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

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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).

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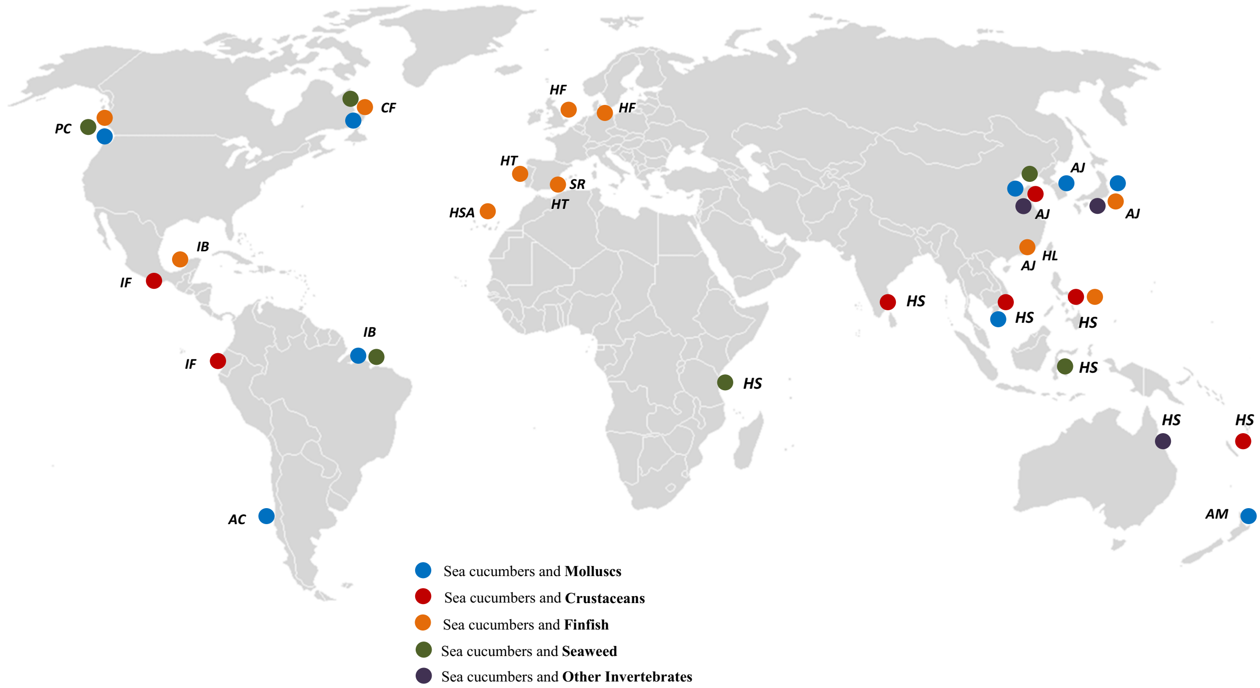

Figure 1 Global distribution of sea cucumber IMTA efforts (Mostly experimental coastal- and land-based systems). AC, *Athyonidium chilensis*; AJ, *Apostichopus japonicus*; AM, *Australostichopus mollis*; CF, *Cucumaria frondosa*; HF, *Holothuria forskali*; HL, *Holothuria leucospilota*; HSA, *Holothuria 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

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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

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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

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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).

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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

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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

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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

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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 over-

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whelmed 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.*

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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.

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