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Role of deposit feeders in integrated multi-trophic aquaculture — A model analysis

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ABSTRACT

The performance of deposit feeders in integrated multi-trophic aquaculture (IMTA) was analysed through the application of mathematical models. Loading of organic particulates to the benthos as a result of finfish cage culture and shellfish suspended culture was analysed by means of a deposition model (ORGANIX), and an individual model for growth and environmental effects was developed for the California sea cucumber *Parastichopus californicus*. Following validation, the model was combined with existing models for finfish, shellfish, and macroalgae into a framework for simulation of IMTA interactions at the local scale. Several scenarios for different culture combinations and densities were simulated using the Farm Aquaculture Resource Management (FARM) model, using a layout which reflects typical stocking densities and spatial occupation in Europe and North America. The model allows an analysis of the different sources and fate of particulate organic matter associated with distinct culture groups. Our results illustrate the production enhancement for deposit feeders cultivated below both finfish (600%) and shellfish (150%). Furthermore, sea cucumbers are responsible for a significant removal of the particulate organic carbon loading to the bottom, reducing the gross load by up to 86% for finfish culture and 99% for shellfish culture. The role of cultivated seaweeds in reducing the dissolved nitrogen concentration in the farm area was also examined—no significant reduction in ambient nutrient concentration was observed, but the added nitrogen provides a clear stimulus (22% increase) to kelp production. By contrast, shellfish grown in suspended culture in the vicinity of finfish cages show very little change in individual growth or harvestable biomass. This work helps to analyse the ecological and economic potential of various forms of IMTA, and the role of co-cultivation in direct extraction and re-use of materials and energy at both the local (farm) and system (bay, estuary) scales.

Statement of relevance: Analysis of the ecological and economic potential of various forms of IMTA, and the relevance of co-cultivation in direct extraction and re-use of materials and energy at both the local (farm) and system (bay, estuary) scales. FARM model framework applied to understand the roles of suspended bivalve culture and benthic deposit-feeder culture in mitigating the negative externalities of finfish culture.

1. Introduction

Marine finfish aquaculture is expected to increase significantly in the coming decades to help feed a rapidly expanding human population (FAO/NACA, 2012). Many of the production areas in Southeast Asia, China, and South America are already at or approaching carrying capacity (Ross et al., 2013), while a combination of factors including food security, trade balance, and a focus on locally-sourced products drives predicted expansion in Europe and North America. This has stimulated debate on site selection and carrying capacity for development of intensive finfish culture—one of the major issues is the accumulation of wastes. Inorganic waste from fed aquaculture in open water cages tends to disperse over a broad area, but the organic component is deposited relatively near the culture units (Mente et al., 2006).

The accumulation of waste feed and faeces below finfish cages may alter the physical and chemical environment of the water column and seabed, potentially leading to important ecological and economic consequences for both the farmed species and the benthic environment (Brooks et al., 2003; Kalantzi and Karakassis, 2006; Soto, 2009), including decreased yields of cultivated species and reduction of biodiversity (Kinoshita et al., 2008; Sanz-Lázaro and Marín, 2011; Stigebrandt, 2011).

In order to expand, the aquaculture sector needs to develop innovative, responsible, sustainable, and profitable practices which should be ecologically-efficient, environmentally-benign, product-diversified,

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and societally-beneficial (Chopin, 2013). Integrated multi-trophic aquaculture (IMTA) promotes the re-use of materials across different trophic groups and has received increasing attention over the last decade as a tool for improving sustainability of fed aquaculture (Chopin et al., 2012; Costa-Pierce, 2008; Nelson et al., 2012a; Neori et al., 2007; Troell et al., 2009).

IMTA aims to diversify fed aquaculture (e.g. finfish or shrimp) with extractive aquaculture, recapturing the inorganic (e.g. through seaweeds) and organic (through suspension feeders and deposit feeders) nutrients from fed aquaculture for the growth of co-cultured species of commercial value (Chopin et al., 2012; Neori et al., 2007). This has been practised in pond culture in Asia for thousands of years (Moo, undated), but the successful utilization of aquaculture-generated organic particles as a food source for marine bivalves cultured in open-water IMTA systems is limited by the time available to intercept solid wastes contained in the horizontal particle flux and the size range and concentration of these particles (Cheshuk et al., 2003; Cranford et al., 2013; Troell et al., 2011). Physiological model estimates suggest that salmon aquaculture solids would need to comprise at least 10–20% of a mussel's total diet to contribute to a net decrease in the organic loading from an IMTA site (Reid et al., 2013a).

Some data suggest that a correct design of IMTA sites could improve this situation and, indeed, mussels grown very close to fish farms were capable of ingesting at least 20% of their diet from fish-derived sources (Lander et al., 2012, Reid et al., 2013b). But to date, studies addressing the possible synergistic growth effects of IMTA systems on bivalves have yielded contradictory results. Several studies have provided evidence for growth benefits to shellfish or evidence of organic uptake from the farm in open-water IMTA systems (Handå et al., 2012; Jiang et al., 2013; Lander et al., 2012; Peharda et al., 2007), while other studies reported no significant effect (Cheshuk et al., 2003; Irisarri et al., 2013; Navarrete-Mier et al., 2010; Parsons et al., 2002). Because of this variability, the effectiveness of multi-trophic culture has been shown mainly in inland ponds where the food link between both trophic levels is more straightforward (Purcell et al., 2006; Slater and Carton, 2009; Yuan et al., 2013) and, except in the extremely high culture density situations typical of Southeast Asia, it is challenging to establish the benefits of IMTA in open-water or coastal farms (Ferreira et al., 2012).

Moreover, the net ecological benefit from the shellfish component of IMTA for reducing benthic organic enrichment to the benthos has not been clearly demonstrated (Department of Fisheries and Oceans Canada, 2013). Based on available data, it is very unlikely that using only fine-particulate filter feeders in IMTA will significantly reduce organic loading underneath cage operations and subsequent impacts to the benthos (Department of Fisheries and Oceans Canada, 2013). A benthic component of deposit feeders that can utilize the vertical fluxes of organic matter to the seabed from fish and shellfish farms may therefore be an important stage in the development of IMTA systems (Cranford et al., 2013).

Deposit-feeding sea cucumbers have shown promise in recycling the larger particulate waste fraction through their feeding activities when co-cultured with other species, playing a bioremediation role while increasing farm profit (e.g. Paltzat et al., 2008; Slater and Carton, 2007; Yuan et al., 2013). Sea cucumbers are capable of consuming finfish waste, resulting in enhanced growth and survival (Hannah et al., 2013; Nelson et al., 2012a; Orr et al., 2014; Yokoyama, 2013; Yu et al., 2012) and have also been raised successfully in co-culture with shrimps (Martínez-Porchas et al., 2010; Pitt et al., 2004; Yaqing et al., 2004). Coculture simulations of sea cucumbers with mussel and fish showed that up to 70% of the material that settles on the seafloor could be consumed by these detritus feeders (Ren et al., 2012), with total organic carbon and total nitrogen contents of fish faeces being reduced by an average of 60.3% and 62.3%, respectively (Hannah et al., 2013).

Holothurians also exhibit good growth (Paltzat et al., 2008; Zhou et al., 2006) and low mortality rates (Slater et al., 2009) when cultured in suspended cages or directly on the seabed under cultured bivalves, feeding on bivalve faeces and pseudofaeces (Slater and Carton, 2007, from field measurements; Yuan et al., 2006; Zamora and Jeffs, 2012a, 2012b from laboratory experiments).

Sea cucumbers (known as their commercial product 'bêche-de-mer' or 'trepang') have long been an important fishery resource, with high commercial values in Asia and the Middle East due to their many nutritional and medicinal properties (Bordbar et al., 2011). However, the increasing market demand and prices for bêche-de-mer led to overexploitation of wild stocks worldwide and stimulated the development of commercial aquaculture of sea cucumbers (Purcell et al., 2012; Toral-Granda et al., 2008).

Large-scale commercial aquaculture has only been developed for the most valuable species; notably the Japanese sea cucumber *Apostichopus japonicus* and the sandfish *Holothuria scabra* (see references in Zamora and Jeffs, 2013). But the ongoing market demand for sea cucumbers has increased research efforts focused on other species with commercial aquaculture potential (Nelson et al., 2012a; Paltzat et al., 2008; Zamora and Jeffs, 2013), including the California sea cucumber *P. californicus* and the northern sea cucumber *Cucumaria frondosa* (Nelson et al., 2012a,b).

Previous studies have addressed the performance of sea cucumbers in co-culture with bivalves (e.g. Zhou, 2006), shrimp (e.g. Pitt et al. 2004), salmon (e.g. Ahlgren 1998), and sablefish (Hannah et al., 2013), but to our knowledge only Ferreira et al. (2012), Ren et al. (2012), and Ferreira et al. (2014a) have modelled co-cultivation.

Mathematical models have been applied to predict yield (Ferreira et al., 2008; Gangnery et al., 2004), environmental effects (Cromey et al., 2002; Fabi et al., 2009), and economic optimisation (Ferreira et al., 2009) of finfish and bivalve monoculture (Brigolin et al., 2009; Ferreira et al., 2009) but only a few IMTA combinations have been studied: finfish-shellfish (Ferreira et al., 2012; Reid et al., 2010, 2013a), finfish-sea cucumber or shellfish-sea cucumber (Ren et al., 2012), and finfish-shrimp-seaweed (Ferreira et al., 2014a).

The objective of the present work is to analyse the growth and mitigation potential of deposit-feeding organisms in open water IMTA, in co-cultivation with both finfish and shellfish.

The specific aims are to:

1. Compare the environmental and economic performance of finfish and shellfish monoculture and IMTA with sea cucumbers by means of mathematical models;
2. Explore optimization scenarios in terms of production, environmental sustainability, and economic returns;
3. Discuss the potential role of farm-scale models in supporting the suitability assessment of different IMTA combinations.

2. Methodology

Individual growth and environmental effects models for the species of interest were adapted, extended, or developed. After testing these were integrated into a broader farm-scale framework (Fig. 1). The components of the framework are summarized below.

1. An individual model for finfish (AquaFish; Ferreira et al., 2012), parameterized and validated for Atlantic salmon (*Salmo salar*). The model was applied to calculate finfish production and particulate and dissolved emissions to the environment. An individual model for Pacific oyster *Crassostrea gigas* (AquaShell; Silva et al., 2011) was used in a similar way for the shellfish component. Only changes to parameterization of the finfish model are reported herein—no changes were made to the conceptual framework and computer code of either individual model except the appropriate parameterization of AquaFish for Atlantic salmon. Finally, an individual model for seaweed production (Ferreira et al., 2014a; Saurel et al., 2014) was parameterised for winged kelp (*Alaria esculenta*) to examine the effects on the dissolved emissions from fed and organically extractive aquaculture;