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Contribution to the Theme Section 'Integrated Multi-Trophic Aquaculture (IMTA) in Sanggou Bay, China'

INTRODUCTION

Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China

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ABSTRACT: Integrated multi-trophic aquaculture (IMTA) involves the farming of species from different trophic positions or nutritional levels in the same system. In China, IMTA has been practiced for many decades, with dozens of species farmed in close proximity to each other at the scale of whole coastal bays. Articles in this Theme Section present results from the MoST-China Project on 'Sustainability of Marine Ecosystem Production under Multi-stressors and Adaptive Management' (2011–2015). This project sought to understand the interactions between biogeochemical cycles and ecosystem function in the IMTA system of Sanggou Bay, China, which produces a total of >240 000 t of seafood each year from >30 species in approximately 100 km^2 of production space. Results include measurements of carbon, nitrogen flow and trophic relationships among cultured species; impacts of IMTA on benthic nutrient fluxes, reduced inorganic sulfur in sediments, distribution of dissolved inorganic selenium, and nutrient cycling; distribution and seasonal variation of picoplankton; and a model for kelp growth. Combined, the articles enable a complex understanding of the dynamics between IMTA and the environment in one of the most important coastal aquaculture production systems in the world.

KEY WORDS: Integrated multi-trophic aquaculture · Sanggou Bay · Biogenic elements · Ecological aquaculture

Introduction

In the 'Millennium Ecosystem Assessments' of the United Nations, climate, water, food, and health were identified as critical issues that need to be considered in adaptive ecosystem-based management plans to sustain human well-being (www.millenniumassessment.org). Marine aquaculture is increasingly seen as an alternative to fishing to provide a growing human population with high-quality protein. Aquaculture of high value species (e.g. fish in cages) relies on external food supplies and has a negative impact on water quality. Culture of seaweeds, which can reduce nutrient loadings to the environment from fish aquaculture, has

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not been attractive in many countries as algal products typically have a low value. However, combining different species in aquaculture systems could provide more profit and have concomitant ecological benefits.

In 2011, the Ministry of Science and Technology (MoST) of China launched a 5 yr research project on 'Sustainability of marine ecosystem production under multi-stressors and adaptive management' (MEcoPAM; MoST Grant No. 2011CB409800). The project addressed the following questions: (1) What are the impacts of multi-stressors on biogeochemical cycles in coastal ecosystems? (2) How do ecosystem functions in the hypoxic zone of the East China Sea respond to multi-stressors? (3) What adaptive strategies are possible for coastal aquaculture systems with multi-stressors?

Implementation of MEcoPAM's research strategy involved investigations off the Shandong Peninsula of North China, particularly in aquaculture areas of Sanggou Bay (Fig. 1). Field observations, microcosm experiments and modeling studies analyzed the combined effects of fish-catch, aquaculture, and enhancement activities on the structure and function of the coastal ecosystem, as well as responses of the ecosystem to multiple stressors. The goal was to develop adaptive management strategies for sustainable aquaculture systems.

Aquaculture in Sanggou Bay

Sanggou Bay is located on the eastern tip of Shandong Peninsula, China and is well known in the field of marine aquaculture, especially in integrated multi-trophic aquaculture (IMTA). Overall, >100 km^2 of the 163 km^2 bay area are used for aquaculture, producing >240 000 t of seafood per year (China Bay Records Compiling Committee 1991, Liu et al. 2014). More than 30 important aquaculture species, including kelp, scallops, oysters, abalone and sea cucumbers, are grown using various culturing methods such as long-lines, cages, bottom sowing and enhancement, pools in the intertidal zone, and tidal flat culture (Zhang et al. 2007).

The concept of IMTA was coined in 2004 and refers to the incorporation of species from different trophic positions or nutritional levels in the same system (Chopin & Robinson 2004). However, IMTA has been successfully practiced in Sanggou Bay since the late 1980s (Fang et al. 1996). There are several IMTA modes in Sanggou Bay (Fig. 2), with benefits at the ecosystem level. For instance, co-culture of abalone and kelp provides combined benefits of a food source and waste reduction: abalone feed on kelp, and the kelp takes up nutrients released from the abalone (Tang et al. 2013). Co-culture of finfish, bivalves and kelp links organisms from different trophic levels so that the algae absorb nutrients released from finfish and bivalves, and bivalves feed on suspended fecal particles from the fish. Since kelp and *Gracilaria lemaneiformis* are cultured from December to May and from June to November, respectively, nutrients are absorbed by the algae throughout the year. These examples of multi-trophic culture maximize the utilization of space by aquaculture as they combine culture techniques in the pelagic and benthic zones. Implementation of IMTA in Sanggou Bay has improved economic benefits, maintained environmental quality, created new jobs, and led to culture technique innovations (Fang & Zhang 2015).

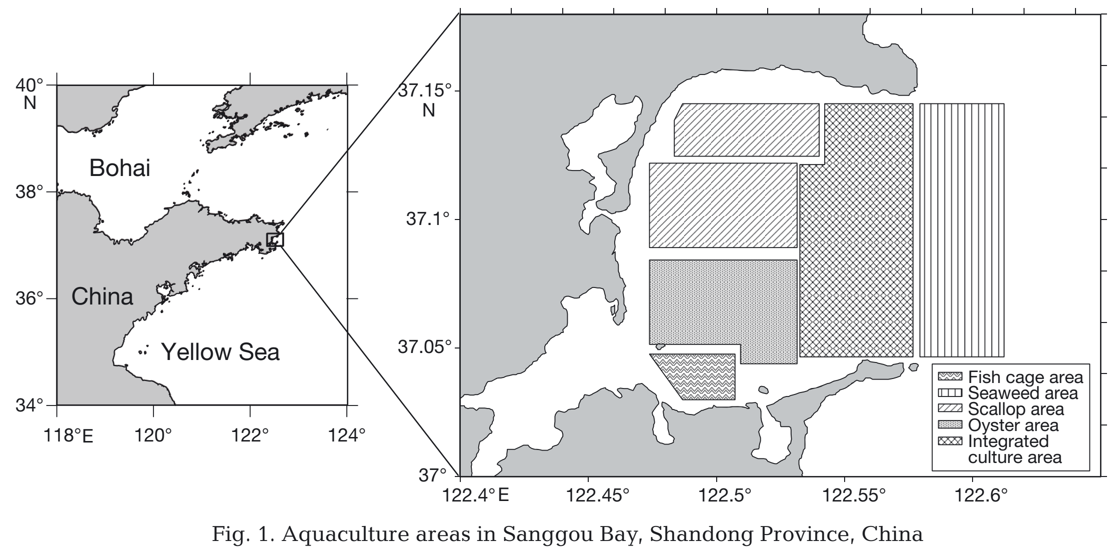

Fig. 1. Aquaculture areas in Sanggou Bay, Shandong Province, China

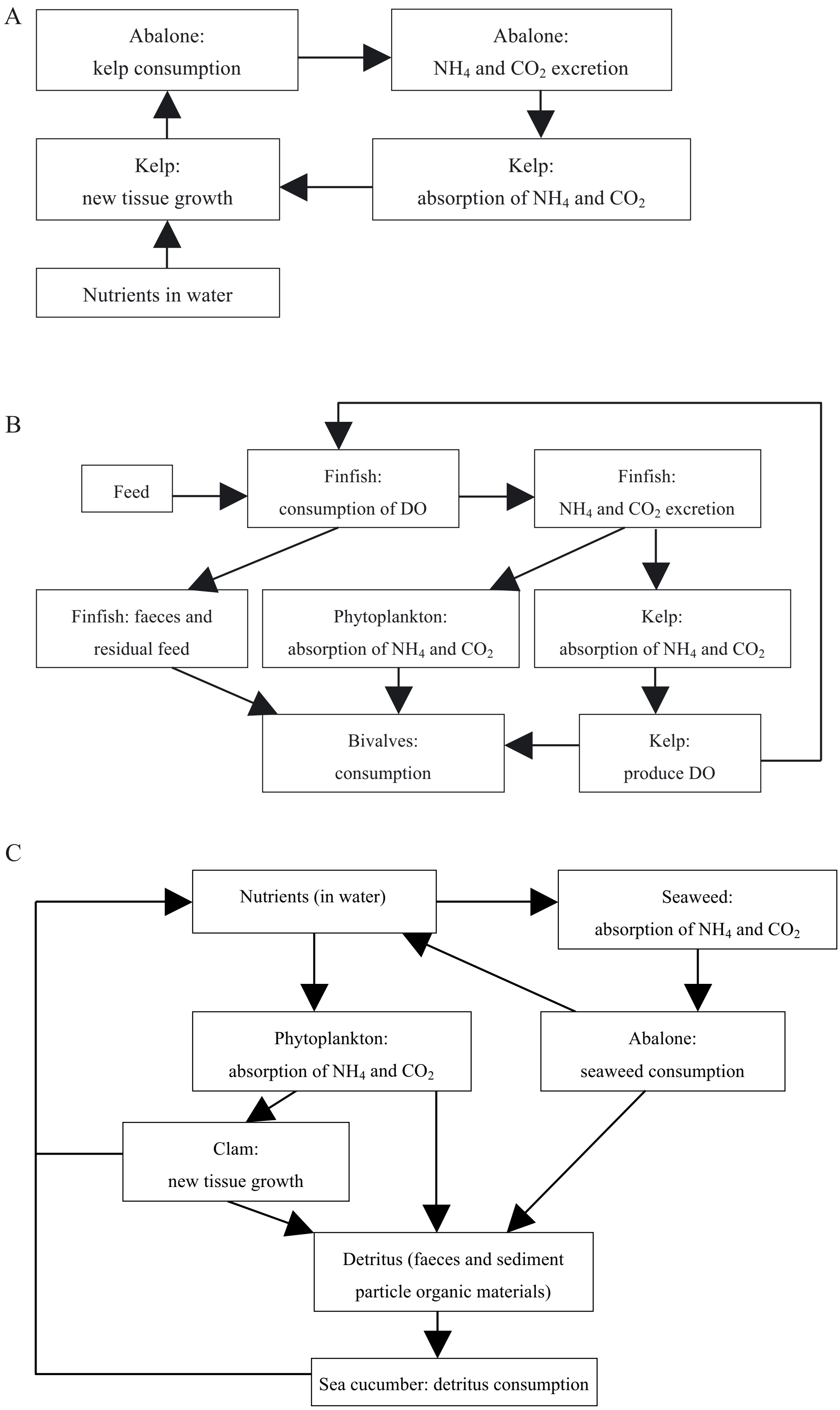

Fig. 2. Integrated multi-trophic aquaculture (IMTA) modes in Sanggou Bay, China, modified from Tang et al. (2013). (A) Long-line culture of abalone and kelp, (B) long-line culture of finfish, bivalve and kelp, and (C) benthic culture of abalone, sea cucumber, clam and seaweed. DO: dissolved oxygen

Moreover, the implementation of IMTA can increase the beneficial functions of an ecosystem. For instance, cage-culture of fish produces wastes in the form of uneaten feed, which induces the release of greenhouse gases into the atmosphere (i.e. a CO_2 source). Fish farming in combination with seaweed culture can turn the system into a CO_2 sink through photosynthesis and uptake of nutrients (Tang et al. 2011).

Studies included in this Theme Section

During the implementation of MEcoPAM in 2011–2015, Sanggou Bay has been a focal area to examine IMTA practices through interdisciplinary studies, combining physics, chemistry, biology and fisheries research. The papers included in this Theme Section reveal important connections between growth and production of cultured organisms and environmental quality, using approaches to understand cycling of biogenic elements and the function of the microbial loop.

Mahmood et al. (2016) measured stable isotopic signatures of organic carbon ($\delta^{13}C$) and total nitrogen ($\delta^{15}N$) in suspended particulates and sediments to understand the sources of organic matter (OM), water quality and flow of organic carbon and nitrogen among IMTA species, as well as to evaluate the role of IMTA practices in accumulation and assimilation of OM during both wet and dry seasons.

Ning et al. (2016) measured benthic nutrient fluxes in Sanggou Bay in June and September 2012. In June, the early growth phase of cultured finfish and bivalves contributed little to biodeposition, and benthic nutrient fluxes tended to come from the sediment to the seawater and contributed to algal growth. In September, culture of finfish and bivalves resulted in high concentrations of nutrients in seawater and TOC in the sediment; 64 % of the nitrogen and 25 % of the phosphorus metabolized by bivalves were transferred from the seawater to the sediment.

Kang et al. (2016) compared reduced inorganic sulfur (including sediment acid-volatile sulfide, pyrite sulfur, elemental sulfur) and organic matter (OM) between a mariculture region of Sanggou Bay and a reference station to assess the influence of mariculture on sulfide accumulation and the benthic environment. They found that given the mariculture activities in Sanggou Bay, there was no potential threat of toxic sulfide to the benthic biomass.

Chang et al. (2016) investigated dissolved inorganic selenium concentrations in the water column, selenium content in biological species and sources of dissolved inorganic selenium entering Sanggou Bay. They discovered that the main source of dissolved inorganic selenium was water exchange with the Yellow Sea, whereas the most important sink was the intensive and widespread seaweed and bivalve aquaculture, which removed 53 % of incoming selenium from bay waters.

Brown tide, caused by picoplankton, is a serious environmental problem in the world (Gastrich & Wazniak 2002, Nuzzi & Waters 2004, Zhang et al. 2012). Zhao et al. (2016) observed different patterns of picoplankton abundance and biomass, and analyzed the factors that affect the distribution and variation in abundance and biomass of picoplankton in aquaculture areas of Sanggou Bay.

Kelp *Saccharina japonica* is one of the most important mariculture species in China (Ministry of Agriculture 2015). Zhang et al. (2016) developed a dynamic growth model to evaluate environmental effects on kelp growth in Sanggou Bay. The model output provided useful information for improving the production and quality of kelp.

Aquaculture activities play an important role in nutrient cycling in Sanggou Bay (Li et al. 2016). Seasonal variations in nutrient concentrations were detected in the rivers entering the bay, particularly enrichment of dissolved inorganic nitrogen and silicate. The composition and distribution of nutrients were also affected by the species being cultured. The bivalve aquaculture was the major source of PO_4^{3-}, contributing 64 % of total influx, and led to increased riverine fluxes of PO_4^{3-}. The substantial quantities of nitrogen and dissolved silicate accumulated in sediments or were transformed into other forms. Large quantities of DIN and PO_4^{3-} were removed from the bay through harvesting of seaweeds and bivalves.

Future directions

Sustainable development in coastal ecosystems should be an important focus of modern aquaculture. Where aquaculture is to be embedded in coastal ecosystems, the inter-connections between production systems and the environment must be thoroughly understood. As a result, interest in exploring the potential for integrated aquaculture in brackish and marine ecosystems is growing (Soto 2009). The interactions among species in IMTA systems are complicated. Observational data and previous experience have shown the many positive aspects, both economic and environmental, of IMTA systems. Currently, management of large-scale IMTA areas remains difficult, principally due to limited knowledge of how the separate components interact and function as a whole. The papers in this Theme Section provide detailed knowledge of how different IMTA species interact and affect the environment in regions that practice IMTA. Constructing and applying diagnostic models based on an understanding of the connections among species in IMTA systems and the surrounding environment can provide guidance to adaptively manage IMTA systems to ensure ongoing sustainability.

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