvenile *Holothuria scabra* with initial wet body weight of 97 g ± 31 (mean ± SE) ranging from 40 to 162 g were allocated to experimental cages at approximate intended low (124 ± 22 SD g m^{-2}, range by cage 104–145 g m^{-2}) and high (218 ± 16 SD g m^{-2}, range by cage 206–242 g m^{-2}) stocking densities (Table 1). Sea cucumbers were removed from enclosures, left out of water for 1 min in order to expel the seawater from their respiratory trees, and weighed before assignment to cages (Slater & Carton 2007; Davis *et al.* 2011). As sea cucumbers were assigned and allocated to the cages, each 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 & Carton 2007; Robinson, Slater, Jones & Stead 2013).

Experimental design

Four treatments were established, each with four replicate cages within the limited available space at the operating farm (Table 1). Densities of sea cucumbers varied among the treatments and were intended to reflect 'low' (whereby optimal growth may be observed) and 'high' density stocking (whereby growth limitation may occur) as per the literature (Battaglene, Seymour & Ramofafia 1999; Pitt & Duy 2004; Purcell & Simutoga 2008). Cages in Treatment 0 held seaweed in monoculture (no sea cucumbers) (T0); Cages in Treatment 1 held sea cucumbers at low stocking density combined with seaweed (T1); Cages in Treatment 2 held sea cucumbers at a high-stocking density combined with seaweed (T2); and cages in Treatment 3 held sea cucumbers at a high-stocking density in monoculture (T3) (Table 1). The initial seaweed density was constant across treatments, reflecting the actual cultivation method of the seaweed farm. Treatments were assigned as per a Latin square design within a 4 × 4 grid of cages.

Survival and growth of culture species

Growth and survival of both seaweed and sea cucumbers were measured at approximately two-week intervals. Sea cucumbers were maintained for 83 days in cages while seaweed was maintained for two consecutive production cycles of 42 and 41 days respectively. Seaweed rope lines were untied, brought inshore and excess water was removed before weighting. During the first cycle, whole line weights were taken and stocking density in g m^{-2} was calculated. During the second cycle, in response to plant losses in first cycle, individual plant weight was recorded and added to calculate stocking density in g m^{-2}. Each seaweed plant was individually weighed and the tracking of single fragments was achieved by consecutive identification markings on the ropes. Percentage survival of seaweed was calculated by dividing the number of surviving plants (initial number of planted fragments minus the number of breakages or die-offs throughout the duration of the culture) by the initial number of planted fragments.

Sea cucumber survival was recorded as presence/absence of individuals in the assigned cage (Slater & Carton 2007). Sea cucumbers were removed from individual cages, photo-identified and weighed using digital scales to 2 g precision as outlined above before replacement in assigned

Table 1 Stocking densities (mean ± SD) of the sea cucumber *Holothuria scabra* and the commercial seaweed *Kappaphycus striatum* in the co-culture treatments

	Sea cucumbers		Seaweed		
				Density (g m^{-2})	
Treatment	Ind cage^{-1}	Density (g m^{-2})	Ind cage^{-1}	1st cycle	2nd cycle
T0	0	0	21	633 ± 50	570 ± 22
T1	3	124 ± 22	21	691 ± 38	582 ± 6
T2	5	218 ± 16	21	608 ± 37	571 ± 21
T3	5	218 ± 21	0	0	0

T0 = Seaweed in monoculture, T1 = Seaweed and sea cucumber at low stocking density (n = 4), T2 = Seaweed and sea cucumber at high-stocking density (n = 4), T3 = Sea cucumber in monoculture at high-stocking density (n = 4).

cages. At day 83, all sea cucumbers were harvested, gutted, and their wet weight recorded.

The difference between initial and final wet weights at each sampling period divided by the duration in time of each sampling period (g d^{-1}) were calculated to obtain growth rates (GR) in both cultures species. Negative values in seaweed growth rates were included in statistical analysis despite the fact that these constituted breakages or die-offs.

Statistical analysis

Linear mixed models were employed using the 'lme4' package (Bates *et al.* 2012) of the statistical software R version 2.15.1 (R Development Core Team 2008). To compare the effect of stocking density and seaweed on sea cucumber growth performance, non-normal data for sea cucumber growth rates were square root transformed [sqrt (Y + 5)]. After transformation, data fulfilled the assumptions of parametric statistical testing, normality and homogeneity of variances.

The effect of stocking density and presence or absence of seaweed requires the use of two separate models: First with stocking density (low and high levels) and measurement period taken as fixed effects, starting weights at each measurement period of sea cucumber as covariate, and the experimental subjects (individuals), which were repeatedly measured across six time periods, as random effect nested in cage; Second using seaweed presence or absence and the measurement period as fixed effects, starting weights of sea cucumber at each measurement period as covariate, and individuals nested in cage as random effect.

Effect of stocking density on seaweed growth performance was tested using mixed models on sign(Y)*abs(Y)^(3/4) transformed values to correct for leptokurtosis, covariates included sea cucumber stocking density (no, low and high levels), log-transformed starting weights at each measurement period as fixed effects, and experimental subjects nested in cage as random effect.

Results

Study site abiotic factors

Mean pH of surface seawater at the site during the experimental period was 7.92 (±0.07 SE), mean salinity was 34.61 (±1.79 SE) and mean oxygen concentration was 6.01 mg L^{-1}(±0.07 SE). Recorded surface water temperature at low water slack tide at the site ranged from 32 to 38°C during the experimental period with temperatures of 38, 36, and 38°C on the first three measurement dates (days 0–51), falling to 32°C on the last two measurement dates (days 51–82).

Seaweed survival and growth

During the first seaweed growth cycle (42 days), survival of seaweed fragments averaged 57% across all treatments. Mean growth rate across all treatments was 0.51 (±0.17 SE) g d^{-1}. Growth rates of 0.94 (±0.3 SE) g d^{-1} were recorded for T0, 0.62 (±0.4 SE) g d^{-1} for T1 (with sea cucumber at 124 g m^{-2} stocking density), and 0.02 (±0.2 SE) g d^{-1} for T2 (with sea cucumber at 218 g m^{-2}) (Fig. 3). Approximately 50% of individual plants across all treatments showed outward signs of 'ice-ice' disease including decreased pigment content, softening of the branches and increased breakage. A number of 'diseased' seaweed fragments also exhibited epiphytic filamentous algae (EFA) infection.

During the second seaweed growth cycle survival averaged 79% and no disease was observed in the crop. Mean initial individual plant weight of 62 (±1 SE) g increased fivefold to 288 (±6 SE) g after 41 days at a mean growth rate of 5.6 (±0.2 SE) g d^{-1}. Seaweed growth rates did not differ significantly between treatments (seaweed in monoculture or combined with low and high sea

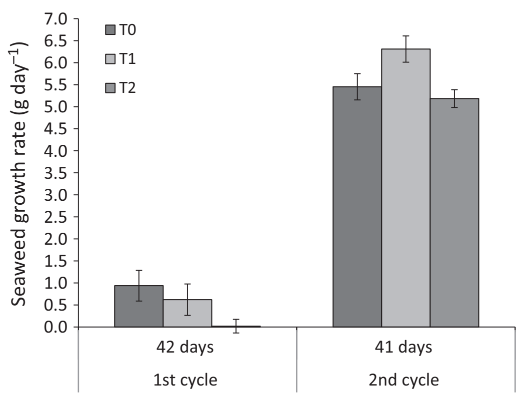

Figure 3 Mean growth rate of seaweed *Kappaphycus striatum* at the end of first and second cycle (42 and 41 days respectively) in co-culture with sea cucumber stocked at initial densities of 0 g m^{-2} (T0) (n = 4), 124 g m^{-2} (T1) (n = 4) and 218 g m^{-2} (T2) (n = 4). Error bars indicate standard error.

Table 2 Initial and final wet weights, gutted weight at harvest, growth rates (GR) and density at harvest (mean ± SE) of farmed *Holothuria scabra* juveniles at different treatments of co-culture with seaweed

Treatment	Stocking size (g)	Weight at harvest (g)	Gutted weight at harvest (g)	GR (g d^{-1})	Density at harvest (g m^{-2})
T1	93 (±10)	225 (±20)	113 (±6)	1.6 (±0.2)	300 (±24)
T2	98 (±7)	179 (±11)	98 (±5)	0.9 (±0.1)	378 (±26)
T3	98 (±7)	181 (±9)	100 (±3)	0.9 (±0.1)	348 (±34)

T1 = Seaweed and sea cucumber at low stocking density (n = 4), T2 = Seaweed and sea cucumber at high-stocking density (n = 4), T3 = Sea cucumber in monoculture at high-stocking density (n = 4).

cucumber stocking density) (χ^2 = 3.089, d.f. = 2, P = 0.21), however, sampling period (χ^2 = 35.6, d.f. = 2, P < 0.0001 and starting weights of the planted seaweed (χ^2 = 49.14, d.f. = 1, P < 0.0001) had a significant effect. A growth rate of 5.51 (±0.3 SE) g d^{-1} was recorded in the treatment in monoculture without sea cucumbers (T0), 6.27 (±0.3 SE) g d^{-1} in co-culture with sea cucumber at 124 g m^{-2} stocking density (T1), and 5.15 (±0.2 SE) g d^{-1} in co-culture with sea cucumber at 218 g m^{-2} (T2) (Fig. 3).

Sea cucumber survival and growth

Overall, survival of sea cucumber was 100% in treatment 1, 92% in treatment 2 (one animal lost) and 85% in treatment 3 (2 animals lost). All losses were considered most likely to be escapees and/or due to human interference with cages. Final densities at harvest varied among treatments from 300 to 378 g m^{-2} (Table 2). Total growth rate at low stocking density (1.6 g d^{-1}) was significantly higher compared to those at high-stocking density (0.9 g d^{-1}, χ^2 = 8.2923, d.f. = 1, P = 0.00398) (Tables 1 and 2). The growth rate varied significantly between measurement periods (χ^2 = 23.81, d.f. = 5, P = 0.0002), being highest in the last time period and lowest at intermediate time periods (Fig. 4). Starting weight did not contribute significantly to sea cucumber growth rates (χ^2 = 0.669, d.f. = 1, P = 0.413). The viscera and coelomic fluid accounted for 45.1 ± 8.7% of fresh weight of the live sea cucumber juveniles at harvest (Table 2). Co-culture status – whether sea cucumbers had been grown together with seaweed or in isolation – did not affect sea cucumber growth rates (χ^2 = 0.08, d.f. = 1, P = 0.777), but varied between measurement periods (χ^2 = 31.769, d.f. = 5, P < 0.0001) and starting weight in the measurement period (χ^2 = 7.372, d.f. = 1, P = 0.0066). A growth rate of 0.9 (±0.1 SE) g d^{-1} was recorded in both high density treatments – in monoculture and in co-culture with seaweed. Sea cucumber at low density in co-culture with seaweed grew at 1.6 (±0.2 SE) g d^{-1} (Table 2).

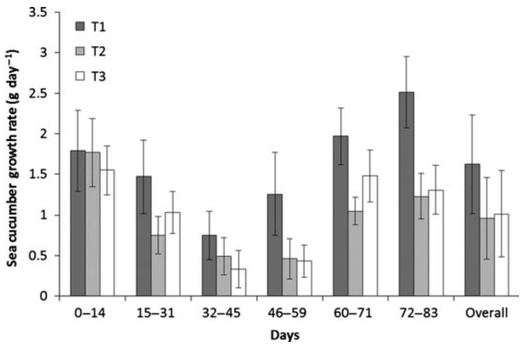

Figure 4 Mean growth rate of sea cucumbers stocked at 124 g m^{-2} (T1) (n = 4) and 218 g m^{-2} (T2) (n = 4) in co-culture with seaweed and stocked at 218 g m^{-2} without seaweed (T3) (n = 3). Values shown are based on untransformed data. Error bars indicate standard error.

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. The current study piloted co-culture of the sea cucumber *H. scabra* with the seaweed *K. striatum* in existing lagoon-based seaweed farms in Zanzibar, United Republic of Tanzania. Survival and commercially viable growth of both species clearly showed such a system's viability for up-scaling and commercial development.

Poor growth performance of seaweed during the first harvest cycle (0.6% d^{-1}) in the current study

(December–February) can be attributed to heat stress, which is the main factor in the 'ice-ice' disease observed in farmed *Kappaphycus* sp. (Msuya 2011). The sensitivity of *Kappaphycus* to fluctuations in environmental parameters, such as salinity and temperature, also correlates with the observed EFA infestation in the current study (Vairappan 2006). Epiphytes commonly affect growth and carrageenan yields of seaweed (Ask & Azanza 2002), and infestation by the red algae *Neosiphonia* sp. has been previously reported for Tanzanian *Kappaphycus* sp. farms (Vairappan, Chung, Hurtado, Soya, Bleicher-Lhonneur & Critchley 2008; Msuya & Kyewalyanga 2010). During the second harvest cycle (February to March), growth (reported here as percentage weight increase per day for comparison with previous studies) for all cultivated seaweed treatments was 5.3% d^{-1} compared to 1.1–4.0% for *K. striatum* cultured in its native Philippines (Hurtado, Critchley, Trespoey & Bleicher-Lhonneur 2008), 1.4–5.9%, in Japan (Mairh, Soe-Htun & Ohno 1986) and 2.4–7.6% in India (Mairh, Zodape, Tewari & Rajyaguru 1995). While *K. striatum* growth rates are unreported for Tanzania; growth of *K. alvarezii* ranges from 1.5% d^{-1} to 7.3% d^{-1} (Mtolera 2003; Msuya & Salum 2012). Integration of sea cucumbers into existing seaweed farms thus has no significant positive or negative short-term effect on seaweed growth or health, but seaweed yields remain viable under co-culture. If seaweed growth was nutrient limited in the current study, sea cucumbers did not recycle nutrients from the sediment in a manner significantly affecting seaweed growth.

Higher growth rates of juvenile *H. scabra* stocked at low density (here in co-culture with *K. striatum*) are in close agreement with the literature for *H. scabra* of similar sizes grown in coastal lagoons and in land-based ponds (James 1999; Purcell & Simutoga 2008; Lavitra, Rasolofonirina & Eeckhaut 2010; Purcell *et al.* 2012). The current mean growth rates (1.6 g d^{-1}) for sea cucumbers initially stocked at 124 g m^{-2} are similar to peak growth rates (1.8 g d^{-1}) reported for *H. scabra* in commercial lagoon monoculture by Robinson and Pascal (2012) and exceed the 0.49–1.5 g d^{-1} reported for similar-sized animals (up to 262 g mean weight) in pond culture (James 1999; Pitt & Duy 2004; Purcell 2004; Purcell & Kirby 2006). Growth rates continued to increase over the experimental period, however, the observation that growth varied markedly and decreased at days 32–45 across all treatments may indicate that unhealthy or partially diseased seaweed plants can impact sea cucumber growth rates. Alternatively the trend may be indicative of negative effects of commensurate environmental conditions in particular temperature (Dong, Dong, Tian, Wang & Zhang 2006; Zamora & Jeffs 2012).

Sea cucumber growth in co-culture was stable at densities exceeding the 300 g m^{-2} reported for commercial lagoon culture and the maximum biomass densities for pond-based culture (Battaglene *et al.* 1999; Pitt & Duy 2004; Purcell & Simutoga 2008). Battaglene *et al.* (1999) observed sandfish growth rates to decline when densities exceeded 225 g m^{-2}, while Pitt and Duy (2004) suggested an optimal balance between growth rates and total production at a density of one animal or ~300 g m^{-2}. Lavitra *et al.* (2010), however, report potential maximum juvenile sea cucumber biomass of up to 700 g m^{-2} in optimum sea pen areas before growth is limited. Growth rate would certainly have become limited in the current study over a longer experimental period. Results indicate, however, that biomass densities of more than 370 g m^{-2} may be achieved in co-culture. The experimental design applied in the current study was strongly space-limited and did not gauge effect of seaweed presence on sea cucumbers at the lower density of 124 g m^{-2}. While results clearly indicate no effect of seaweed presence on growth of sea cucumbers at high densities, this cannot be assumed for lower densities of sea cucumbers without additional research.

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 (Olafsson *et al.* 1995). The results of the current study clearly demonstrate the potential of integration of commercially valuable sea cucumbers with seaweed. This contributes to a growing body of literature establishing suitability of sea cucumbers for co-culture with existing finfish (Mills, Duy, Juinio-Meñez, Raison & Zarate 2012) and bivalve (Kang, Kwon & Kim 2003; Slater & Carton 2007; Paltzat, Pearce, Barnes & McKinley 2008; Jianguang, Funderud, Zhanhui, Jihong, Zengjie & Wei 2009) culture. Results support ecosystem models developed by Ren, Stenton-Dozey, Plew, Fang and Gall (2012) showing that integration of species into existing aquaculture can markedly increase farm productivity but that seaweed nutrient input to detritivores may be negligible. However, the strong growth rates reported for densities exceeding 300 g sea cucumber biomass per m^2 in the current and previous studies under operating mussel farms, would indicate that the modelled production densities of 125 g sea cucumber biomass per m^2 are grossly underestimated at non-finfish sites, particularly where natural sediment primary productivity may influence food availability (Slater & Carton 2007; Ren *et al.* 2012). 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 – reducing poaching and predation (Robinson & Pascal 2012). 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.

Future research related to the piloted co-culture system is required to determine optimal methods to reduce capital costs and ensure the system is practical for producer. Predation, escapes, natural disturbances and poaching reduce yields in open system sea cucumber culture (Eriksson, Robinson, Slater & Troell 2012; Juinio-Meñez, Paña, de Peralta, Catbagan, Olavides & Edullantes 2012; Robinson & Pascal 2012). The fully covered cage design used in this study partially overcomes these disturbances, assimilated well into operations within the existing seaweed farm, and may also allow smaller juveniles to be stocked, reducing nursery costs (Battaglene *et al.* 1999; Purcell, Blockmans & Agudo 2006; Robinson & Pascal 2012). If larger, cheaper cages for whole plots (mean 150 m^2) (Msuya, Shalli, Sullivan, Crawford, Tobey & Mmochi 2007) prove impractical, roofless sea pen caging systems can be constructed beyond the borders of the seaweed farm (Lavitra *et al.* 2010).

Conclusion

The current study demonstrates the potential viability of the co-culture of two commercially valuable species, the sea cucumber *H. scabra* and the seaweed *K. striatum*. Growth and survival rates for both species compare positively with those reported in commercial monoculture. Commercial scale integration of sea cucumbers into existing seaweed farms offers marked benefits to farmers and allows the production of significant amounts of valuable additional aquaculture product in the coastal lagoons, without increasing pressure on coastal resources.

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