Available online at www.sciencedirect.com
ScienceDirect
Aquaculture 264 (2007) 160 – 174
Aquaculture
www.elsevier.com/locate/aqua-online

Management of productivity, environmental effects and profitability of shellfish aquaculture — the Farm Aquaculture Resource Management (FARM) model

J.G. Ferreira [a,*], A.J.S. Hawkins [b], S.B. Bricker [c]

[a] IMAR — Institute of Marine Research, Centre for Ecological Modelling, IMAR–DCEA, Fac. Ciencias e Tecnologia, Qta Torre, 2829-516 Monte de Caparica, Portugal
[b] Plymouth Marine Laboratory, The Hoe, Plymouth PL1 3DH, Devon, United Kingdom
[c] NOAA — National Ocean Service, National Centers for Coastal Ocean Science, 1305 East West Highway, Silver Spring, MD 20910, USA

Received 24 August 2006; received in revised form 29 October 2006; accepted 6 December 2006

Abstract

This paper describes a model for assessment of coastal and offshore shellfish aquaculture at the farm-scale. The Farm Aquaculture Resource Management (FARM) model is directed both at the farmer and the regulator, and has three main uses: (i) prospective analyses of culture location and species selection; (ii) ecological and economic optimisation of culture practice, such as timing and sizes for seeding and harvesting, densities and spatial distributions (iii) environmental assessment of farm-related eutrophication effects (including mitigation).

The modelling framework applies a combination of physical and biogeochemical models, bivalve growth models and screening models for determining shellfish production and for eutrophication assessment. FARM currently simulates the above interrelations for five bivalve species: the Pacific oyster *Crassostrea gigas*, the blue mussel *Mytilus edulis*, the Manila clam *Tapes phillipinarum*, the cockle *Cerastoderma edule* and the Chinese scallop *Chlamys farreri*. Shellfish species combinations (i.e. polyculture) may also be modelled.

We present results of several case studies showing how farm location and practice may result in significant (up to 100%) differences in output (production). Changes in seed density clearly affect output, but (i) the average physical production decreases at higher densities and reduces profitability; and (ii) gains may additionally be offset by environmental costs, e.g. unacceptable reductions in dissolved oxygen. FARM was used for application of a Cobb–Douglas function in order to screen for economically optimal production: we show how marginal analysis can be used to determine stocking density. Our final case studies examine interactions between shellfish aquaculture and eutrophication, by applying a subset of the ASSETS methodology. We provide a tool for screening various water quality impacts, and examine the mass balance of nutrients within a 6000 m^2 oyster farm. An integrated analysis of revenue sources indicates that about 100% extra income could be obtained by emissions trading, since shellfish farms are nutrient sinks. FARM thus provides a valuation methodology useful for integrated nutrient management in coastal regions.

The model has been implemented as a web-based client–server application and is available at http://www.farmscale.org/.

Keywords: Shellfish carrying capacity; Screening model; Farm-scale management; Aquaculture; Eutrophication; Nutrient trading

* Corresponding author. Fax: +44 20 7691 7827.
E-mail address: joao@hoomi.com (J.G. Ferreira).

0044-8486/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.aquaculture.2006.12.017

1. Introduction

Shellfish aquaculture is of great importance worldwide, with production increasing at an average of 7.8% per annum over the last 30 years (FAO, 2004), stimulated by market demand and by legislative initiatives such as the proposed U.S. Offshore Aquaculture Act (NOAA, 2006). The potential diversity of cultivated species (e.g. oysters, mussels, scallops, clams), each with different environmental adaptations, the pressure towards optimising species combinations within polyculture and integrated multi-trophic aquaculture (IMTA) (Fang et al., 1996; Nunes et al., 2003; Neoria et al., 2004) and the technical developments that increasingly afford suspended "pelagic" habitats in addition to bottom culture together provide significant challenges to sustainable management. These challenges are made more acute by pressures for further expansion in an industry whose production has doubled every 15 years in the recent past.

Assessments of sustainable mariculture in general and shellfish culture in particular are conditioned by different definitions of carrying capacity, which may be regarded as physical, production, ecological and social (Inglis et al., 2000). These are themselves modulated by scaling, usually considered to be either system scale (bay, estuary or sub-units thereof), or local scale (farm). McKindsey et al. (2006) provide a critical review of methods, including models, used for evaluating these various types of carrying capacity.

System-scale management of shellfish aquaculture requires a top-down assessment of carrying capacity, and has many similarities to any other large-scale plan for optimising the multiple uses of goods and services. Models (of varying complexity) that address system-scale issues include those of Carver and Mallet (1990), Raillard and Ménesguen (1994), Ferreira et al. (1998), Gangnery et al. (2001) and Nunes et al. (2003). At the local scale, the evaluation of potential fish aquaculture sites has also been supported by models such as DEPOMOD (Cromey et al., 2002) and MOM (Stigebrandt et al., 2004), but there are very few models for analysis of shellfish farms. Most recently, Bacher et al. (2003) combined a hydrodynamic model, measured data on food concentration and the simulation of individual shellfish growth to optimise density according to biological production alone.

Environmental influences of bivalve filter-feeders have been discussed by many authors (e.g. Cloern, 1982; Gerritsen et al., 1994; Lucas et al., 1999), and are most likely to be seen in systems dominated by aquaculture (Nobre et al., 2005). Effects may include a top-down control of eutrophication symptoms (*sensu* Bricker et al., 2003), when selective filtration may additionally influence the composition of phytoplankton species (Shumway et al., 1985; Bougrier et al., 1997), as well as consequences for water column biogeochemistry (Souchu et al., 2001). On the other hand, causative factors of coastal eutrophication, such as increased nitrogen and phosphorus loading, may by virtue of higher primary production be associated with enhanced shellfish growth (Weiss et al., 2002).

This paper presents a modelling approach for the analysis of farm-scale aquaculture, applicable to a range of widely cultivated shellfish species. The Farm Aquaculture Resource Management (FARM) model is targeted at farmers and managers. Whilst distilled from more complex models, FARM has therefore been designed as a simplified screening model, using a reduced parameter set, based on data which are easily available. The main objectives of this work are:

(i) to develop a model for determining sustainable carrying capacity in shellfish aquaculture farms;
(ii) to optimise culture practice, such as timing and sizes for seeding and harvesting, densities and spatial distributions, both in terms of total production and economic returns;
(iii) to assess the role of shellfish farms in eutrophication control and emissions trading.

2. Methods

2.1. Conceptualisation

The FARM model simulates processes at the farm scale (about 100–1000 m), considering advective water flow and the corresponding transport of relevant water properties. These properties include the total concentration of suspended particulate matter (TPM), separate components of that suspended food resource which include living phytoplankton organics as distinct from all remaining "detrital" organics, and dissolved materials which include ammonia and dissolved oxygen (DO). The general layout for the model is shown in Fig. 1, and is applicable to suspended culture from rafts or longlines as well as to bottom culture. Horizontal water transport is simulated using a one-dimensional model, following e.g. Bacher et al. (2003), to which vertical transport is added for suspended culture.