Marine Pollution Bulletin 110 (2016) 484–492

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Assessing the bio-mitigation effect of integrated multi-trophic aquaculture on marine environment by a numerical approach

Junbo Zhang *, Daisuke Kitazawa

Institute of Industrial Science, the University of Tokyo, Tokyo 153-8505, Japan

ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form 3 May 2016
Accepted 2 June 2016
Available online 28 June 2016

Keywords:
Integrated multi-trophic aquaculture
IMTA
MEC ocean model
Impact assessment
Bio-mitigation effect

ABSTRACT

With increasing concern over the aquatic environment in marine culture, the integrated multi-trophic aquaculture (IMTA) has received extensive attention in recent years. A three-dimensional numerical ocean model is developed to explore the negative impacts of aquaculture wastes and assess the bio-mitigation effect of IMTA systems on marine environments. Numerical results showed that the concentration of surface phytoplankton could be controlled by planting seaweed (a maximum reduction of 30%), and the percentage change in the improvement of bottom dissolved oxygen concentration increased to 35% at maximum due to the ingestion of organic wastes by sea cucumbers. Numerical simulations indicate that seaweeds need to be harvested in a timely manner for maximal absorption of nutrients, and the initial stocking density of sea cucumbers >3.9 individuals m^{-2} is preferred to further eliminate the organic wastes sinking down to the sea bottom.

1. Introduction

In aquaculture zones, large amounts of wastes are released from fish cages, transported by water flow, and eventually settle on the sea bottom, consequently resulting in deoxygenation of the aquatic environment (Yokoyama, 2002; Troell et al., 2009). With growing concern over the risks of self-pollution in aquaculture, integrated multi-trophic aquaculture (IMTA) has received extensive attention in recent years as an alternative approach to achieve the sustainability of aquaculture. The main concept of IMTA is to recycle wastes as food resources by cocultivating the targeted species with others, which have different feeding habits in different trophic levels (Neori et al., 2004; Yokoyama, 2013; Zhang and Kitazawa, 2015; Zhang et al., 2015).

Two general candidates for cocultivation with the main culture species in IMTA systems are nutrient absorbers and deposit feeders (Troell et al., 2009; Yokoyama and Ishihi, 2010). The nutrient absorbers, such as seaweeds, can absorb and therefore remove the dissolved nutrients produced in fish-farming operations (Chopin et al., 2001; Neori et al., 2004; Buschmann et al., 2008; Yokoyama and Ishihi, 2010). The deposit feeders, for example, sea cucumbers, ingest substantial amounts of organic wastes from the surface layer of bottom sediments, thereby reducing the content of organic wastes in sediments (Kitano et al., 2003; Ren et al., 2010). When the nutrients released from fish-farming operations are fully balanced by the harvest of the extractive components such as seaweeds, mussels, and sea cucumbers, the IMTA system can create the maximum benefit in the aspects of both environment and economy (Troell et al., 2009). Matter and energy flux within IMTA, and between IMTA and its surrounding environment need to be qualified and quantified, to assess the bio-mitigation effect of IMTA and investigate its optimal design, so that the sustainability of aquaculture can be achieved (Reid et al., 2009; Chopin et al., 2013).

Nevertheless, the high complexity of an IMTA system may complicate the assessment of its bio-mitigation effect through the traditional technique of trials and small-scale experiments (Troell et al., 2009; Ren et al., 2012). To some degree, a mathematical model is a potential tool to evaluate the overall bio-mitigation effect of an IMTA system and facilitate an understanding of the interactions among physical, biochemical, and hydrodynamic characteristics in an IMTA system (Reid, 2011).

The purpose of this study is to explore the negative impacts of aquaculture wastes and assess the bio-mitigation effect of IMTA systems on marine environments by a three-dimensional (3D) numerical simulation approach. The original Marine Environmental Committee (MEC) ocean model was composed of physical and ecosystem submodels (Kitazawa, 2001; Sato et al., 2006; Mizumukai et al., 2008; Kitazawa and Yang, 2012). The model was recently developed by considering the drag of fish cages and the diffusion of particulate organic waste submodels by Zhang and Kitazawa (2015). In this study, the extended MEC ocean model was further improved by coupling the seaweed *Ulva ohnoi* and the sea cucumber *Apostichopus japonicus* submodels to represent the ecological processes in IMTA systems. The seaweed submodel in this study follows the previous works (e.g. Solidoro et al., 1997; Ren et al., 2012), while the submodel of sea cucumbers is originally developed by the authors based on the theory of scope for growth.

---

* Corresponding author.
E-mail addresses: zjb@iis.u-tokyo.ac.jp, zhangjunbo1985@gmail.com (J. Zhang).

http://dx.doi.org/10.1016/j.marpolbul.2016.06.005

2. Materials and methods

2.1. Study area

Gokasho Bay is a typical marine embayment in Japan. With the development of fish farming over the last several decades, the surrounding marine environment has become severely degraded, especially in Hazama-ura area (Fig. 1), because of the large amount of wastes produced by mariculture operations (Yokoyama, 2002; Yokoyama et al., 2009). With great concerns over the seasonal deoxygenation of bottom water, a small-scale IMTA trial was conducted in Gokasho Bay, where the Japanese sea cucumber *A. japonicus* and the seaweed *U. ohnoi* were cocultured (Yokoyama and Ishihi, 2010; Yokoyama, 2013; Zhang et al., 2015).

The stations for data monitoring are also represented in Fig. 1. The observation data of dissolved inorganic nitrogen (DIN) and phosphorus in station A at 2 m below sea surface were monitored by the National Institute for Environmental Studies, Japan. The data of water temperature, phytoplankton, and dissolved oxygen (DO) in station B were observed by Mie Prefecture Fisheries Research Institute (Japan) at 0.5 m below sea surface and 0.5 m above sea bottom.

2.2. Numerical model

On the basis of hydrostatic and Boussinesq assumptions, the governing equations of physical component in MEC ocean model basically consist of the equation of continuity, 3D Reynolds-averaged Navier–Stokes (RANS) equations, advection–diffusion equations of water temperature and salinity, and the equation of state. The eddy viscosity and diffusivity coefficients are given as constant values or calculated from stratification functions. The effect of fish cages is added to the RANS equations (Zhang and Kitazawa, 2015).

Up to 15 state variables are generally formulated in the numerical model to reproduce the complex processes of material cycling in an IMTA system (Fig. 2). The primary production process is controlled by phosphorus and nitrogen, because phytoplankton and seaweed generally experience these two nutrient sources as the possible limitation factors. The species of phytoplankton or zooplankton are summarized by one state variable for simplicity. Particulate organic carbon is composed of three sources: the feces of zooplankton and sea cucumber, the death of organisms, and the bacteria. After particulate organic wastes sink down to the sea bottom, a fraction of them are resuspended as the particulate organic carbon. The detritus from seaweeds is also one of the

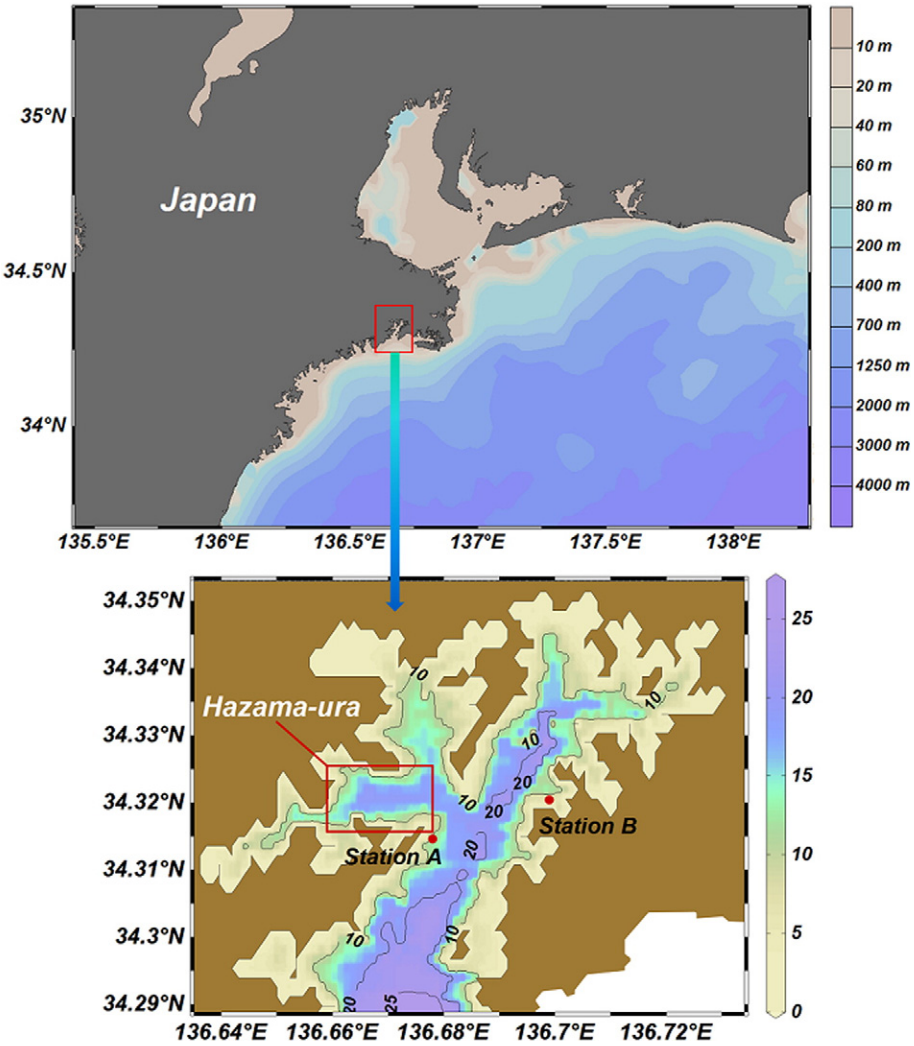

Fig. 1. Map of the study area. The red rectangle shows the location of the fish farm in the Hazama-ura area, Japan, and the red dots denote the stations A and B where data on water temperature, nutrients, phytoplankton, and dissolved oxygen are observed.