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A bio-physical coastal ecosystem model for assessing environmental effects of marine bivalve aquaculture

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Abstract

A simple lower trophic level, bio-physical marine ecosystem model is developed for the purpose of assessing the environmental effects of bivalve aquaculture in coastal embayments. The ecosystem box model includes pelagic and benthic components and describes the cycling of a most-limiting nutrient. The pelagic compartment is comprised of phytoplankton, zooplankton, nutrients and detritus. These populations interact following predator–prey dynamics and biogeochemical processes. Mixing processes within the bay, and exchange of waters with the adjacent open ocean, are included. The pelagic ecosystem is coupled to a simple benthos containing a dynamically active organic matter pool. Benthic–pelagic coupling includes episodic resuspension, remineralization, sinking, and permanent burial. A population of grazing bivalves is superimposed on this system as a diagnostic variable. The model is applied to a coastal bay and used to determine how bivalve populations affect nutrient cycling in the ecosystem. This is done by examining changes in the standing stock of the various populations, as well as associated nutrient (mass) fluxes, for cases both with and without intensive bivalve culture. It was demonstrated that bivalves divert production from the pelagic to benthic food webs. Phytoplankton and detritus are depleted from the water by bivalve filter feeding and biodeposited to the benthos as fecal matter. This organic loading causes order of magnitude changes in the benthic detrital pool and the associated benthic–pelagic fluxes. It was also shown that water motion and mixing is important in structuring the ecological dynamics in the bay. To faciliate future applications and observational studies, a retrospective analysis of parameter identifiability and uncertainty was also undertaken.

Keywords: Aquaculture; Benthic–pelagic coupling; Nutrient cycling; Box model; Differential equations; Regression

1. Introduction

The global production of marine bivalve aquaculture, including species such as mussels, clams, oysters and scallops, continues to expand (New, 1999). Filter feeding bivalves depend on the coastal marine

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ecosystem to supply food in the form of suspended particulate matter, both living and detrital. Large bivalve populations can lead to a variety of ecosystem effects. This includes the localized depletion of suspended particulate matter in the vicinity of dense aggregates of bivalves (Incze et al., 1981; Fréchette et al., 1989). It has also been suggested that the grazing activity of bivalve populations controls plankton dynamics on the scale of entire embayments (Cloern, 1982; Dame and Prins, 1998). Alpine and Cloern (1992) conclude that the establishment of large bivalve populations can significantly alter mass and energy flows in coastal ecosystems. Bivalves filter particulate matter suspended in the water column and biodeposit it to the seabed in the form of large and rapidly sinking fecal matter; this diverts production from the pelagic to benthic food webs (Cloern, 1982; Noren et al., 1999). Such high rates of organic biodeposition have been shown to result in anaerobic benthic environments (Hatcher et al., 1994), and change the benthic faunal community (Crawford et al., 2003). Benthic nutrient remineralization may also increase near aquaculture sites due to increased organic matter sedimentation (Grant et al., 1995). Ammonia excretions associated with bivalve culture can influence nutrient levels in seawater in some coastal regions (Dame et al., 1991). Harvesting activities remove biomass directly and Kaspar et al. (1985) suggests that this may contribute to nitrogen limitation in some systems.

Bivalve aquaculture depends on the biological production of the coastal marine ecosystem. Mathematical models are useful for understanding and assessing the potential interactions in these complex manipulated ecosystems. Bio-physical models are required which consider both interacting populations in the coastal marine ecosystem, as well as hydrodynamic influences brought about by water circulation and mixing (Dowd, 2003; Duarte et al., 2003). Ecosystem box models that focus on predicting bivalve growth and carrying capacity have been proposed by Raillard and Ménesguen (1994) and Dowd (1997). Chapelle et al. (2000) also considers an aquaculture ecosystem using a box model approach with an emphasis on the ecosystem effects of land runoff. Both Pastres et al. (2001) and Duarte et al. (2003) present sophisticated ecosystem models fully coupled to hydrodynamic models, and including bivalve bioenergetics. Here, we offer a general, and relatively simple, bio-physical coastal ecosystem model for the purpose of systematically investigating the effects of intensive marine bivalve culture on its supporting ecosystem.

This study outlines the development and application of a simple lower trophic level ecosystem model. The physical situation is one of a shallow, semi-enclosed embayment exchanging its waters (and the freely floating ecosystem components) with the adjacent open ocean. Seasonal time scales are emphasized. The pelagic compartment is comprised of phytoplankon, zooplankton, nutrients and detritus. The pelagic ecosystem is coupled to a very simple, but dynamically active, benthos. A population of grazing bivalves is also included. In Dowd (1997), it was shown that treating the bivalve population as a prognostic variable (i.e. superimposing a bioenergetic model on one of the supporting ecosystem) lead to a degradation in the predictive skill of the model. Since the focus here is not on the prediction of bivalve growth and carrying capacity, bivalve biomass is prescribed and interacts with the ecosystem as a diagnostic variable or forcing function (Kremer and Nixon, 1978; Chapelle et al., 2000). The primary objective of this study is to develop and apply a general mathematical modelling framework for the assessment of ecosystem effects of marine bivalve culture. A secondary emphasis considers how one might analyse the model dynamics in order to identify important parameters, and to determine which variables should be measured in an observational program.

This paper is organized as follows. Section 2 describes the lower trophic level bio-physical ecosystem model including a description of the various pelagic and benthic processes. In Section 3, a specific application of the model is outlined for a semi-enclosed tidal embayment located off eastern Canada. Section 4 presents results from model simulations with an emphasis on how bivalve culture can alter ecosystem fluxes. A retrospective analysis of the model dynamics is also undertaken. A summary and conclusions follows in Section 5.

2. Model

The model describes a simple coastal marine ecosystem with bivalve aquaculture. A conceptual diagram showing the ecological components and their interactions is given in Fig. 1. Population interactions occur within a finite volume of water, or a box. Pelagic ecosystem components include phytoplankton