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Integrated assessment of sustainable marine cage culture through system dynamics modeling

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ABSTRACT

The high growth of marine cage culture faces challenges for sustainable development. This study applied system dynamics modeling for an integrated assessment of nitrogenous nutrient enrichment caused by marine cage culture on the surrounding environment in Magong Bay, Penghu Archipelago, Taiwan, along with its consequences to farm profitability. Simulations were run to explore the effect of the relationship between the farm and its environment on higher production levels. Results showed that there exist a production level for which the farm profitability is highest and that this level might lead to a dissolved oxygen level that is lower than the standard of the Environmental Protection Agency of Taiwan. Consequently, an estimation of the maximal production level that abides the rule was made. We argue that although this level of production is legally reachable, it may not be environmentally sustainable.

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1. Introduction

During the last two decades, production from marine cage culture has expanded worldwide (Tacon and Halwart, 2007). Meanwhile, it has become increasingly clear that marine cage culture also poses serious risks of negative environmental impacts, like pollution to the marine environment and changes in biodiversity (Loya, 2007; Tovar et al., 2000). Previous studies have indicated that marine cage culture introduces massive amounts of uneaten feed and fecal material that are characterized by high levels of organic matter that supports the growth of bacteria around the cages (Caruso, 2014; De Silva, 2012; Kondo et al., 2012; Tamminen et al., 2011). Decomposition of this organic matter by bacteria not only consumes oxygen but also liberates nutrients (e.g., nitrogen and phosphorus compounds) and may result in hypoxia in the water and sediments (Brooks and Mahnken, 2003; Diaz and Rosenberg, 1995, 2008; Gray et al., 2002; Nogales et al., 2011), nutrient enrichment (Pearson and Black, 2001), and algae blooms and eutrophication in the surrounding water (Baula et al., 2011; Loya and Kramarsky-Winter, 2003). Consequently, it further causes a suite of physical, chemical, and biological modifications that potentially occur because of the spread of waste over a long period (Loya, 2007; Pearson and Black, 2001; Wu, 1995).

The sustainable management of marine cage culture requires properly siting the fish cages for hydrodynamic regimes (Aksu et al., 2010; McKinnon et al., 2010; Neofitou and Klaoudatos, 2008) and stocking density (Ellis et al., 2002; Wu, 1995). Both of these objectives are related to the carrying capacity of the water concerned, which is mainly controlled by its flushing characteristics. In semienclosed areas, where water circulation is relatively slow, the dispersal of wastes from the cages is expected to be limited. However, poorly flushed and shallow areas with long water-residence times are more susceptible to eutrophication and algal blooms, leading to cultured-fish kills (Baula et al., 2011; San Diego-McGlone et al., 2008). In addition, over-expansion of cage farming, high stocking density, and poor environmental management also tend to decrease the survival rates of cultured fish (Shih et al., 2009).

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Therefore, incorporating the local hydrodynamic regimes of the farming site into fishery management systems may help reduce environmental risks and lead to more well-informed decision-making.

The carrying capacity of the water also depends on the capacity of the water body to assimilate pollutants. It is well documented that dissolved oxygen (DO) is one of the most critical factors for the growth and survival of cultured organisms (Wu, 1995). In Japan, the DO content of water within fish cages (>5.7 mg/l; criteria for identifying healthy farms) was an indicator for environmental reform and became a criterion adopted as part of the *Law to Ensure Sustainable Aquaculture Production* in 1999 (Yokoyama, 2003). In Taiwan, the authorities (Fisheries Agency of the Council of Agriculture) have largely encouraged the development of modern marine cage culture with the predominant cultivation of cobia (*Rachycentron canadum*) and groupers in Penghu Archipelago in the early 1990s (Chen and Hsu, 2006; Liao et al., 2004). Recently, marine cage culture has been recognized as the main pollution source in the coastal area because of minimal environmental quality criteria and management guidelines (Hsieh et al., 2011; Shih et al., 2009). In Magong Bay, nutrient and organic enrichment have been observed in the surrounding environment and have varied mainly in response to the seasonal movement of water driven by local climatic occurrences (Huang et al., 2012a,b).

Previous research has widely adopted modeling methods to minimize the risk of environmental degradation caused by marine cage culture and to provide crucial information and decision support (Halide et al., 2009; Stigebrandt et al., 2004; Tsagaraki et al., 2011; Wu et al., 1999). As a modeling method, system dynamics (SD) is particularly appropriate for simulating complex systems and long-term decision-making analysis, such as for integrated management systems (Chang et al., 2008; Dyson and Chang, 2005; Lee and Chang, 2006). SD particularly emphasizes the value of feedback loops between elements of the system, because these are the drivers of system behavior. Several SD models have been built for studying aquaculture systems (Arquitt et al., 2005; Jamu and Piedrahita, 2002a,b).

To generate sustainable development strategies and effective decision-making for the marine cage culture in the Penghu Archipelago, an SD model was developed. In this study, the possible carrying capacity of the water for the fish stock in Magong Bay was investigated as the DO reached the critical level of the water quality standard (>5 mg/l) of the Environmental Protection Administration (EPA) of Taiwan. The model provides an experimental simulation platform for exploring the complex and interdependent relationships between the various components of economic and ecological subsystems. The model components include fishery profits and harvests, as well as several water quality parameters such as concentrations of organic matter (OM), total inorganic nitrogen (TIN), phytoplankton (PP), and DO in the upper and lower layers of the water column. The model was validated using the data of Huang et al. (2012a,b) and the *Annual Fisheries Reports* from 2005 to 2007.

2. Material and method

2.1. Study area and sampling design

This study was conducted at the marine-cage-culture site in Magong Bay (23°52–56′N, 119°54–60′E), a semienclosed bay located in the southern part of the inner sea in the Penghu Archipelago, Taiwan (Fig. 1). There is no river runoff or industrial discharge into the bay. The maximum depth in Magong Bay is approximately 20 m, and the dominant currents mainly flow westward (Fig. 2). The seasonal northeastern (NE) monsoon winds

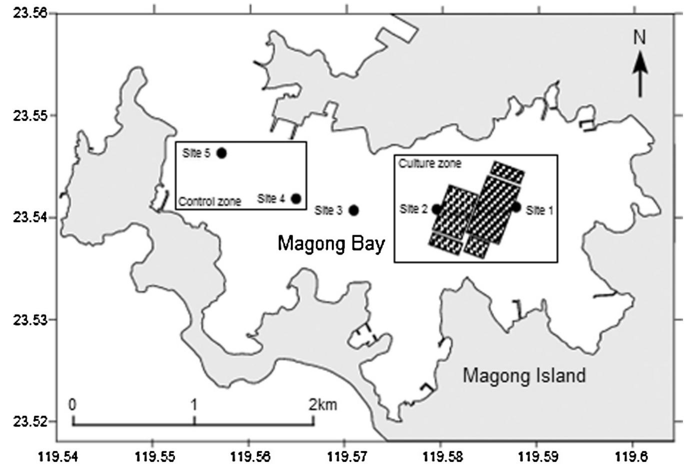

Fig. 1. Map of Magong Bay, showing sampling sites in 2006–2007.

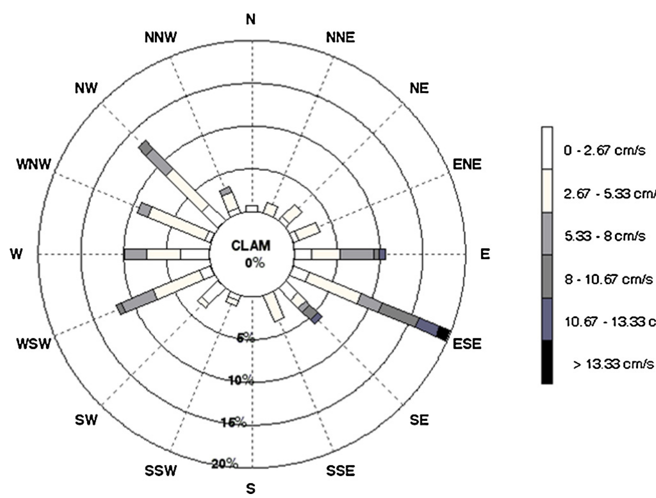

Fig. 2. Water currents speed and direction in Magong Bay, as measured in 2005.

(from October to April) induce stronger currents than those of the southwestern (SW) monsoon season (from April to October): 17 m/s versus 12 m/s, respectively (cited in Huang et al., 2012b). The culture area has expanded its scale up to approximately 13.3 ha since the early 1990s, and its annual production fluctuates between approximately 600 and 1500t (*Annual Fisheries Reports*, 2001–2013[1]). Commercial, pelleted, and extruded diets and trash fish are manually used as fish feed.

In Magong Bay, four sites in two zones were selected for water sample collection. The cage-culture zone includes Sites 1 (on the eastern boundary of the cages) and 2 (500 m away from Site 1 on the western boundary of the cages). The control zone includes Sites 4 and 5, 1000 m and 2000 m away from Site 2, respectively. Except for the OM content, which was measured only in 2006, six water quality parameters, such as nutrients (TIN, NH_3—N, NO_3—N, NO_2—N), chlorophyll-*a* (Chl-*a*), and DO, were measured during two monsoons, the NE monsoon (April and December 2006 and December 2007) and the SW monsoon (August 2006 and May and August 2007). At each site, sampling was performed at the upper layer (water surface down to 10 m) and lower layer (10–20 m below the surface) with three replicate samples being taken at each time of field sampling.

[1] http://www.fa.gov.tw/cht/PublicationsFishYear/index.aspx (in Chinese). Last accessed on 2013/11/12.

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