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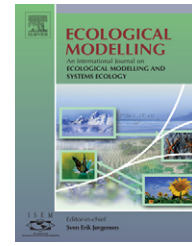

A box model of carrying capacity for suspended mussel aquaculture in Lagune de la Grande-Entrée, Iles-de-la-Madeleine, Québec

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ABSTRACT

An object-oriented model of environment–mussel aquaculture interactions and mussel carrying-capacity within Lagune de la Grande-Entrée (GEL), Iles-de-la-Madeleine, Québec, was constructed to assist in development of sustainable mussel culture in this region. A multiple box ecosystem model for GEL tied to the output of a hydrodynamic model was constructed using Simile software, which has inherent ability to represent spatial elements and specify water exchange between modelled regions. Mussel growth and other field data were used for model validation. Plackett–Burman sensitivity analysis demonstrated that a variety of bioenergetic parameters of zooplankton and phytoplankton submodels were important in model outcomes. Model results demonstrated that mussel aquaculture can be further developed throughout the lagoon. At present culture densities, phytoplankton depletion is minimal, and there is little food limitation of mussel growth. Results indicated that increased stocking density of mussels in the existing farm will lead to decreased mass per individual mussel. Depending on the location of new farm emplacement within the lagoon, implementation of new aquaculture sites either reduced mussel growth in the existing farm due to depletion of phytoplankton, or exhibited minimum negative impact on the existing farm. With development throughout GEL, an excess of phytoplankton was observed during the year in all modelled regions, even at stocking densities as high as 20 mussels m^{-3}. Although mussels cultured at this density do not substantially impact the ecosystem, their growth is controlled by the flux of phytoplankton food and abundance of zooplankton competitors. This model provides an effective tool to examine expansion of shellfish farming to new areas, balancing culture location and density.

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1. Introduction

Suspended culture of the native blue mussel (*Mytilus edulis*) is a growth industry in Canada, and there is widespread interest in predicting product yield as well as potential environmental impacts. Although there are still many feasible culture areas that remain unexploited, a number of bays and estuaries have become overstocked with culture resulting in reduced growth of mussels and lower product yield. In this case, suspended food particles (seston) consisting of phytoplankton and detritus seem to be the limiting factor (Grant et al., 1993). In addition to limiting mussel production, high density culture has the potential to direct biodeposits to the benthos where eutrophication and attendant oxygen stress ensue. Together these effects make up the criteria for carrying capacity defined as (a) the stocking density at which growth is not food limited, and/or (b) the stocking density at which some measure of ecosystem health is not compromised. Although environmental monitoring or mussel growth studies can detect these extremes, it would be useful to predict them in advance to avoid harm to the environment and to the livelihood of culturists. These predictions allow maintenance of a sustainable industry, the latter term defined as culture levels below the above expressions of carrying capacity. This has been the focus of previous modelling studies including Grant et al. (1993), Dowd (1997), Campbell and Newell (1998), and Dowd (2005).

Although exceedance of carrying capacity creates a pressing need for these models, they are also useful in planning sustainable culture as it develops in new locations. One promising area in Canada is the Magdalen Islands (Iles-de-la-Madeleine, Québec), a small archipelago in the Gulf of St. Lawrence. Its shallow interior lagoons are surrounded by barrier beaches with narrow inlets to the sea, and have thus far been ideal for suspended mussel culture. The northern of two lagoons, Lagune de la Grande-Entrée (Grand Entry Lagoon, GEL) has a single mussel farm and a smaller scallop farm. In order to assist with sustainable development of the farmed region, we developed a simulation model of mussel growth in the context of the trophic structure of the lagoon ecosystem.

Ecosystem modelling has a growing tradition in the management of both shellfish and finfish aquaculture (e.g. Dowd, 2005). Its underlying basis is a tidal circulation model, which couples coastal bays or estuaries to the ocean and allows transport of seston as food and removal of waste products. For GEL, the lagoon was partitioned into four boxes representing different regions to distill the results of a circulation model into exchange coefficients that provided communication between the boxes. The trophic model was developed with highly configurable GUI-based software (Simile) that allows explicit coupling between boxes. Using this approach, we provide estimates of mussel growth and culture yield as a function of culture density and location. We explore the potential for expansion of the farm and the consequences of expansion for mussel meat weight. Results quantify the increase in culture feasibility at this site through use of a modular model that can easily be ported to other systems. Below we describe the model, its sensitivity to parameter variation, its validation with field data, and its application in aquaculture management.

2. Ecosystem model

2.1. Overview

The Magdalen Islands are located within the central Gulf of St. Lawrence in eastern Canada, with GEL located at the northeast end of the largest island (Fig. 1). It is the largest lagoon on the island with a surface area of 58 km^2 and average depth at low tide of 3 m (Mayzaud et al., 1992). Water depths are <3 m in most of the areas occupied by Boxes 2–4 (Fig. 1). The lagoon exchanges water with the Gulf of St. Lawrence through the Grande-Entrée pass to the south, and to a lesser extent with the House Harbour lagoon located to the southwest (Koutitonsky et al., 2002). The cross-sectional area for water exchange at the two boundaries are approximately 3300 and 300 m^2, respectively (Drapeau, 1988), with water renewal between GEL and the Gulf of St. Lawrence occurring every 12–20 days (Koutitonsky et al., 2002).

Circulation in GEL is described in Koutitonsky et al. (2002). In the box model, exchange between adjacent boxes was parameterised as per day (day^{-1}) based on the results of the 2D numerical model AquaDyn (http://www.technum.com; see Grant and Bacher, 2001; Grant et al., 2005). The four boxes have volumes of 38.9, 55.9, 36.5, and 47.1 million m^3, respectively. Exchange across a boundary between two boxes was assumed equal in both directions. Patterns of circulation and current speeds in AquaDyn were verified via comparison to a validated 3D model of GEL (Koutitonsky et al., 2002). Differing exchange coefficients across multiple boundaries for a given box allow for the difference in volume between adjacent boxes. This ensures the conservation of water mass within the modelled domain. These summarised exchange results indicate that tidal forcing is stronger at the ocean boundary of GEL (volume exchange = 0.26 day^{-1}) compared to the boundary of House Harbour Lagoon (0.04 day^{-1}). Because Boxes 1 and 2 share a boundary near the GEL inlet, their exchange rate is also high (0.12 day^{-1}). As expected, turnover decreases toward the interior of GEL, with Box 2 weakly communicating with Box 3 (0.05 day^{-1}) and Box 4 (0.03 day^{-1}). The innermost parts of GEL have the lowest exchange (Boxes 3–4 = 0.01 day^{-1}).

Mussels are cultured in the Magdalen Islands using a variation of longline approaches, with continuous socking that loops between floats rather than hanging as separate vertical socks. There are 332 longlines within the existing farm area of 2.53 km^2 (outlined in Box 3, Fig. 1). Mussels are generally socked in October, with limited harvest in December of the following year, and remaining harvest in spring through fall of the second year. Despite simultaneous culture of two cohorts, we combine their numbers into a single density as detailed below.

2.2. Description

The trophic model was established using Simile software (http://www.simulistics.com) following the form of a basic PNZ model with the addition of detritus and other grazers in the form of mussels (Fig. 1). The concentration for each state variable per box was tracked through time, using organic carbon as the model currency (mg C m^{-3}). The model accounted