Reviews in Aquaculture

Reviews in Aquaculture (2016) 0, 1–18

doi: 10.1111/raq.12147

Role of deposit-feeding sea cucumbers in integrated multitrophic aquaculture: progress, problems, potential and future challenges

Leonardo Nicolas Zamora[1], Xiutang Yuan[2], Alexander Guy Carton[3] and Matthew James Slater[4]

1 Leigh Marine Laboratory, Institute of Marine Science, University of Auckland, Warkworth, New Zealand
2 State Oceanic Administration, National Marine Environmental Monitoring Center, Dalian, China
3 Division of Tropical Environments and Societies, College of Marine and Environmental Sciences, Centre for Sustainable Tropical Fisheries and Aquaculture, James Cook University, Townsville, Australia
4 Alfred-Wegener-Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany

Correspondence
Leonardo Nicolas Zamora, Leigh Marine Laboratory, Institute of Marine Science, University of Auckland, PO Box 349, Warkworth, New Zealand. E-mail: lzam004@aucklanduni.ac.nz

Received 12 August 2015; accepted 1 February 2016.

Abstract

There is significant commercial and research interest in the application of sea cucumbers as nutrient recyclers and processors of particulate waste in polyculture or integrated multitrophic aquaculture (IMTA) systems. The following article reviews examples of existing IMTA systems operating with sea cucumbers, and details the role and effect of several sea cucumber species in experimental and pilot IMTA systems worldwide. Historical observations and quantification of impacts of sea cucumber deposit-feeding and locomotion are examined, as is the development and testing of concepts for the application of sea cucumbers in sediment remediation and site recovery. The extension of applied IMTA systems is reported, from basic piloting through to economically viable farming systems operating at commercial scales. The near-global recognition of the ecological and economic value of deposit-feeding sea cucumbers in IMTA applications within existing and developing aquaculture industries is discussed. Predictions and recommendations are offered for optimal development of sea cucumber IMTA globally. Future directions within the industry are indicated, and key areas of ecological, biological and commercial concern are highlighted to be kept in mind and addressed in a precautionary manner as the industry develops.

Key words: bioremediation, deposit-feeding, integrated multitrophic aquaculture, sea cucumber, sea ranching, sustainable aquaculture.

Introduction

Sea cucumbers are a high-value marine aquaculture and fisheries product. Their trophic position and ability to process sediments enriched and impacted by the aquaculture industry has led to strong interest in their use in integrated multitrophic aquaculture systems (IMTAs) worldwide (Fig. 1). The intent of the present review is to summarize the current state of knowledge of the use of sea cucumbers in an IMTA context with reference to observations, pilot studies and commercial practices which have resulted from this interest and further to explore future considerations, precautions and needs as this form of sea cucumber production expands.

Sea cucumber – the high-value marine product

Sea cucumbers are a high-value seafood product exploited in wild fisheries and commercially cultured (Toral-Granda *et al.* 2008; Purcell *et al.* 2012b). The global sea cucumber fishery catch has gone from 4900 t in 1950, to a peak of 23 400 t in 2000 with an export trade value around US$ 130 million, while aquaculture production has been reportedly around 166 712 t per annum in the last few years (2012–2014) in China (Vannuccini 2004; CFSY 2014). The aquaculture production market value in China is estimated to exceed US$ 5 billion assuming a dry yield of 3.5% and a market value of US$ 1000 per dry kilo (Zhang *et al.* 2015).

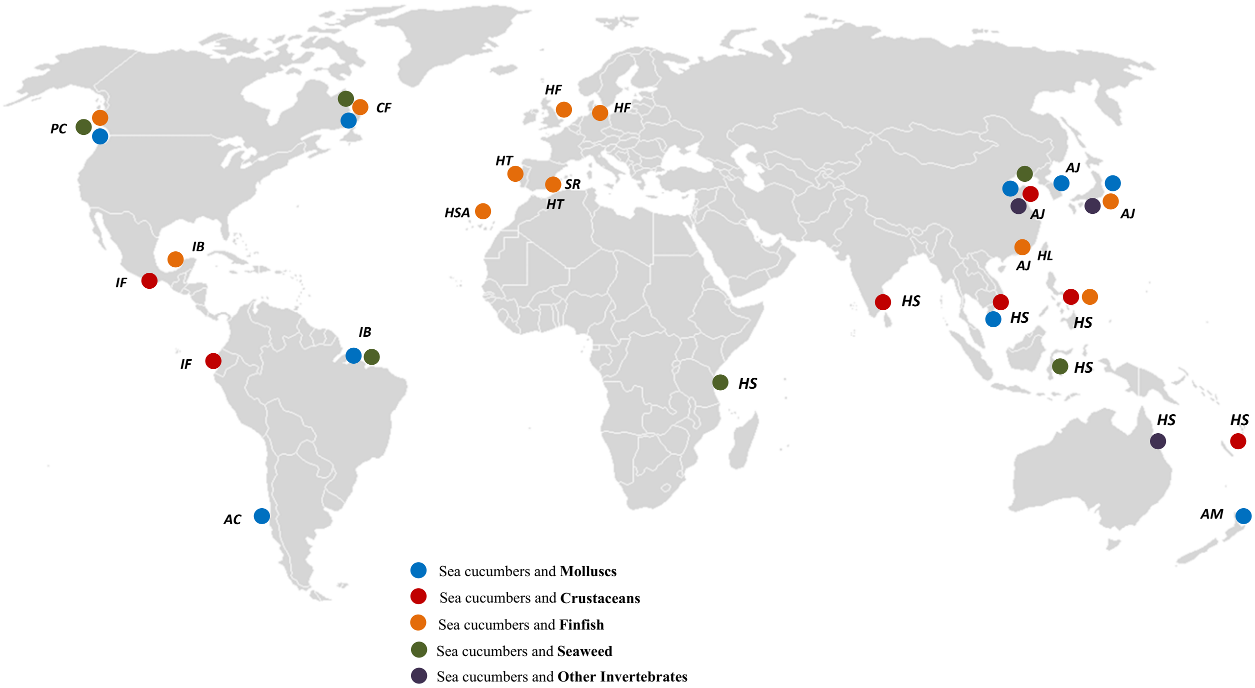

Figure 1 Global distribution of sea cucumber IMTA efforts (Mostly experimental coastal- and land-based systems). AC, *Athyonidium chilensis*; AJ, *Apostichopus japonicus*; AM, *Australostichopus mollis*; CF, *Cucumaria frondosa*; HF, *Holothuria forskali*; HL, *Holothuria leucospilota*; HSA, *Holothuria sanctori*; HS, *Holothuria scabra*; HT, *Holothuria tubulosa*; IB, *Isostichopus badionatus*; IF, *Isostichopus fuscus*; PC, *Parastichopus californicus*; SR, *Stichopus regalis*.

Traditionally, sea cucumbers are consumed as a food, or as a dietary supplement in traditional Asian medicines or as extracts and tonics (e.g. gamat oil in Malaysia). This form of use has more recently expanded into western nutraceutical markets. High-value species can fetch a final retail price of hundreds of US dollars per kg (dry weight) if they are of the desired size and are appropriately processed (Purcell 2014a).

Traditional sea cucumber fisheries have existed for centuries throughout the Western Pacific, Eastern Asian and Indian Oceans being exclusively focused on aspidochirotids of the families Holothuriidae and Stichopodidae. Recently, novel fisheries have developed rapidly in most other marine regions, often with detrimental effects for the stocks targeted (Purcell *et al.* 2010, 2013; Anderson *et al.* 2011). There is now a global fishery for sea cucumber, with more than 60 species currently being actively fished and the largest areas of production in the north-west and south-west Pacific Ocean (Purcell *et al.* 2012b). Around the world, sea cucumber fisheries are extremely diverse in terms of methods and target species. These range from artisanal fisheries, where tropical species are taken by hand in shallow sub-tidal areas or by free-divers, through to industrial scale fisheries using combined scuba/hookah diving and dredge fisheries for temperate species, such as *Cucumaria frondosa* and *Cucumaria japonica* (Conand 2008; Hamel & Mercier 2008; Kinch *et al.* 2008; Toral-Granda 2008). Exploited sea cucumber populations have proven to be highly susceptible to overfishing at both local and regional scales with boom and bust cycles characterizing the majority of these fisheries (Dalzell *et al.* 1996; Skewes *et al.* 2000; Uthicke 2004; Kinch 2005; Toral-Granda 2005; Uthicke & Conand 2005). Overfishing has increased market value while also stimulating efforts to develop aquaculture production of a number of sea cucumber species.

Sea cucumber aquaculture development

Presumably as a result of accessibility and commercial value, current commercial and experimental aquaculture of sea cucumbers is limited to high-value intertidal and shallow subtidal aspidochirotids, primarily the temperate species *Apostichopus japonicus* and the tropical species *Holothuria scabra*. These two species are currently the only commercially hatchery-produced sea cucumber species (e.g. Hair *et al.* 2012; Yang *et al.* 2015). Research during the 1940s and 1950s, initiated in reaction to the overexploitation of wild stocks of these sea cucumbers in Japanese waters, led to the development of spawning and larval rearing methods for *A. japonicus* (Imai & Inaba 1950). This species is now widely cultured in pond monoculture in China (Chang *et al.* 2004; Chen 2004) and in various sea-ranching systems in China, Japan, South Korea and the Russian Federation (Levin 2000; Yang *et al.* 2015). With minimal adaptation, these original culture methods have also been extended to the farming of tropical sandfish, *H. scabra*, and other sea cucumber species (Asha & Muthiah 2005; Agudo 2006; Jimmy *et al.* 2012; Pietrak *et al.* 2014; Heath *et al.* 2015). Overall, depending on the species of sea cucumber, they can be cultured in both coastal and land-based culture systems and due to their feeding habits the addition of extra food is not usually required (Lovatelli *et al.* 2004; Hair *et al.* 2012; Yang *et al.* 2015). Most recently, the possibility of growing sea cucumbers together with other species has attracted great attention worldwide not only for the evident economic benefits but also due to the possibility of reducing the overall environmental impact of the farming activities.

Rationale and history of sea cucumber integrated aquaculture

Deposit-feeding sea cucumbers as candidates for integration

The simultaneous culturing of two or more species within the same aquaculture unit is often referred to as polyculture, coculture, integrated aquaculture or IMTA where specific consideration is given to the integration of species at varying trophic levels (Chopin & Robinson 2004; Chopin *et al.* 2007; Barrington *et al.* 2009; Troell 2009). The species grown together are usually complimentary or do not interact negatively and generally have different trophic positioning, with lower trophic level species selected on the ability to consume waste and by-products generated by higher trophic levels (Lutz 2003). IMTA systems result in reduced nutrient and waste output, lower feeding requirements and increase yields per unit area through more efficient resource utilization and synergistic effects (Swingle 1968; Shpigel & Blaylock 1991; Lin *et al.* 1992; Hu *et al.* 1995). In the following, in the light of the trophic level of sea cucumber and for the sake of simplicity, the term IMTA will be used in this review to refer to all these forms of integrated aquaculture.

Sea cucumbers are considered an ideal candidate species for IMTA systems due to their ability to feed on the particulate waste generated by other animals. This is relevant because of the significant benthic impacts of commercial open aquaculture systems. For instance, in-shore and near-shore aquaculture in sea cages, on long lines or in ponds often results in large-scale biodeposition. This in turn induces a suite of profound changes to the sedimentation regime and sediment characteristics, in particular alteration of the sediment chemistry below the farm or within the pond leading to significant shifts in the composition of associated benthic communities (Dahlbäck & Gunnarsson 1981; Kaspar *et al.* 1985; Brown *et al.* 1987; Hatcher *et al.* 1994; Grant *et al.* 1995; Christensen *et al.* 2003; Hartstein & Rowden 2004; Mente *et al.* 2006). The inclusion of sea cucumbers, which can process enriched benthic sediments, assimilating bacterial, fungal and detrital organic matter, can aid in reducing benthic impacts. These feeding effects are amplified by feeding selectivity (Webb *et al.* 1977; Hauksson 1979; Moriarty 1982; Roberts & Bryce 1982; Roberts *et al.* 2000). Sea cucumbers have not only been shown to reduce organic load, their feeding also results in horizontal redistribution and bioturbation of sediments (Crozier 1918; Hauksson 1979; Lawrence 1982; Moriarty 1982; Uthicke 1999, 2001; Slater & Carton 2009; Yuan *et al.* 2016). It is increasingly apparent that sea cucumbers play a key role in benthic nutrient cycling in both temperate and tropical environments, with recycled nutrients positively impacting benthic primary productivity (Uthicke & Klumpp 1998; Uthicke 1999, 2001; Schneider *et al.* 2011; MacTavish *et al.* 2012). It has even been suggested that they are attracted to and could be used for treatment of human sewage waste (Van Dover *et al.* 1992; Wu 1995). The concept of integrating sea cucumbers into existing aquaculture systems as an extractive species has been enhanced by empiric observations of natural association of sea cucumbers with high deposition or eutrophied sites (Da Silva *et al.* 1986; Van Dover *et al.* 1992; Ahlgren 1998; Slater *et al.* 2010; Cheng & Hillier 2011; Zhang *et al.* 2014).

Early observations of sea cucumbers for IMTA

Intentional integration of sea cucumbers with other species began in northern China in the late 1980s, where *A. japonicus* were naturally attracted to, and ultimately trialed in IMTA with, filter-feeding scallop *Chlamys farreri* in lantern nets (Zhang *et al.* 1990). Also in China, *A. japonicus* was observed actively feeding on the organically enriched sediment in ponds holding *Penaeus monodon*, where some of the first large-scale IMTA experiments started in the early 1990s and are still practised today (Chang *et al.* 2004; Zheng *et al.* 2009). Japanese researchers attempted IMTA of the temperate species *A. japonicus* with sea urchins, as the sea cucumbers were observed feeding on the faeces and fouling of the cages used (Ito 1995).

In the tropics, *H. scabra* were reportedly observed in association with seaweeds (i.e. *Eucheuma cottonii*, *Eucheuma* sp. and *Gracilaria* sp.) in Indonesia (Daud *et al.* 1991, 1993; Rachmansyah *et al.* 1992; Madeali *et al.* 1993; Muliani 1993; Tangko *et al.* 1993a,b). In the late 1990s, the first attempts to incorporate sea cucumbers with finfish were made in Canada with *P. californicus* used for fouling mitigation in coastal salmon sea cage systems after spontaneous association was observed (Ahlgren 1998).

While the results of these very early experiments varied, they set the platform for present day IMTA commercial practices and experimental systems, including more complex multitrophic aquaculture systems. Sea cucumbers have since been widely tested for IMTA with many aquaculture species including bivalves (oysters, scallops, mussels, clams), gastropods (abalones, snails), crustaceans (shrimps, crabs, lobsters), several species of finfish, jellyfish, sea urchins and macroalgae. Past and recent commercial applications and experimental systems will be addressed separately in the following as 'current commercial practice' and 'experimental IMTA'. Land-based integration of sea cucumbers is reviewed separately from marine applications.

Commercial and experimental integration of sea cucumbers into IMTA systems

Current commercial practices for land-based sea cucumber IMTA

Pond culture of sea cucumbers began in China, Philippines and Vietnam, as a partial reaction to faltering shrimp (*Penaeus monodon* and *Litopenaeus vannamei*) yields due to the outbreak of shrimp diseases (Chang *et al.* 2004; Pitt & Duy 2004). Shrimp ponds can be converted for sea cucumber production with minimal alteration (Chang *et al.* 2004; Qin *et al.* 2009; Ren *et al.* 2010). Where coculture with shrimp occurs, shallow shrimp ponds (2–3 m depth) are used to accommodate *A. japonicus* either in an IMTA format or in a crop rotational culture system where sea cucumbers are stocked into ponds following single harvests of shrimp crop (Chang *et al.* 2004; Chen 2004; Zheng *et al.* 2009). In the Philippines and Vietnam, *H. scabra* is grown in abandoned shrimp ponds at small commercial scales. However, this approach more closely resembles a crop rotational culture system, and efforts at integrating shrimp (*Litopenaeus stylirostris* and *L. vannamei*) have been unsuccessful (Purcell 2004; Purcell *et al.* 2006b).

The first full commercial sea cucumber integration in operating shrimp ponds originated from Pulandian Bay located in western Liaoning Peninsula, northern China in 1998–1999 (Xu & Zhu 2002). Although Chang *et al.* (2004) reported widespread (>2000 ha) sea cucumber IMTA with shrimp in Dalian, Liaoning Province alone, there is little evidence from the authors' experience that supports the veracity of the reported areas of coculture currently. Integrated culture with shrimps is currently less widespread than reported in Dalian and other provinces probably due to low prices for shrimp compared to sea cucumber, meaning that farmers have favoured simpler sea cucumber monoculture, especially in recent years.

Increasingly, complex multitrophic pond systems are being commercially piloted in China with larger juvenile *A. japonicus* stocked at high densities (~10 g at density of 10 ind m^{-2}) in IMTA with other species such as the scallop *Chlamys farreri*, and the jellyfish, *Rhopilema esculentum*, the crab *Charybdis japonica*, and shrimps *Penaeus japonicus* and *Fenneropenaeus chinensis* in varying combinations (Zheng *et al.* 2009; Ren *et al.* 2012b, 2014; Feng *et al.* 2014; Li *et al.* 2014a,b).

Experimental land-based sea cucumber IMTA

A particular focus of sea cucumber IMTA in land-based activities has been experimental farming with shrimp. In addition to the developments in China outlined above, the possibility of growing tropical *H. scabra* in ponds with shrimp has also been evaluated in Vietnam (*Penaeus monodon* and *L. vannamei*), New Caledonia (*Litopenaeus stylirostris*) and India (*Penaeus monodon*). Growth and survival results were poor due to predation on juvenile sea cucumbers by shrimps and low salinities in the ponds constraining sea cucumber growth (James 1999; Battaglene & Bell 2004; Pitt & Duy 2004; Pitt *et al.* 2004; Purcell *et al.* 2006b; Bell *et al.* 2007; Mills *et al.* 2012; Watanabe *et al.* 2012). Only in Vietnam, with adequate control of pond salinity, has pond IMTA culture of *H. scabra* in *Penaeus monodon* ponds been successfully tested, however, only using a rotational culture format to avoid predation by the shrimps and using larger juveniles over 50 g that require short grow-out period of 7–9 months (Fig. 2c) (Bell *et al.* 2007; Duy 2012; Mills *et al.* 2012). The rotational use of shrimp ponds has also been tested with juvenile *Isostichopus fuscus* in Ecuador (wild collected) and in Mexico (hatchery produced); however, this proved unsuccessful due to high disease-related mortalities and depressed growth (Mercier *et al.* 2012).

In addition to IMTA with shrimp in land-based systems, *H. scabra* has been integrated with the carnivorous Babylon snail (*Babylonia areolata*) in ponds which improved sea cucumber growth and broodstock conditioning (Pitt & Duy 2004; Duy 2012). Mills *et al.* (2012) reported integration of juvenile *H. scabra* with fish in earthen ponds is promising for farmers in the Philippines that grow different species of fish (milkfish, *Chanos chanos*; pompano, *Trachinotus blochii*; and Asian sea bass, *Lates calcarifer*). However, not all temperate species of sea cucumber perform well in earthen ponds, such as *Holothuria tubulosa* which was unsuccessful in culturing attempts with finfish and oysters in Portugal (Cunha *et al.* 2013). Herbivorous species such as abalone and sea urchins have been held in combination with *A. japonicus*, with sea cucumbers feeding on the faeces of these macroalgal feeders (e.g. Zhang *et al.* 1993; Wang *et al.* 2008). The inclusion of sea cucumbers

Figure 2 Different forms of experimental and commercial integration of deposit-feeding sea cucumbers into existing culture systems. (a) Suspended cage systems used for the IMTA of abalone (*Haliotis discus hannai*) with *Apostichopus japonicus* in coastal areas in northern China (Photo credit: Xiutang Yuan). (b) Lantern nets used for the IMTA of bivalves, together with *Apostichopus japonicus* in coastal areas of northern China (Photo credit: Xiutang Yuan). (c) Former shrimp intertidal pond conditioned for the growing of *Holothuria scabra* in Vietnam (Photo credit: Leonardo Zamora). (d) Experimental cage designed for the IMTA of the red seaweed *Kappaphycus striatum* and the tropical sandfish, *Holothuria scabra*, in a lagoon located in the United Republic of Tanzania (Photo courtesy of Marisol Beltran-Gutierrez). (e) Hatchery-reared juvenile *Australostichopus mollis* held together with the Greenshell™ mussel *Perna canaliculus* in experimental tanks (Photo credit: Leonardo Zamora). (f) Checking the experimental bottom cages for holding *Australostichopus mollis* under a Pacific oyster, *Crassostreas gigas*, rack and rail farming system in an intertidal mudflat in north-eastern New Zealand (Photo credit: Leonardo Zamora). (g) Naturally settled juveniles of *Parastichopus californicus* in an oyster line, which then fall down to the sediment and become part of the fishing stock or are collected and reseeded in a licensed IMTA shellfish/finfish farm in British Columbia, Canada (Photo courtesy of Dan Curtis, DFO). (h) Experimental recirculation aquaculture system for the IMTA of the starry flounder, *Platichthys stellatus*, with *Holothuria forskali* in northern Germany (Photo credit: Matthew Slater).

with sea urchins (*Strongylocentrotus intermedius*) in land systems has not received much attention, with *A. japonicus* growth and survival depending on the sea urchin–sea cucumber densities proportions (Wang *et al.* 2007a, 2008). According to these studies, juvenile sea cucumbers (1.4 g) should be stocked with juvenile sea urchins (3.4 g) at a proportion of 3 sea cucumbers for every 11 sea urchins for better results. Similar results have been obtained in Townsville, Australia, when coculturing the sea urchin *Tripneustes gratilla* with *H. scabra* in a recirculation system (Guy Carton, unpublished data).

Juvenile *A. japonicus* have been successfully incorporated into land-based systems usually used for the production of abalone, *Haliotis discus hannai*, in Korea (Kang *et al.* 2003; Jin *et al.* 2011; Kim *et al.* 2015). Early studies in China also demonstrated the success of integration of abalone *Haliotis discus* with *A. japonicus* in land-based farming, and a stocking density of 120 ind m^{-2} abalone (1.32 mm in body length) with 5–10 ind m^{-2} sea cucumber (17.8 g in body weight) was recommended (Lin *et al.* 1993; Zhang *et al.* 1993). Economically successful trials of sea cucumber IMTA with abalone with artificially added stones or in cages in intertidal ponds resulted in positive yields for both species (Chang & Hu 2000; Li *et al.* 2001). Recent, laboratory-scale experiments suggested an optimal stocking density of 200 ind m^{-2} abalone (8.75 g in body weight) with 5 ind m^{-2} sea cucumber (2.24 g in body weight) (Wang *et al.* 2007b,c). Similarly in New Zealand, juveniles of the Australasian sea cucumber, *Australostichopus mollis*, were successfully integrated into the land-based production of the abalone *Haliotis iris* (Maxwell *et al.* 2009).

As land-based finfish production expands, there is also growing interest in feeding solid waste generated from recirculating aquaculture systems (RAS) to high-value sea cucumbers. In the United Kingdom, the feasibility of integrating the sea cucumber *Holothuria forskali* with sea bass, *Dicentrarchus labrax,* in RAS has been tested, with sea cucumbers able to feed on high organic content waste from farming activities, reducing the organic load of the waste from RAS (MacDonald *et al.* 2013). For example in Germany, the sea cucumber *H. forskali* has been integrated directly into the tank recirculation aquaculture systems of olive flounder, *Paralichthys olivaceus* and *P. stellatus,* without detrimental effects for either species in terms of survival; however, flounder growth may be reduced when cultured in direct contact with the sea cucumbers (Fig. 2h) (Spreitzenbrath & Slater, unpublished data).

Current commercial practices for marine and near-shore sea cucumber IMTA

Open culture systems in coastal areas offer large amounts of space, and a broad spectrum of aquaculture species and existing systems for integration of sea cucumbers. As with land-based systems, China has led commercial integration of sea cucumber into coastal aquaculture systems beginning with IMTA with filter-feeding bivalves (Fig. 2b). The earliest sea cucumber IMTA with bivalves in China was practised in lantern nets in 1989 (Zhang *et al.* 1990). A 46-fold weight increase in 0.17 g body weight juvenile sea cucumbers (2 cm in body length) and a 2.9-fold weight increase in 24 g body weight juvenile sea cucumbers (6–8 cm in body length) were observed after 11 months IMTA. An optimal density of 20 individual sea cucumbers (6–8 cm in body length) per net was recommended (Zhang *et al.* 1990). The integration of sea cucumbers into scallop lantern nets gained some commercial acceptance; however, sea cucumber IMTA with bivalves developed slowly in China due to operational difficulties and labour cost. The integration of high-value abalone, *H. discus hannai*; kelp, *L. japonica;* and sea cucumbers, *A. japonicus* in suspended culture is currently gaining greater commercial popularity in China (Fig. 2a), possibly due to higher income offsetting higher labour costs (Lin 2005; Fang *et al.* 2009; Liu *et al.* 2009; Dong *et al.* 2013; Qi *et al.* 2013). Commercial scale, sea cucumber IMTA with abalone occurs in offshore systems in Shandong and Liaoning provinces. This type of IMTA accounted for a large proportion of Chinese sea cucumber and abalone production over the last 10 years. More than 700 ha, for example, are set aside for such systems near Zhangzidao Island off the east of the Liaoning Peninsula (Barrington *et al.* 2009) and in 2010, 600 t of sea cucumbers and 80 t of abalone were harvested, valued at more than RMB 0.2 billion. Sea cucumbers are also seeded below extensive kelp longline areas in China (Yang *et al.* 1999; Chen 2004).

In other countries, IMTA systems are practised, but the amount of information available and scale compared to China is minor. For instance, many lobster farmers in Vietnam grow mussels next to the lobster cages and some reportedly integrate *H. scabra* in net enclosures under the lobster cage to reduce the concentrations of organic matter in the water column and in the sediments (Pham *et al.* 2004, 2005).

Experimental marine and near-shore sea cucumber IMTA

Growing sea cucumbers, *A. japonicus,* in particular with bivalves such as Pacific oyster, *Crassostrea gigas* and scallops, *Argopecten irradians*, *Chlamys farreri*, *Patinopecten yessoensis* has been widely studied (Zhang *et al.* 1990; Zhou *et al.* 2006; Yuan *et al.* 2008, 2012, 2013). For example, in lantern net IMTA, Zhou *et al.* (2006) estimated that a stocking density of 34 sea cucumbers (20 g in body weight) per net could be optimally cocultured with bivalves, growth rates of 0.09–0.31 g ind^{-1} d^{-1} were achieved in Sishili Bay and Jiaozhou Bay, western Shandong Peninsula. Yuan *et al.* (2008) found that *A. japonicus* could be cocultured with many kinds of bivalves and that a density-effect-specific growth rate was exhibited. A stocking density of 1200 g sea cucumbers per lantern net was recommended in pilot studies in Sanggou Bay, eastern Shandong Peninsula (Yuan *et al.* 2008).

Zhang *et al.* (1990) early work in China has served as a base for the development of IMTA technologies in other countries in which bivalves are cultured and sea cucumbers are present. For instance, *A. japonicus* and *P. californicus* have been cocultured in suspended cages underneath Pacific oysters in Japan and Canada, respectively (Fig. 2g), while in New Zealand, *A. mollis* has been placed under rack-and-rail Pacific oyster farms in intertidal mud flats (Fig. 2f) (Paltzat *et al.* 2008; Zamora *et al.* 2014; Yokoyama 2015). In Chile, *Athyonidium chilensis* has been experimentally cocultured with clams (Maltrain 2007). Mussel–sea cucumber IMTA has been widely studied in New Zealand, focusing mainly on how environmental variables affect the feeding biology and physiology of *A. mollis* in an IMTA context with the Greenshell™ mussel *Perna canaliculus* (Fig. 2e) (Slater & Carton 2007, 2009, 2010; Stenton-Dozey 2007a; Slater *et al.* 2009; Stenton-Dozey & Heath 2009; Zamora & Jeffs 2011, 2012a,b, 2013, 2015). In China, the integration of scallops and sea cucumber with kelp has also been investigated, in systems including *A. japonicus*, *C. farrery* and the kelp *Laminaria japonica*, in which the growth of the sea cucumbers appears to be density dependent and is highly affected by seawater temperature (Yang *et al.* 1999; Dong *et al.* 2013). Integrated systems with only macroalgae have also been tested, and the sandfish, *H. scabra,* has been successfully integrated into the culture of the red macroalgae, *Kappaphycus striatum* in lagoon systems, greatly increasing the income of the seaweed farmers (Fig. 2d) (Beltran-Gutierrez *et al.* 2014).

After Ahlgren (1998) made early observations and research linking Atlantic Salmon, *Salmo salar*, with *P. californicus*, the integration of sea cucumbers and finfish in coastal environments remained understudied until recently. Under adequate culture management, juvenile *A. japonicus* have recently been shown to grow well when placed in bottom cages under fish farms in southern parts of China despite seasonal limitations (Yu *et al.* 2014). Integration of juvenile *A. japonicus* into red sea bream farms in open waters has been tested in Japan with positive results in terms of survival and growth of the sea cucumbers (Yokoyama 2013). Equally, *A. japonicus* juveniles grow and survive well under Yellowtail (*Seriola lalandi)* pens in Japan although the comparatively high organic loading of biodeposits may limit long-term juvenile sea cucumber growth (Yokoyama *et al.* 2015). Similar limitations have been observed with the tropical sea cucumber, *Holothuria leucospilota*, which when placed under fish farms in bottom cages in southern China died due to anoxia of the sediments (Yu *et al.* 2012). Animals in suspended cages, however, survived. Other temperate sea cucumber species to be tested for integration with finfish include, on the Pacific coast of Canada, *P. californicus*, which has been integrated at a pilot scale test with sablefish, *Anoplopoma fimbria*, Pacific hybrid scallops and kelp, *Saccharina latissima*, in an open water system (Hannah *et al.* 2013). Also in Canada, the sea cucumber *C. frondosa* is being tested as a candidate for integration into multitrophic aquaculture sites with Atlantic salmon (*Salmo salar*), blue mussels (*Mytilus edulis*) and kelp (*S. lattisima*) (Nelson *et al.* 2012a,b; McPhee *et al.* 2015). In Spain, researchers are investigating the possibility of incorporating wild collected *H. tubulosa* and *Stichopus regalis* in bottom cages beneath sea bream *Sparus aurata* on the Mediterranean coast, as well as the culture of *Holothuria sanctori* in suspended cages associated with floating sea bass (*D. labrax*) cages in the Canary Islands (Macías *et al.* 2008; Ramón *et al.* 2010; Navarro *et al.* 2013; Felaco 2014). While in Mexico and Brazil, there are ongoing projects to integrate *Isostichopus badionotus* into existing finfish, filter feeder bivalves and macroalgae cultures (Olvera-Novoa *et al.* 2014; Rombenso *et al.* 2014).

Ecological and economic benefits of integration of sea cucumber into IMTA systems

In most previously described experimental cases, emphasis is placed on the ecological benefits associated with the integration of deposit-feeding sea cucumbers into IMTA systems and the overall feasibility of this type of culture. Very few studies examine the tangible economic benefit of IMTA systems that incorporate sea cucumbers. Yet, perceived economic benefits are a primary reason why including sea cucumber into IMTA systems is attractive and widely piloted. However, the real economic benefits are rarely measured and focus mostly in income, failing to mention costs such as seed production and labour costs most of the times. For instance in China, the economic benefits can be extremely high considering that the monoculture of kelp yields US\$ 19 153 ha^{-1} yr^{-1}. This amount increases to US\$ 107 541 ha^{-1} yr^{-1} when integrating abalone and kelp. When sea cucumbers are integrated into the system, the total product value, deducting the cost of juveniles of abalone and sea cucumber production, is increased to about US\$ 157 158 ha^{-1} yr^{-1} (Fang *et al.* 2009; Dong *et al.* 2013). Beltran-Gutierrez *et al.* (2014) found that integrating sea cucumbers (*H. scabra*) into existing lagoon seaweed farms resulted in a sixfold increase in farm per unit area annual profit. This is particularly important for developing nations in which IMTA systems that do not require the addition of expensive extra food offer significant potential for livelihood provision (Slater *et al.* 2013).

As previously mentioned, the ecological benefits have been widely studied as deposit-feeding sea cucumbers are able to reduce the overall system waste output (faeces and uneaten food) and nutrient loading by direct consumption and by sediment bioturbation. *Australostichopus mollis* grazing on sediments impacted by mussel farming activities significantly reduces the accumulation of both organic carbon and phytopigments associated with biodeposition, stimulating bacterial activity and mineralization, while bioturbation increases the level of organic matter that is dissolved to interstitial water and the water column (Slater & Carton 2009; MacTavish *et al.* 2012). Similar observations have been made for *A. japonicus* when cocultured in suspended systems with bivalves in China (Michio *et al.* 2003; Zhou *et al.* 2006; Yuan *et al.* 2008, 2016) and even the dendrochirotid *C. frondosa* in Canada (Nelson *et al.* 2012a). When cultured in shrimp earthen ponds, the sea cucumbers (*H. scabra* and *A. japonicus*) are able to consume both faeces and uneaten food from shrimps, reducing the organic load (particulate organic carbon and nitrogen) on the ponds and the biochemical oxygen demand thus reducing the risk of anoxia (Purcell *et al.* 2006b; Ren *et al.* 2010; Watanabe *et al.* 2012). Similar results were obtained when incorporating *A. japonicus* with shrimps and jellyfish in ponds after building carbon, nitrogen and phosphorus budgets, making this an efficient culture system as well as an environmental remediation system by reducing the organic load of the water that enters the system (Li *et al.* 2014a,b). Recently, another species, *Stichopus monotuberculatus*, has shown promise for the utilization of shrimp farming waste as part of the sea cucumber diet in southern China (Chen *et al.* 2015a,b). It has also been shown that sea cucumbers (*P. californicus*, *H. forskali*, *H. leucospilota* and *A. japonicus*) can reduce the impact of fish farm activities, by reducing the organic carbon and nitrogen content of the high organic content faeces of the fish by up to 60%, reducing waste biodeposition (Ahlgren 1998; Yu *et al.* 2012, 2014; Hannah *et al.* 2013; MacDonald *et al.* 2013). However, it is worth noting that the capability of the sea cucumbers to reduce the waste generated by the aquaculture farms will depend on the physiological performance of the species. This is variable in temperate species exposed to seasonal changes in environmental conditions. Species such as *A. japonicus* undergo a series of physiological changes as seawater temperature increases thus effectively halting feeding activity during the summer time (e.g. Ji *et al.* 2008). *Australostichopus mollis* feeding activity also reduces markedly as seawater temperature increases (Zamora & Jeffs 2012b, 2015). *P. californicus* is affected in a similar way as *A. japonicus* but by lower seawater temperatures during winter (Hannah *et al.* 2012). This seasonal component should be evaluated for these and other species when estimating their bioremediation capabilities.

Future directions and opportunities

The value and the opportunity presented by sea cucumber inclusion in IMTA approaches are recognized globally among the scientific community and increasingly widely among commercial aquaculture producers (Fig. 1). As the many forms of IMTA discussed herein expand commercially, a number of benefits will be enjoyed. Equally, unforeseen biological risks and practical challenges will also undoubtedly arise. These are addressed in the following.

Biological risk

Hatchery producers will need to give consideration to future potential genetic impacts of juvenile releases where wild stocks are present. Eriksson *et al.* (2012) provide an overview of risks to existing wild stocks in terms of genetic pollution and transfer of disease by large-scale juvenile releases and suggest following breeding lines as developed for other species (Blankenship & Leber 1995; Leber *et al.* 2004). Similarly, disease transfer risks to wild populations are impossible to estimate. More importantly, in the case of IMTA, the potential for sea cucumbers to act as disease vectors to IMTA species is comparatively high and individual risk levels must be resolved in commercial applications (Cho *et al.* 2011). A precautionary approach is recommended particularly as concerns animal health checks prior to release into IMTA systems. This should be supported by increased research into sea cucumber diseases and symbionts, with pilot holding with coculture species under controlled conditions to reveal potential disease or parasite transmission (Eriksson *et al.* 2012; Simon *et al.* 2014).

The concern exists, despite proven remediation effects, that mass production of sea cucumbers may in fact have a negative effect on the surrounding environment. In China where the intensive culture of *A. japonicus* is practised in ponds, concerns have been raised regarding nutrient leaching from pond systems into coastal areas, particularly where formulated diets are added to ponds (Feng *et al.* 2014). Equally, increasing media attention is being given to chemical and antibiotic use in high-density farms (Bin 2014). Purcell *et al.* (2012a) argue that alternative options for culturing tropical sea cucumbers, such as *H. scabra*, in IMTA with fish, shellfish or algae should be supported and encouraged; however, IMTA may not be the panacea mainly due to a possible increase in waste production and low culture densities. However, in (unfed) existing IMTA research and pilot applications, concerns related to excess nutrient and waste production are highly unlikely to arise. The benthic effects of integration of sea cucumbers suggested by Eriksson *et al.* (2012) into an already heavily eutrophied and altered benthic environment are unlikely to occur as most studies point to likely benthic remediation (Slater & Carton 2009; Feng *et al.* 2014).

The effect of sea cucumber farming on the hydrodynamics of a region will depend largely on whether any structure or enclosure is used to contain the crop, where necessary structures may affect site hydrodynamics, deposition and scouring rates. The effect of structures on currents will be greatest in shallow sites. Altered current flows are likely to be greatest for suspended structures, followed by bottom structures. Structures on the seabed will decrease current velocities near the bed, with the possibility of local scouring around cages or piles, and near-bottom turbulence. Any local-scale changes in hydrodynamics from sea cucumber culture will be reversible on removal of all structures. Despite the overall positive environmental effects indicated by existing studies, mass IMTA expansion is likely to bring forth new, unexpected environmental impacts; therefore, a precautionary approach is essential to monitor and limit undesirable effects.

Economic potential

It is true that this activity has a great economic potential; however, care should be taken when considering moving forward with commercial integration of deposit-feeding sea cucumbers and several variables should be taken into account. Firstly, species selection is primordial as there is a high variability in terms of market price depending on the sea cucumber species selected as presented by Purcell *et al.* (2012b), and therefore, the initial investment required needs to be weighed against the potential profits. Ways to increase profits are developing cost-effective growing and processing technologies to reduce costs and selective breeding for fast growing families with the desired market characteristics to increase economic returns. Another factor to consider is whether or not the implementation of IMTA systems is a viable option, which could be more plausible for countries in which open aquaculture systems for bivalves, crustaceans and finfish are already established and in search for economic diversification and growth. Such is the case of New Zealand where a medium-value sea cucumber species is readily present (i.e. *A. mollis*), and the main aquaculture species are Greenshell™ mussels (*P. canaliculus*, 4747 ha), the Pacific oyster (*C. gigas*, 750 ha) and the King salmon (*Oncorhynchus tshawytscha*, 60 ha) (Aquaculture New Zealand 2012). Therefore, there is a huge potential area for inclusion of *A. mollis* if the adequate growing sites (i.e. farms) are selected and if stocking densities and seeding times are managed taking into account food availability and environmental factors (Zamora & Jeffs 2013). The current market price of *A. mollis* is US$ 275 kg^{-1} dry weight with, a 8% dry weight recovery, and there could be a conservative yearly production of 2 t of wet weight ha^{-1} in both mussel and oyster farms (Slater & Carton 2007; Zamora et al. 2014). Therefore there is the potential to obtain around US$ 44 000 worth of sea cucumber product per hectare of shellfish/finfish farm, without taking into account production costs, which are currently poorly known. A similar approach can be possible for a number of aquaculture producer nations for which the integration of sea cucumber is a real alternative such as Canada, Australia, Chile and several European and Tropical countries if the adequate information is available (Fig. 1). A clear understanding of the biology of the selected sea cucumber species is required, because due to physiological constrains, not all the current farms would be suited for integration as growth may be hindered by environmental factors (Ren *et al.* 2012a). Furthermore, not all the existing farms could be adapted for the integration of another species therefore practicality needs to be considered as well. Overall in reality, only part of the potential area for inclusion of sea cucumbers would be really suited for integration, and even within selected farm sites there may be some variation depending on the organic load produced which determines the sea cucumber's stocking densities and carrying capacity (Zamora & Jeffs 2012a). Finally, it is important to note that the value of sea cucumber products is, in the authors' experience, frequently overestimated. Caution is required when considering potential economic benefits. Sea cucumber consumption and the sea cucumber 'global market' are in fact overwhelmingly controlled through Hong Kong and Mainland China (Ferdouse 2004; Vannuccini 2004; Purcell 2014b). This market is prone not only to market forces of supply and demand but also to internal and external regulatory forces (Eriksson & Clarke 2015; Godfrey 2015).

Need for practicable IMTA farming systems

Despite clear economic potential, most existing systems for sea cucumber culture and IMTA have been developed in China or other comparatively low labour cost nations. Alternative, more mechanized systems of production, particularly for harvest and processing, are likely to be required in Europe, and other places where low labour availability and high labour costs are the norm.

This challenge includes the development of practical large-scale IMTA methods for sea cucumbers. Most caging methods will be highly impractical on a commercial scale. Installing large holding structures such as cages or trays beneath an operating farm is likely to be both expensive and disruptive to farm cycles. Submerged holding structures may be damaged during normal farming operations, may obstruct or tangle farm structures, or be overwhelmed by larger debris, all of which would result in animal losses and intensive maintenance requirements. Another aspect associated with the use of structures to contain the sea cucumbers is that depending on the materials/design/mesh size selected, combined with the amount of biofouling settling in the structures, the supply of waste/food entering the structures is likely to be reduced. Appropriate selections and design must be carried out to preserve the bioremediation potential of the sea cucumbers. In addition, cleaning and maintaining the cages will add an extra cost to the operation. The option of sea-ranching IMTA is, at first analysis, most practicable and worthy of investigation. Comparatively low organic matter (hence low food value) sediment at the edge of farm footprint may act as a habitat border for selectively feeding sea cucumbers, essentially keeping seeded sea cucumbers within the IMTA system (Slater & Carton 2010). Specific physical structures on the seabed or seabed profile types may also be useful to delineate habitat boundaries (Massin & Doumen 1986). Such a system may create difficulties in monitoring crop growth and density, as these sea-ranching systems often fail to distinguish wild from culture stocks, also creating conflicts with the fisheries sector. Where IMTA is planned, appropriate legislation, possibly supported by suitable stock identification (e.g. tagging with appropriate methods if available), will be necessary (Purcell *et al.* 2006a; Stenton-Dozey 2007b; Purcell & Blockmans 2009).

Systems must be suited to species as not all current culture systems suit all sea cucumber species (e.g. *I. fuscus* cannot be grown in ponds, Mercier *et al.* 2012), and the selection of the correct sea cucumber species to integrate is critical as not all species can process the same organic loading which increases considerably from bivalves to finfish farms. Tropical species like *H. scabra* and *H. leucospilota* seldom consume sediments containing high levels of organic matter (i.e. over 10%), while temperate species show different tolerances, for instance *A. mollis* and *A. japonicus* grow optimally when feeding on sediments up to 20%, while *H. forskali* and *P. californicus* process sediments containing 60% organic matter (Sun *et al.* 2004; Purcell *et al.* 2006b; Yuan *et al.* 2006; Zamora & Jeffs 2012a; MacDonald *et al.* 2013). The primary aims of integration also need to be defined, and methods varied accordingly. Many experimental and pilot study results provide tentative stocking densities for IMTA systems aimed at optimizing sea cucumber output. The recommended stocking density can, however, be varied to suit the level of impact of the individual farm. Stocking densities may also be varied depending on the primary aim of the IMTA system. If ecologically significant reduction of sediment impacts or remediation of impacted areas is the primary aim, then densities can be increased beyond those optimal for sea cucumber growth.

Food quality and safety

Sea cucumbers are considered a premium seafood due to their high protein to lipid ratio, containing high levels of beneficial polyunsaturated fatty acids, essential amino acids, collagens, vitamins and minerals (Cui *et al.* 2007; Zhong *et al.* 2007; Wen *et al.* 2010; Aydın *et al.* 2011; Bordbar *et al.* 2011; Lee *et al.* 2012). Although the nutritional quality changes from species to species, there is a space for improvement as the selection of adequate IMTA systems (in terms of the environmental conditions and the food available for the sea cucumbers) can enhance the nutritional value of the sea cucumbers (Wen *et al.* 2010; Seo *et al.* 2011; Lee *et al.* 2012). An adequate processing method is another way to maximize the quality of the final product as traditional sun-drying methods fare poorly with techniques such as freeze-drying but costs and processing times are a concern (Zhong *et al.* 2007; Duan *et al.* 2010; Purcell 2014a). Due to its feeding habits, sea cucumbers are able to incorporate and eliminate heavy metals into/from their body depending on their external availability (Warnau *et al.* 2006; Sicuro *et al.* 2012; Jinadasa *et al.* 2014). Although reported levels of heavy metal so far have been below dangerous threshold, benthic areas with known high levels of heavy metals should be avoided (Denton *et al.* 2009). Organoleptic characteristics such as flavour, taste and aroma are important for consumers; however, the sea cucumber market is driven mostly by the size, shape and colour of the dried end product. Any concerns regarding the quality of the product caused by the aquaculture conditions, especially when sea cucumbers are taken from their natural habitat and are feeding on waste diets otherwise not available in 'natural environs' should be addressed prior to the escalation of commercial production. This is very important in particular for IMTA with species that are fed artificial feeds such as finfish.

Conclusion

Sea cucumbers, in particular deposit-feeding aspidochirotids, are optimal candidates for integration into existing commercial aquaculture systems. A variety of sea cucumber species worldwide has been shown, in experimental, pilot and commercial applications, to grow rapidly at economically viable densities below operating aquaculture systems producing finfish, bivalves, crustaceans and macroalgae. These sea cucumber species reprocess and remediate biodeposits and impacted sediments from commercial aquaculture across a wide spectrum of degrees of organic impact or enrichment, across farming system types from pond to open cage to longline. Despite the wealth of supporting data, large-scale commercial IMTA systems including sea cucumbers remain limited to Mainland China (Yuan *et al.*

2015), although many pilot-to-commercial systems are being developed in other temperate and tropical nations.

In taking advantage of the significant potential of such integrated aquaculture with highly valued sea cucumbers, consideration must be given to suiting the farming methods applied to the species farmed and also to the economic and operational constraints of the existing aquaculture facilities in the nation in question. Appropriate future aquaculture engineering development and process engineering research are thus essential. When ranching systems, or caging where breeding/spawning can occur are applied, informed decisions must be made with regard to potential genetic impacts of large-scale culture. Equally, biological risks in terms of sea cucumbers role as a disease vector to natural conspecifics, coculture species and other marine species must be understood and taken into account. Strong economic potential should be exploited, but not overestimated, product quality must be certified and consumers assured that products from IMTA are acceptable. The impact of market forces on future returns, even for perceived luxury products, must not be ignored.

As these challenges are met, and if appropriate precautionary approaches are taken and sustainable development of the industry is aided by bespoke supporting legislative frameworks, the integration of sea cucumbers into existing aquaculture facilities will deliver significant economic and environmental benefits where it is applied.

Acknowledgements

Dr. Yuan is supported by National Natural Science Foundation of China (no. 30871932), National Marine Public Welfare Research Project of China (no. 201305043). The authors are thankful for the constructive and thorough review provided by anonymous reviewers that significantly improved the manuscript.

References

Agudo NS (2006) *Sandfish Hatchery Techniques*. Australian Centre for International Agricultural Research, , Secretariat of the Pacific Community and WorldFish Center, Noumea, New Caledonia, 43 pp.

Ahlgren MO (1998) Consumption and assimilation of salmon net pen fouling debris by the red sea cucumber *Parastichopus californicus*: implications for polyculture. *Journal of the World Aquaculture Society* **29**: 133–139.

Anderson SC, Flemming JM, Watson R, Lotze HK (2011) Serial exploitation of global sea cucumber fisheries. *Fish and Fisheries* **12**: 317–339.

Aquaculture New Zealand (2012) *New Zealand Aquaculture: A Sector Overview With Key Facts, Statistics and Trends*. Aquaculture New Zealand, Nelson, 22 pp.

Asha PS, Muthiah P (2005) Effects of temperature, salinity and pH on larval growth, survival and development of the sea cucumber *Holothuria spinifera* Theel. *Aquaculture* **250**: 823–829.

Aydın M, Sevgili H, Tufan B, Emre Y, Köse S (2011) Proximate composition and fatty acid profile of three different fresh and dried commercial sea cucumbers from Turkey. *International Journal of Food Science & Technology* **46**: 500–508.

Barrington K, Chopin T, Robinson S (2009) Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In: Soto D (ed) *Integrated Mariculture: A Global Review, FAO Fisheries and Aquaculture Technical Paper. No. 529.*, pp. 7–46. FAO, Rome.

Battaglene SC, Bell JD (2004) The restocking of sea cucumbers in the Pacific Islands. In: Bartley DM, Leber KM (eds) *Marine Ranching, FAO Fisheries and Aquaculture Technical Paper. No. 429.*, pp. 109–132. FAO, Rome.

Bell JD, Agudo NN, Purcell SW, Blazer P, Simutoga M, Pham D *et al.* (2007) Grow-out of sandfish *Holothuria scabra* in ponds shows that co-culture with shrimp *Litopenaeus stylirostris* is not viable. *Aquaculture* **273**: 509–519.

Beltran-Gutierrez M, Ferse S, Kunzmann A, Stead SM, Msuya FE, Hoffmeister TS *et al.* (2014) Co-culture of sea cucumber *Holothuria scabra* and red seaweed *Kappaphycus striatum*. *Aquaculture Research*. doi:10.1111/are.12615.

Bin L (2014) Massive Antibiotics Use Found in Sea Cucumber Farming. [Cited 11 December 2014.] Available from URL: http://english.cri.cn/12394/12014/12309/12310/13781s843618.htm

Blankenship HL, Leber KM (1995) A responsible approach to marine stock enhancement. *American Fisheries Society Symposium* **15**: 167–175.

Bordbar S, Anwar F, Saari N (2011) High-value components and bioactive from sea cucumbers for functional foods – a review. *Marine Drugs* **9**: 1761–1805.

Brown JR, Gowen RJ, McLusky DS (1987) The effect of salmon farming on the benthos of a Scottish sea loch. *Journal of Experimental Marine Biology and Ecology* **109**: 39–51.

CFSY (2014) *China Fishery Statistical Yearbook*. China Agriculture Publishing Press, China, Beijing.

Chang Z, Hu Z (2000) Technique for culturing sea cucumber in the intertidal abalone-cultured ponds. *Fisheries Science* **19**: 1.

Chang Y, Yu C, Song X (2004) Pond culture of sea cucumbers, *Apostichopus japonicus*, in Dalian. In: Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel J-F, Mercier A (eds) *Advances in Sea Cucumber Aquaculture and Management*, pp. 269–272. FAO, Rome.

Chen J (2004) Present status and prospects of sea cucumber industry in China. In: Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel J-F, Mercier A (eds) *Advances in Sea Cucumber Aquaculture and Management*, pp. 39–47. FAO, Rome.

Chen Y, Hu C, Ren C (2015a) Application of wet waste from shrimp (*Litopenaeus vannamei*) with or without sea mud to feeding sea cucumber (*Stichopus monotuberculatus*). *Journal of Ocean University of China* **14**: 114–120.

Chen Y, Luo P, Hu C, Ren C (2015b) Effect of shrimp (*Litopenaeus vannamei*) farming waste on the growth, digestion, ammonium-nitrogen excretion of sea cucumber (*Stichopus monotuberculatus*). *Journal of Ocean University of China* **14**: 484–490.

Cheng YW, Hillier LK (2011) Use of Pacific oyster *Crassostrea gigas* (Thunberg, 1793) shell to collect wild juvenile sea cucumber *Parastichopus californicus* (Stimpson, 1857). *Journal of Shellfish Research* **30**: 65–69.

Cho M-Y, Park S-Y, Won K-M, Han H-J, Lee S-J, Cho Y-A *et al.* (2011) Detection of fish pathogens in cultured juveniles for stock enhancement in 2010. *Journal of Fish Pathology* **24**: 121–129.

Chopin T, Robinson SMC (2004) Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: introduction to the workshop and positioning of the issues. *Bulletin-Aquaculture Association of Canada* **104**: 4–10.

Chopin T, Yarish C, Sharp G (2007) Beyond the monospecific approach to animal aquaculture—the light of integrated multi-trophic aquaculture. In: *Ecological and Genetic Implications of Aquaculture Activities*, pp. 447–458. Springer, Netherland.

Christensen PB, Glud RN, Dalsgaard T, Gillespie P (2003) Impacts of longline mussel farming on oxygen and nitrogen dynamics and biological communities of coastal sediments. *Aquaculture* **218**: 567–588.

Conand C (2008) Population status, fisheries and trade of sea cucumbers in Africa and the Indian Ocean. In: Toral-Granda V, Lovatelli A, Vasconcellos M (eds) *Sea Cucumbers: A Global Review of Fisheries and Trade*, pp. 143–194. FAO, Rome.

Crozier WJ (1918) The amount of bottom material ingested by holothurians (*Stichopus*). *Journal of Experimental Zoology* **26**: 379–389.

Cui F-X, Xue C-H, Li Z-J, Zhang Y-Q, Dong P, Fu X-Y *et al.* (2007) Characterization and subunit composition of collagen from the body wall of sea cucumber *Stichopus japonicus*. *Food Chemistry* **100**: 1120–1125.

Cunha ME, Quental-Ferreira H, Soares F, Ribeiro L, Matias D, Joaquim S *et al.* (2013) Ecological multi-trophic aquaculture in earthen ponds. In: *Asian-Pacific Aquaculture Conference 2013, Positioning for Profit*. WAS, Ho Chi Min City, Vietnam.

Da Silva J, Cameron JL, Fankboner PV (1986) Movement and orientation patterns in the commercial sea cucumber *Parastichopus californicus* (Stimpson) (Holothuroidea: Aspidochirotida). *Marine Behaviour and Physiology* **12**: 133–147.

Dahlbäck B, Gunnarsson LÅH (1981) Sedimentation and sulfate reduction under a mussel culture. *Marine Biology* **63**: 269–275.

Dalzell P, Adams TJH, Polunin NVC (1996) Coastal fisheries in the Pacific Islands. *Oceanography and Marine Biology: An Annual Review* **34**: 395–531.

Daud R, Tangko AM, Mansyur A, Wardoyo SE, Sudradjat A, Cholik F (1991) Budidaya rumput laut (*Gracilaria* sp.) dengan teripang (*Holothuria scabra*) dalam sistem polikutur. In: *Laporan Penelitian*. Balai Penelitian Perikanan Budidaya Pantai, Maros, Indonesia.

Daud R, Tangko AM, Mansyur A, Sudradjat A (1993) Polyculture of sea cucumber, *Holothuria scabra* and seaweed, *Eucheuma* sp. in Sopura Bay, Kolaka Regency, southwest Sulawesi. In: *Prosiding Seminar Hasil Penelitian*, pp. 95–98.

Denton GRW, Morrison RJ, Bearden BG, Houk P, Starmer JA, Wood HR (2009) Impact of a coastal dump in a tropical lagoon on trace metal concentrations in surrounding marine biota: a case study from Saipan, Commonwealth of the Northern Mariana Islands (CNMI). *Marine Pollution Bulletin* **58**: 424–431.

Dong S, Fang J, Jansen H, Verreth J (2013) *Review on Integrated Mariculture in China, Including Case Studies on Successful Polyculture in Coastal Chinese Waters. Public report to support the application of multi-trophic aquaculture (IMTA)*, 39 pp.

Duan X, Zhang M, Mujumdar AS, Wang S (2010) Microwave freeze drying of sea cucumber (*Stichopus japonicus*). *Journal of Food Engineering* **96**: 491–497.

Duy NDQ (2012) Large-scale sandfish production from pond culture in Vietnam. In: Hair CA, Pickering TD, Mills DJ (eds) *Asia-Pacific Tropical Sea Cucumber Aquaculture*, pp. 34–39. ACIAR Proceedings No 136, Noumea, New Caledonia.

Eriksson H, Clarke S (2015) Chinese market responses to overexploitation of sharks and sea cucumbers. *Biological Conservation* **184**: 163–173.

Eriksson H, Robinson G, Slater MJ, Troell M (2012) Sea cucumber aquaculture in the Western Indian Ocean: challenges for sustainable livelihood and stock improvement. *Ambio* **41**: 109–121.

Fang J, Funderud J, Qi Z, Zhang J, Jiang Z (2009) Sea cucumbers enhance IMTA system with abalone, kelp in China. *Global Aquaculture Advocate* **12**, 49–51.

Felaco L (2014) *Evaluation of Multitrophic Biofiltration System With New Algae Species and the Sea Cucumber "Holothuria Sanctori"*. Universidad de las Palmas Gran Canaria, España, 69 pp.

Feng J-X, Gao Q-F, Dong S-L, Sun Z-L, Zhang K (2014) Trophic relationships in a polyculture pond based on carbon and nitrogen stable isotope analyses: a case study in Jinghai Bay, China. *Aquaculture* **428–429**: 258–264.

Ferdouse F (2004) World markets and trade flows of sea cucumber/beche-de-mer. In: Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel JF, Mercier A (eds) *Advances in Sea Cucumber Aquaculture and Management*, pp. 101–117. FAO, Rome.

Godfrey M (2015) Sea cucumber glut hurts Chinese producer's financials. Available from URL: http://www.seafoodsource.com/news/supply-trade/28165-sea-cucumber-glut-hurts-chinese-producer-s-financials?utm_source=Informz&utm_medium=Email&utm_campaign=eNewsletter#sthash.CsLolJnf.dpuf. Beijing, China.

Grant J, Hatcher A, Scott DB, Pocklington P, Schafer CT, Winters GV (1995) A multidisciplinary approach to evaluating impacts of shellfish aquaculture on benthic communities. *Estuaries* **18**: 124–144.

Hair CA, Pickering TD, Mills DJ (2012) Asia-Pacific Tropical Sea Cucumber Aquaculture: Proceedings of an International Symposium Held in Noumea, New Caledonia, 15-17 February, 2011. Australian Centre for International Agricultural Research, Noumea, New Caledonia, 209 pp.

Hamel J-F, Mercier A (2008) Population status, fisheries and trade of sea cucumbers in temperate areas of the Northern Hemisphere. In: Toral-Granda V, Lovatelli A, Vasconcellos M (eds) *Sea Cucumbers: A Global Review of Fisheries and Trade*, pp. 257–291. FAO, Rome.

Hannah L, Duprey N, Blackburn J, Hand CM, Pearce CM (2012) Growth rate of the California Sea cucumber *Parastichopus californicus*: measurement accuracy and relationships between size and weight metrics. *North American Journal of Fisheries Management* **32**: 167–176.

Hannah L, Pearce CM, Cross SF (2013) Growth and survival of California sea cucumbers (*Parastichopus californicus*) cultivated with sablefish (*Anoplopoma fimbria*) at an integrated multi-trophic aquaculture site. *Aquaculture* **406–407**: 34–42.

Hartstein ND, Rowden AA (2004) Effect of biodeposits from mussel culture on macroinvertebrate assemblages at sites of different hydrodynamic regime. *Marine Environmental Research* **57**: 339–357.

Hatcher A, Grant J, Schofield B (1994) Effects of suspended mussel culture (*Mytilus* spp.) on sedimentation, benthic respiration and sediment nutrient dynamics in a coastal bay. *Marine Ecology Progress Series* **115**: 219–235.

Hauksson E (1979) Feeding biology of *Stichopus tremulus*, a deposit-feeding holothurian. *Sarsia* **64**: 155–160.

Heath P, Stenton-Dozey J, Jeffs A (2015) Sea cucumber aquaculture in New Zealand. In: Brown N, Eddy S (eds) *Aquaculture of Echinoderms*. John Wiley and Sons, New York.

Hu J, Zhong Y, Wang L (1995) The technological research on shrimp and oyster mixed-culture in the penaeid pond. *Jang Xiamen Fisheries Collection* **17**: 22–26.

Imai T, Inaba D (1950) *On the Artificial Breeding of Japanese Sea-Cucumber, Stichopus Japonicus Selenka*. Tohoku University, Bull. Inst. Agricul. Res 2.

Ito S (1995) Studies on the technological development of the mass production for sea cucumber juvenile, *Stichopus japonicus*. *Bulletin of the Saga Prefectural Sea Farming Center* **4**: 1–87.

James DB (1999) Hatchery and culture technology for the sea cucumber, *Holothuria scabra* Jaeger, in India. *The ICLARM Quarterly* **22**: 12–16.

Ji T, Dong Y, Dong S (2008) Growth and physiological responses in the sea cucumber, *Apostichopus japonicus* Selenka: aestivation and temperature. *Aquaculture* **283**: 180–187.

Jimmy RA, Pickering TD, Hair CA (2012) Overview of sea cucumber aquaculture and stocking research in the Western Pacific region. In: Hair CA, Pickering TD, Mills DJ (eds) *Asia-Pacific Tropical Sea Cucumber Aquaculture*. ACIAR Proceedings No. 136, Noume, New Caledonia, pp. 12–21.

Jin Y-G, Oh B-S, Park M-W, Cho J-K, Jung C-K, Kim T-I (2011) Survival and growth of the abalone, *Haliotis discus* hannai and sea cucumber, *Stichopus japonicus* co-cultured in indoor tank. *The Korean Journal of Malacology* **27**: 331–336.

Jinadasa BKKK, Samanthi RI, Wicramsinghe I (2014) Trace Metal Accumulation in Tissue of Sea Cucumber Species; North-Western Sea of Sri Lanka. *American Journal of Public Health Research* **2**: 1–5.

Kang KH, Kwon JY, Kim YM (2003) A beneficial coculture: charm abalone *Haliotis discus hannai* and sea cucumber *Stichopus japonicus*. *Aquaculture* **216**: 87–93.

Kaspar HF, Gillespie PA, Boyer IC, MacKenzie AL (1985) Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepuru Sound, Marlborough Sounds, New Zealand. *Marine Biology* **85**: 127–136.

Kim T, Yoon H-S, Shin S, Oh M-H, Kwon I, Lee J *et al.* (2015) Physical and biological evaluation of co-culture cage systems for grow-out of juvenile abalone, *Haliotis discus hannai*, with juvenile sea cucumber, *Apostichopus japonicus* (Selenka), with CFD analysis and indoor seawater tanks. *Aquaculture* **447**: 86–111.

Kinch J (2005) National Report-Papua New Guinea. In: Bruckner A (ed) *The Proceedings of the Technical Workshop on the Conservation of Sea Cucumbers in the Families Holothuridae and Stichopodidae*. NOAA Technical Memorandum NMFS-OPR, pp. 218–225.

Kinch J, Purcell S, Uthicke S, Friedman K (2008) Population status, fisheries and trade of sea cucumbers in the Western Central Pacific. In: Toral-Granda V, Lovatelli A, Vasconcellos M (eds) *Sea Cucumbers: A Global Review of Fisheries and Trade*, pp. 7–55. FAO, Rome.

Lawrence JM (1982) Digestion. In: Jangoux M, Lawrence JM (eds) *Echinoderm Nutrition*, pp. 283–316. A.A. Balkema, Rotterdam.

Leber KM, Kitada S, Blankenship HL, Svasand T (2004) *Stock Enhancement and Sea Ranching: Developments*. Blackwell Publishing, Oxford, UK, Pitfalls and Opportunities.

Lee M-H, Kim Y-K, Moon HS, Kim K-D, Kim G-G, Cho H-A *et al.* (2012) Comparison on proximate composition and nutritional profile of red and black sea cucumbers (*Apostichopus japonicus*) from Ulleungdo (Island) and Dokdo (Island), Korea. *Food Science and Biotechnology* **21**: 1285–1291.

Levin V (2000) *Japanese Sea Cucumber: Biology, Fisheries, Cultivation*. Saint Petersburg, Goland, 200 pp.

Li S, Wang L, Gao Y, Wang D, Li J, Chang Z (2001) Co-culture technique of abalone with sea cucumber in the intertidal ponds. *Chinese Journal of Aquaculture* **3**: 15–17.

Li J, Dong S, Gao Q, Wang F, Tian X, Zhang S (2014a) Total organic carbon budget of integrated aquaculture system of sea cucumber *Apostichopus japonicus*, jellyfish *Rhopilema esculenta* and shrimp *Fenneropenaeus chinensis*. *Aquaculture Research* **45**: 1825–1831.

Li J, Dong S, Gao Q, Zhu C (2014b) Nitrogen and phosphorus budget of a polyculture system of sea cucumber (*Apostichopus japonicus*), jellyfish (*Rhopilema esculenta*) and shrimp (*Fen-

neropenaeus chinensis). *Journal of Ocean University of China* **13**: 503–508.

Lin ZQ (2005) Abalone culture 2: polyculture of abalone and sea cucumber (Apostichopus japonicus) in raft cages. *China Fisheries* **2**: 54–55.

Lin CK, Ruamthaveesub P, Wanuchsoontorn P, Pokaphand C (1992) Integrated culture of green mussel (*Perna viridis*) and marine shrimp (*Penaeus monodon*). *Journal of Shellfish Research* **11**: 201.

Lin G, Ji Y, Gou J, Sun G (1993) Studies on over-wintering technic of polyculture abalone and sea cucumber by means of cooling seawater from coastal power plant. *Marine Sciences* **1**: 4–7.

Liu G, Ding Z, Sun X (2009) Polyculture of abalone and sea cucumber in raft cages at Haizhou Bay. *Shandong Fisheries* **26**: 28–29.

Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel J-F, Mercier A (2004) *Advances in Sea Cucumber Aquaculture and Management*. FAO, Rome, 425 pp.

Lutz CG (2003) Polyculture: principles, practices, problems and promise. *Aquaculture Magazine* **29**: 34–39.

MacDonald CLE, Stead SM, Slater MJ (2013) Consumption and remediation of European Seabass (*Dicentrarchus labrax*) waste by the sea cucumber *Holothuria forskali*. *Aquaculture International* **21**: 1279–1290.

Macías JC, Aguado F, González N, Guerrero S, Estévez A, Valencia JM *et al.* (2008) Acuicultura Integrada: desarrollo de experiencias de cultivos multitróficos en la costa española. *Foro dos Recursos Mariños e da Acuicultura das Rías Galegas* **10**: 483–490.

MacTavish T, Stenton-Dozey J, Vopel K, Savage C (2012) Deposit-feeding sea cucumbers enhance mineralization and nutrient cycling in organically-enriched coastal sediments. *PLoS ONE* **7**: 1–11.

Madeali MI, Tangko AM, Pantai DER, Maros B (1993) Polyculture of sea cucumber, *Holothuria scabra* and seaweed, *Eucheuma cottoni* in Battoa waters, Polmas Regency, South Sulawesi. *Prosiding Seminar Hasil Penelitian*, pp. 105–109.

Maltrain R (2007) *Crecimiento de Athyonidium Chilensis (Semper, 1868) (Echinodermata: Holothuroidea) en Cautiverio y Policultivo con Eurhomalea Lenticularis (Sowerby, 1835)*. Facultad de Ciencias del Mar, Universidad Católica del Norte, Coquimbo, 59 pp.

Massin C, Doumen C (1986) Distribution and feeding of epibenthic holothuroids on the reef flat of Laing Island (Papua-New-Guinea). *Marine Ecology Progress Series* **31**: 185–195.

Maxwell K, Gardner J, Heath P (2009) The effect of diet on the energy budget of the brown sea cucumber, *Stichopus mollis* (Hutton). *Journal of the World Aquaculture Society* **40**: 157–170.

McPhee D, Donaghy T, Duhaime J, Parsons GJ (2015) *Canadian Aquaculture R&D Review 2015*, 122 pp.

Mente E, Pierce GJ, Santos MB, Neofitou C (2006) Effect of feed and feeding in the culture of salmonids on the marine aquatic environment: a synthesis for European aquaculture. *Aquaculture International* **14**: 499–522.

Mercier A, Ycaza RH, Espinoza R, Arriaga-Haro VM, Hamel J-F (2012) Hatchery experience and useful lessons from *Isostichopus fuscus* in Ecuador and Mexico. In: Hair CA, Pickering TD, Mills DJ (eds) *Asia-Pacific Tropical Sea Cucumber Aquaculture*. ACIAR Proceedings No. 136, Noume, New Caledonia, pp. 79–90.

Michio K, Kengo K, Yasunori K, Hitoshi M, Takayuki Y, Hideaki Y *et al.* (2003) Effects of deposit feeder *Stichopus japonicus* on algal bloom and organic matter contents of bottom sediments of the enclosed sea. *Marine Pollution Bulletin* **47**: 118–125.

Mills DJ, Duy NDQ, Juinio-Meñez MA, Raison CM, Zarate JM (2012) Overview of sea cucumber aquaculture and sea-ranching research in the South-East Asian region. In: Hair CA, Pickering TD, Mills DJ (eds) *Asia-Pacific Tropical Sea Cucumber Aquaculture*. ACIAR Proceedings No. 136, Noumea, New Caledonia, pp. 22–31.

Moriarty DJW (1982) Feeding of *Holothuria atra* and *Stichopus chloronotus* on bacteria, organic carbon and organic nitrogen in sediments of the Great Barrier Reef. *Marine and Freshwater Research* **33**: 255–263.

Muliani (1993) Effect of different supplemental feeds and stocking densities on the growth rate and survival of sea cucumber, *Holothuria scabra* in Tallo river mouth, South Sulawesi. *Journal Penelitian Budidaya Pantai* **9**: 15–22.

Navarro PG, García-Sanz S, Barrio JM, Tuya F (2013) Feeding and movement patterns of the sea cucumber *Holothuria sanctori*. *Marine Biology* **160**: 2957–2966.

Nelson EJ, MacDonald BA, Robinson SMC (2012a) The absorption efficiency of the suspension-feeding sea cucumber, *Cucumaria frondosa*, and its potential as an extractive integrated multi-trophic aquaculture (IMTA) species. *Aquaculture* **370–371**: 19–25.

Nelson EJ, MacDonald BA, Robinson SMC (2012b) A Review of the Northern Sea Cucumber *Cucumaria frondosa* (Gunnerus, 1767) as a Potential Aquaculture Species. *Reviews in Fisheries Science* **20**: 212–219.

Olvera-Novoa M, Martinez-Millan G, Sanchez-Tapia I (2014) Advances and challenges of sea cucumber *Isostichopus badionotus* farming in Yucatan, Mexico. World Aquaculture Society Conference, Adelaide, Australia.

Paltzat DL, Pearce CM, Barnes PA, McKinley RS (2008) Growth and production of California sea cucumbers (*Parastichopus californicus* Stimpson) co-cultured with suspended Pacific oysters (*Crassostrea gigas* Thunberg). *Aquaculture* **275**: 124–137.

Pham TD, Do HH, Hoang TD, Vo THT (2004) Combined culture of mussel: a tool for providing live feed and improving environmental quality for lobster aquaculture in Vietnam. In: Williams KC (ed) *Spiny Lobster Ecology and Exploitation in the South China Sea Region*, pp. 57–58. Institute of Oceanography, Nha Trang, Vietnam.

Pham TD, Do HH, Hoang TD, Vo THT (2005) The results of the experimental study on combined culture of mussel *Perna* *viridis* with lobster at Xuan Tu (Van Ninh, Khanh Hoa). *Journal of Marine Science and Technology*.

Pietrak M, Kim JK, Redmond S, Kim Y-D, Yarish C, Bricknell I (2014) *Culture of Sea Cucumbers in Korea: A Guide to Korean Methods and the Local Sea Cucumber in the Northeast U.S.* Maine Sea Grant College Program, Orono, ME.

Pitt R, Duy NDQ (2004) Breeding and rearing of the sea cucumber *Holothuria scabra* in Viet Nam. In: Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel J-F, Mercier A (eds) *Advances in Sea Cucumber Aquaculture and Management*, pp. 333–346. FAO, Rome.

Pitt R, Duy NDQ, Duy TV, Long HTC (2004) Sandfish (*Holothuria scabra*) with shrimp (*Penaeus monodon*) co-culture tank trials. *SPC Beche-de-mer Information Bulletin* **20**: 12–22.

Purcell SW (2004) Rapid growth and bioturbation activity of the sea cucumber *Holothuria scabra* in earthen ponds. *Proceedings of Australasian Aquacuzrlture* **1**: 244.

Purcell SW (2014a) *Processing Sea Cucumbers Into Beche-de-mer: A Manual for Pacific Island Fishers,* . Southern Cross University, Lismore, and the Secretariat of the Pacific Community, Noumea, New Caledonia, 44 pp.

Purcell SW (2014b) Value, Market Preferences and Trade of Beche-De-Mer from Pacific Island Sea Cucumbers. *PLoS ONE* **9**: e95075.

Purcell SW, Blockmans BF (2009) Effective fluorochrome marking of juvenile sea cucumbers for sea ranching and restocking. *Aquaculture* **296**: 263–270.

Purcell SW, Blockmans BF, Nash WJ (2006a) Efficacy of chemical markers and physical tags for large-scale release of an exploited holothurian. *Journal of Experimental Marine Biology and Ecology* **334**: 283–293.

Purcell SW, Patrois J, Fraisse N (2006b) Experimental evaluation of co-culture of juvenile sea cucumbers, *Holothuria scabra* (Jaeger), with juvenile blue shrimp, *Litopenaeus stylirostris* (Stimpson). *Aquaculture Research* **37**: 515–522.

Purcell SW, Lovatelli A, Vasconcellos M, Yimin Y (2010) *Managing Sea Cucumber Fisheries With an Ecosystem Approach*. FAO, Rome, 157 pp.

Purcell SW, Hair CA, Mills DJ (2012a) Sea cucumber culture, farming and sea ranching in the tropics: progress, problems and opportunities. *Aquaculture* **368–369**: 68–81.

Purcell SW, Samyn Y, Conand C (2012b) *Commercially Important Sea Cucumbers of the World*. FAO, Rome, 150 pp.

Purcell SW, Mercier A, Conand C, Hamel J-F, Toral-Granda MV, Lovatelli A *et al.* (2013) Sea cucumber fisheries: global analysis of stocks, management measures and drivers of overfishing. *Fish and Fisheries* **14**: 34–59.

Qi Z, Wang J, Mao Y, Liu H, Fang J (2013) Feasibility of Offshore Co-culture of Abalone, Haliotis discus hannai Ino, and Sea Cucumber, Apostichopus japonicus, in a Temperate Zone. *Journal of the World Aquaculture Society* **44**: 565–573.

Qin C, Dong S, Tan F, Tian X, Wang F, Dong Y *et al.* (2009) Optimization of stocking density for the sea cucumber, *Apostichopus japonicus* Selenka, under feed-supplement and non-feed-supplement regimes in pond culture. *Journal of Ocean University of China* **8**: 296–302.

Rachmansyah, Madeali MI, Tangko AM, Tonnek S, Ismail DA (1992) Polyculture of sea cucumber, *Holothuria scabra* and seaweed, *Eucheuma* sp. in pen culture at Parepare Bay, South Sulawesi. *Journal Penelitian Budidaya Pantai* **8**: 63–70.

Ramón M, Lleonart J, Massutí E (2010) Royal cucumber (*Stichopus regalis*) in the northwestern Mediterranean: distribution pattern and fishery. *Fisheries Research* **105**: 21–27.

Ren Y, Dong S, Wang F, Gao Q, Tian X, Liu F (2010) Sedimentation and sediment characteristics in sea cucumber *Apostichopus japonicus* (Selenka) culture ponds. *Aquaculture Research* **42**: 14–21.

Ren JS, Stenton-Dozey J, Plew DR, Fang J, Gall M (2012a) An ecosystem model for optimising production in integrated multitrophic aquaculture systems. *Ecological Modelling* **246**: 34–46.

Ren Y, Dong S, Chuanxin Q, Wang F, Tian X, Gao Q (2012b) Ecological effects of co-culturing sea cucumber *Apostichopus japonicus* (Selenka) with scallop *Chlamys farreri* in earthen ponds. *Chinnese Journal of Oceanology and Limnology* **30**: 71–79.

Ren Y, Dong S, Wang X, Gao Q, Jiang S (2014) Beneficial co-culture of jellyfish *Rhopilema esculenta* (Kishinouye) and sea cucumber *Apostichopus japonicus* (Selenka): implications for pelagic-benthic coupling. *Aquaculture Research* **45**: 177–187.

Roberts D, Bryce C (1982) Further observations on tentacular feeding mechanisms in holothurians. *Journal of Experimental Marine Biology and Ecology* **59**: 151–163.

Roberts D, Gebruk A, Levin V, Manship BAD (2000) Feeding and digestive strategies in deposit-feeding holothurians. *Oceanography and Marine Biology: An Annual Review* **38**: 257–310.

Rombenso AN, Lisboa V, Sampaio LA (2014) Mariculture in Rio de Janeiro, Brazil: an approach to IMTA. In: *World Aquaculture Society Conference*. WAS, Adelaide, Australia.

Schneider K, Silverman J, Woolsey E, Eriksson H, Byrne M, Caldeira K (2011) Potential influence of sea cucumbers on coral reef $CaCO_3$ budget: a case study at One Tree Reef. *Journal of Geophysical Research: Biogeosciences (2005–2012)* **116**: 6.

Seo Y, Shin I, Lee S (2011) Effect of dietary inclusion of various ingredients as an alternative for *Sargassum thunbergii* on growth and body composition of juvenile sea cucumber *Apostichopus japonicus*. *Aquaculture Nutrition* **17**: 549–556.

Shpigel M, Blaylock RA (1991) The Pacific oyster, *Crassostrea gigas*, as a biological filter for a marine fish aquaculture pond. *Aquaculture* **92**: 187–197.

Sicuro B, Piccinno M, Gai F, Abete MC, Danieli A, Dapra F *et al.* (2012) Food quality and safety of Mediterranean sea cucumbers *Holothuria tubulosa* and *Holothuria polli* in Southern Adriatic Sea. *Asian Journal of Animal and Veterinary Advances* **7**: 851–859.

Simon C, Martin GS, Robinson G (2014) Two new species of *Syllis* (Polychaeta: Syllidae) from South Africa, one of them viviparous, with remarks on larval development and vivipary.

Journal of the Marine Biological Association of the United Kingdom **94**: 729–746.

Skewes T, Dennis D, Burridge CM (2000) Survey of *Holothuria scabra* (sandfish) on Warrior Reef, Torres Strait. Report to Queensland Fisheries Management Authority, Queensland, Australia.

Slater MJ, Carton AG (2007) Survivorship and growth of the sea cucumber *Australostichopus* (*Stichopus*) *mollis* (Hutton 1872) in polyculture trials with green-lipped mussel farms. *Aquaculture* **272**: 389–398.

Slater MJ, Carton AG (2009) Effect of sea cucumber (*Australostichopus mollis*) grazing on coastal sediments impacted by mussel farm deposition. *Marine Pollution Bulletin* **58**: 1123–1129.

Slater MJ, Carton AG (2010) Sea cucumber habitat differentiation and site retention as determined by intraspecific stable isotope variation. *Aquaculture Research* **41**: 695–702.

Slater MJ, Jeffs AG, Carton AG (2009) The use of the waste from green-lipped mussels as a food source for juvenile sea cucumber, *Australostichopus mollis*. *Aquaculture* **292**: 219–224.

Slater MJ, Carton AG, Jeffs AG (2010) Highly localised distribution patterns of juvenile sea cucumber *Australostichopus mollis*. *New Zealand Journal of Marine and Freshwater Research* **44**: 201–216.

Slater MJ, Mgaya YD, Mill AC, Rushton SP, Stead SM (2013) Effect of social and economic drivers on choosing aquaculture as a coastal livelihood. *Ocean & Coastal Management* **73**: 22–30.

Stenton-Dozey J (2007a) Finding hidden treasure in aquaculture waste. *Water Atmosphere* **15**: 9–11.

Stenton-Dozey J (2007b) Tagging sea cucumbers. *Water Atmosphere* **15**: 6.

Stenton-Dozey J, Heath P (2009) A first for New Zealand: culturing our endemic sea cucumber for overseas markets. *Water Atmosphere* **17**: 1–2.

Sun H, Liang M, Yan J, Chen B (2004) Nutrient requirements and growth of the sea cucumber, *Apostichopus japonicus*. In: Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel J-F, Mercier A (eds) *Advances in Sea Cucumber Aquaculture and Management*, pp. 327–332. FAO, Rome.

Swingle HS (1968) Biological means of increasing productivity in ponds. *FAO Fisheries Report* **44**: 243–257.

Tangko AM, Madeali MI, Ratnawati E, Danakusumah E, Suwardi (1993a) Polyculture of sea cucumber, *Holothuria scabra* and seaweed, *Gracilaria* sp. in Luki waters, Kolaka Regency, Southeast Sulawesi. *Prosiding Seminar Hasil Penelitian* **11**: 91–94.

Tangko AM, Rachmansyah AM, Madeali MI, Tonnek S, Ismail A (1993b) Polyculture of sea cucumber, *Holothuria scabra* and seaweed, Eucheuma sp. in Sanisani Bay waters, Kolaka Regency, Southeast Sulawesi. *Prosiding Seminar Hasil Penelitian* **11**: 85–89.

Toral-Granda MV (2005) Requiem for the Galápagos sea cucumber fishery. *SPC Beche-de-Mer Information Bulletin* **21**: 5–8.

Toral-Granda V (2008) Population status, fisheries and trade of sea cucumbers in Latin America and the Caribbean. In: Toral-Granda V, Lovatelli A, Vasconcellos M (eds) *Sea Cucumbers: A Global Review of Fisheries and Trade*, pp. 213–229. FAO, Rome.

Toral-Granda V, Lovatelli A, Vasconcellos M (2008) *Sea Cucumbers: A Global Review of Fisheries and Trade*. FAO Fisheries and Aquaculture Technical Paper No. 516. FAO, Rome, 317 pp.

Troell M (2009) Integrated marine and brackishwater aquaculture in tropical regions: research, implementation and prospects. *Integrated Mariculture: A Global Review*, pp. 47–131. FAO, Rome.

Uthicke S (1999) Sediment bioturbation and impact of feeding activity of *Holothuria* (*Halodeima*) *atra* and *Stichopus chloronotus*, two sediment feeding holothurians, at Lizard Island, Great Barrier Reef. *Bulletin of Marine Science* **64**: 129–141.

Uthicke S (2001) Nutrient regeneration by abundant coral reef holothurians. *Journal of Experimental Marine Biology and Ecology* **265**: 153–170.

Uthicke S (2004) Overfishing of holothurians: lessons from the Great Barrier Reef. In: Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel J-F, Mercier A (eds) *Advances in Sea Cucumber Aquaculture and Management*, pp. 163–171. FAO, Rome.

Uthicke S, Conand C (2005) Local examples of beche-de-mer overfishing: an initial summary and request for information. *SPC Beche-de-mer Information Bulletin* **21**: 9–14.

Uthicke SS, Klumpp DDW (1998) Microphytobenthos community production at a nearshore coral reef: seasonal variation and response to ammonium recycled by holothurians. *Marine Ecology Progress Series* **169**: 1–11.

Van Dover CL, Grassle JF, Fry B, Garritt RH, Starczak VR (1992) Stable isotope evidence for entry of sewage-derived organic material into a deep-sea food web. *Nature* **360**: 153–156.

Vannuccini S (2004) Sea cucumbers: a compendium of fishery statistics. In: Lovatelli A, Conand C, Purcell S, Uthicke S, Hamel J-F, Mercier A (eds) *Advances in Sea Cucumber Aquaculture and Management*, pp. 399–412. FAO, Rome.

Wang J-Q, Cheng X, Yang Y, Wang N-B (2007a) Polyculture of juvenile sea urchin (*Strongylocentrotus intermedius*) with juvenile sea cucumber (*Apostichopus japonicus* Selenka) at various stocking densities. *Journal of Dalian Fisheries University* **2**: 102–108.

Wang J-Q, Yang Y, Cheng X, Wang N-B, Zhang J-C (2007b) Polyculture of juvenile abalone (*Haliotis discus hannai* Ino) with juvenile sea cucumber (*Apostichopus japonicus* Selenka) at various stocking densities. *Modern Fisheries Information* **10**: 3–7.

Wang J-Q, Yang Y, Cheng X, Wang N-B, Zhang J-C (2007c) Polyculture of juvenile abalone with juvenile sea cucumber at various stocking densities. *Fishery Modernization* **5**: 34–37.

Wang J-Q, Cheng X, Gao Z-Y, Chi W, Wang N-B (2008) Primary results of polyculture of juvenile sea cucumber

(*Apostichopus japonicus* Selenka) with juvenile sea urchin (*Strongylocentrotus intermedius*) and manila clam (*Ruditapes philippinarum*). *Journal of Fisheries of China* **5**: 740–747.

Warnau M, Dutrieux S, Ledent G, Rodriguez y Baena AM, Dúbois P (2006) Heavy metals in the sea cucumber *Holothuria tubulosa* (Echinodermata) from the Mediterranean *Posidonia oceanica* ecosystem: body compartment, seasonal, geographical and bathymetric variations. *Environmental Bioindicators* **1**: 268–285.

Watanabe S, Kodama M, Zarate JM, Lebata-Ramos MJH, Nievales MFJ (2012) Ability of sandfish (*Holothuria scabra*) to utilise organic matter in black tiger shrimp ponds. In: Hair CA, Pickering TD, Mills DJ (eds) *Asia-Pacific Tropical Sea Cucumber Aquaculture*. ACIAR Proceedings No. 136, Noumea, New Caledonia, pp. 113–120.

Webb KL, D'Elia CF, Dupaul WD (1977) Biomass and nutrition flux measurements on *Holothuria atra* populations on windward reef flats at Enewetak, Marshall Islands. In: Taylor DL (ed) *Third International Coral Reef Symposium, Miami, Florida*, pp. 410–441.

Wen J, Hu C, Fan S (2010) Chemical composition and nutritional quality of sea cucumbers. *Journal of the Science of Food and Agriculture* **90**: 2469–2474.

Wu RSS (1995) The environmental impact of marine fish culture: towards a sustainable future. *Marine Pollution Bulletin* **31**: 159–166.

Xu G, Zhu S (2002) Technique for polyculture of shrimp and sea cucumber. *China Fisheries* **6**: 42–43.

Yang H-S, Zhou Y, Wang J, Zhang T, Wang P, He Y-C *et al.* (1999) A modelling estimation of carrying capacities for *Chlamys farreri*, *Laminaria japonica* and *Apostichopus japonicus* in Sishilivan Bay, Yarntai, China. *Journal of Fishery Sciences of China* **7**: 27–31.

Yang H, Hamel J-F, Mercier A (2015) *The Sea Cucumber Apostichopus japonicus. History, Biology and Aquaculture*. Academic Press (Elsevier), Salt Lake City, UT, 437 pp.

Yokoyama H (2013) Growth and food source of the sea cucumber *Apostichopus japonicus* cultured below fish cages – potential for integrated multi-trophic aquaculture. *Aquaculture* **372–375**: 28–38.

Yokoyama H (2015) Suspended culture of the sea cucumber *Apostichopus japonicus* below a Pacific oyster raft – potential for integrated multi-trophic aquaculture. *Aquaculture Research* **46**: 825–832.

Yokoyama H, Tadokoro D, Miura M (2015) Quantification of waste feed and fish faeces in sediments beneath yellowtail pens and possibility to reduce waste loading by co-culturing with sea cucumbers: an isotopic study. *Aquaculture Research* **46**: 918–927.

Yu Z, Hu C, Zhou Y, Li H, Peng P (2012) Survival and growth of the sea cucumber *Holothuria leucospilota* Brandt: a comparison between suspended and bottom cultures in a subtropical fish farm during summer. *Aquaculture Research* **44**: 114–124.

Yu Z, Zhou Y, Yang H, Ma Y, Hu C (2014) Survival, growth, food availability and assimilation efficiency of the sea cucumber *Apostichopus japonicus* bottom-cultured under a fish farm in southern China. *Aquaculture* **426–427**: 238–248.

Yuan X, Yang H, Zhou Y, Mao Y, Zhang T, Liu Y (2006) The influence of diets containing dried bivalve feces and/or powdered algae on growth and energy distribution in sea cucumber *Apostichopus japonicus* (Selenka) (Echinodermata: Holothuroidea). *Aquaculture* **256**: 457–467.

Yuan XT, Yang HS, Zhou Y, Mao YZ, Xu Q, Wang LL (2008) Bioremediation potential of *Apostichopus japonicus* (Selenka) in coastal bivalve suspension aquaculture system. *Chinese Journal of Applied Ecology* **19**: 866–872.

Yuan XT, Wang LL, Yang HS, Yang DZ (2012) Bio-scavenging on self-pollutants with different carbon and nitrogen loads from a raft bivalve and macroalgae culture system by the deposit-feeding sea cucumber *Apostichopus japonicus* Selenka. *Chinese Journal of Ecology* **31**: 374–380.

Yuan X, Yang H, Meng L, Wang L, Li Y (2013) Impacts of temperature on the scavenging efficiency by the deposit-feeding holothurian *Apostichopus japonicus* on a simulated organic pollutant in the bivalve–macroalgae polyculture from the perspective of nutrient budgets. *Aquaculture* **406–407**: 97–104.

Yuan X, Zhou Y, Mao Y (2015) *Apostichopus japonicus*: a key species in integrated polyculture systems. In: Hongsheng Y, Jean-François H, Annie M (eds) *The Sea Cucumber Apostichopus japonicus. History, Biology and Aquaculture*, pp. 323–332. Academic Press (Elsevier), Salt Lake City, UT.

Yuan X, Meng L, Wang L, Zhao S, Li H (2016) Responses of scallop biodeposits to bioturbation by a deposit-feeder *Apostichopus japonicus* (Echinodermata: Holothuroidea): does the holothurian density matter? *Aquaculture Research* **47**: 512–523.

Zamora LN, Jeffs AG (2011) Feeding, selection, digestion and absorption of the organic matter from mussel waste by juveniles of the deposit-feeding sea cucumber, *Australostichopus mollis*. *Aquaculture* **317**: 223–228.

Zamora LN, Jeffs AG (2012a) The ability of the deposit-feeding sea cucumber *Australostichopus mollis* to use natural variation in the biodeposits beneath mussel farms. *Aquaculture* **326–329**: 116–122.

Zamora LN, Jeffs AG (2012b) Feeding, metabolism and growth in response to temperature in juveniles of the Australasian sea cucumber, *Australostichopus mollis*. *Aquaculture* **358–359**: 92–97.

Zamora LN, Jeffs AG (2013) A Review of the Research on the Australasian Sea Cucumber, *Australostichopus mollis* (Echinodermata: Holothuroidea) (Hutton 1872), with Emphasis on Aquaculture. *Journal of Shellfish Research* **32**: 613–627.

Zamora LN, Jeffs AG (2015) Macronutrient selection, absorption and energy budget of juveniles of the Australasian sea cucumber, *Australostichopus mollis*, feeding on mussel biodeposits at different temperatures. *Aquaculture Nutrition* **21**: 162–172.

Zamora LN, Dollimore J, Jeffs AG (2014) Feasibility of co-culture of the Australasian sea cucumber (*Australostichopus mol-*

lis) with the Pacific oyster (*Crassostrea gigas*) in northern New Zealand. *New Zealand Journal of Marine and Freshwater Research* **48**: 394–404.

Zhang Q, Wang L, Li S, Song Y, Wang D, Zhang J *et al.* (1990) Studies on co-cultured technique of bivalves and sea cucumber in lantern nets. *Marine Sciences* **5**: 63–67.

Zhang Q, Wang X, Zhang B, Jiang K (1993) Studies on co-cultured technique of abalone and sea cucumber. *Marine Sciences* **2**: 5–6.

Zhang L, Gao Y, Zhang T, Yang H, Xu Q, Sun L *et al.* (2014) A new system for bottom co-culture of the scallop, *Patinopecten yessoensis*, with the sea cucumber, *Apostichopus japonicus*, and the sea urchin, *Anthocidaris crassispina*, in shallow water in China. *Aquaculture International* **22**: 1403–1415.

Zhang L, Song X, Hamel J-F, Mercier A (2015) Auqaculture, stock enhancement, and restocking. In: Hongsheng Y, Jean-François H, Annie M (eds) *The Sea Cucumber Apostichopus japonicus. History, Biology and Aquaculture*, pp. 289–322. Academic Press (Elsevier), Salt Lake City, UT.

Zheng Z, Dong S, Tian X, Wang F, Gao Q, Bai P (2009) Sediment-water Fluxes of Nutrients and Dissolved Organic Carbon in Extensive Sea Cucumber Culture Ponds. *CLEAN – Soil, Air, Water* **37**: 218–224.

Zhong Y, Khan MA, Shahidi F (2007) Compositional characteristics and antioxidant properties of fresh and processed sea cucumber (*Cucumaria frondosa*). *Journal of Agricultural and Food Chemistry* **55**: 1188–1192.

Zhou Y, Yang H, Liu S, Yuan X, Mao Y, Liu Y *et al.* (2006) Feeding and growth on bivalve biodeposits by the deposit feeder *Stichopus japonicus* Selenka (Echinodermata: Holothuroidea) co-cultured in lantern nets. *Aquaculture* **256**: 510–520.