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Cultivation of gilthead bream in monoculture and integrated multi-trophic aquaculture. Analysis of production and environmental effects by means of the FARM model

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ABSTRACT

The aquaculture growth required to meet increasing protein demand by a growing world population, predicted to reach 9 billion people by 2050, is driving innovation in both siting and culture practice. Limited possibilities for expansion on land and in inshore coastal areas, and technological improvements in farming structures, have led to widespread interest in offshore aquaculture.

A gilthead bream (*Sparus aurata*) model has been developed and integrated with existing shellfish models in the Farm Aquaculture Management System (FARM) model, in order to analyse various aspects of onshore and offshore aquaculture. The FARM model was used to compare the quantitative effects of finfish monoculture with Integrated Multi-Trophic Aquaculture (IMTA) in ponds, in terms of production, environmental externalities, and economic performance. Very clear benefits of IMTA could be seen in the comparison. The same approach was then applied to offshore culture, considering a combination of gilthead in cages and Pacific oyster (*Crassostrea gigas*) suspended from longlines. For offshore culture, the primary production and diagenesis modules of FARM were switched off, since there are no feedbacks from those processes to the farm area. Except in upwelling areas, the concentration of food drivers for filter-feeding shellfish falls markedly with distance from the shore—simulations with FARM suggest that in food-poor areas, co-cultivation of bivalves with fish can significantly improve shellfish production, and that the distribution of finfish can be optimised to reduce shellfish food depletion in the inner parts of the farm. We calculate the environmental benefits of IMTA both in terms of population-equivalents and the potential for nutrient credit trading. The finfish model integrated in FARM deals explicitly with the metabolic energy cost of opposing offshore currents in cage culture, and a model analysis suggests that gilthead cultivation at current speeds in the range of 0.1 to 0.5 m s^{-1} is optimal. The lower end of that spectrum probably translates into a greater deviation from the fillet quality obtained from wild fish, and above that limit there is a rapid increase of the feed conversion ratio (FCR) and cultivation becomes financially unattractive.

1. Introduction

Marine finfish aquaculture in Europe is dominated by two major species, Atlantic salmon (*Salmo salar*) in the north, with an annual production of almost 900,000 t (EC Fisheries, 2011), and gilthead bream (*Sparus aurata*) in the south, with an estimated production (2008) of almost 129,000 t y^{-1} (FEAP, 2009). In both cases, as well as for species such as the European sea bass *Dicentrarchus labrax*, which is cultivated in smaller quantities, the market acceptance of the cultivated product is high (e.g. Verbeke et al., 2007), and wild-captured fish are often available only at premium prices that are inaccessible to most consumers.

Two important developments are currently occurring in Europe and North America, driven by competition for marine space and by increased environmental awareness (Olesen et al., 2010). The first is an increased interest in offshore aquaculture (Aguilar-Manjarrez et al., 2008), made possible through improvements in culture structures, and the second is the co-cultivation of different trophic groups in Integrated Multi-Trophic Aquaculture (IMTA, e.g. Chopin et al., 2010; Neori et al., 2004; Troell et al., 2009).

In the first case, there are a number of potential benefits in placing culture structures such as sea cages some distance from the shore, reducing visual impacts (Byron and Costa-Pierce, 2010; Byron et al., 2011), and promoting greater dispersion of waste products and uneaten

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food, by taking advantage of stronger hydrodynamics and greater water column depth (see Holmer, 2010, for a review). The disadvantages include higher operating costs and potentially lower yields at higher current speeds (Kapetsky et al., 2012).

Allied to the social and environmental carrying capacity advantages of cultivating finfish further out to sea, is the possibility of co-cultivation with bivalve shellfish in longlines or rafts in IMTA (e.g. Ferreira et al., 2010, 2011). The additional food supply to species such as mussels and oysters may to some extent compensate for the more oligotrophic nature of offshore waters, and will reduce the environmental footprint of finfish culture, while providing an extra cash crop for the farmer.

IMTA was documented thousands of years ago in China (Moo, undated), and has been standard practice in SE Asia for hundreds of years (Ferreira et al., in press), but the effectiveness of multi-trophic culture has been shown mainly in inland pond culture, e.g. by combining shrimp or fish with razor clams, together with a primary producer such as water spinach (*Ipomoea aquatica*). It is more difficult to establish the practical consequences of IMTA in open water, due to hydrodynamic effects, except in situations where the cultivation intensity at the whole-bay scale turns embayments or estuaries into the equivalent of a pond. Such high-density culture is widespread in China; for instance in Sanggou Bay (Zhang et al., 2009), an annual production of 150,000 t of kelp, shellfish, and finfish is documented for an area of 140 km^2 (Ferreira et al., 2008a).

Although the importance of IMTA is increasingly recognised in North America and Europe, it is effectively practised only in a few farms in Canada (Cross, pers. com.), and the cultivation densities are characteristic of aquaculture in the western world, i.e. they are presently too low to allow the environmental benefits to be easily quantified.

Mathematical models have been applied to analyse the production and environmental effects of finfish cultivation (e.g. Corner et al., 2006; Cromey et al., 2002; Skogen et al., 2009; Stigebrandt et al., 2004), and have likewise been used to predict the yield, environmental impact, and economic optimisation of shellfish farming operations (e.g. Brigolin et al., 2009; Chamberlain, 2002; Ferreira et al., 2009; Giles et al., 2009), but the combined production and effects of finfish and shellfish cultivations in IMTA have not to our knowledge been modelled previously, either in ponds or open water farms.

This work aims to develop and test an integrated modelling approach for IMTA of finfish and shellfish, both at the pond scale and in offshore conditions. This combination has been implemented in the FARM model (e.g. Ferreira et al., 2011; Silva et al., 2011), and uses gilthead bream and Pacific oysters (*Crassostrea gigas*) as test species for co-cultivation.

The main objectives are:

1. To examine the production, environmental effects, and economic externalities of monoculture of gilthead bream in ponds, and compare this to IMTA with oysters.
2. To extend this analysis to offshore farms, taking into account both the variation in current speed and the effects of co-cultivation of finfish on oyster growth.
3. To illustrate how models of this nature can assist in supporting site selection, from the standpoints of production, environment, and economic viability.

2. Methodology

The models applied in this work were developed, tested, and combined using a stepwise approach, building on an existing framework. The sequence was:

- development or adaptation of individual models, using the simplest set of formulations that allowed for an analysis of feeding, growth, metabolism, and environmental effects;
- integration of individual growth models into a population dynamics framework (see e.g. Nunes et al., 2011), enabling the models to provide results on the marketable cohorts of finfish and shellfish, in order to focus on the harvestable biomass of interest to producers; population-scale modelling also allowed for food consumption and environmental effects to be simulated at the culture scale;
- simulation of the physical systems where the cultivated species are grown. In the case of pond culture this requires a simulation of sediment diagenesis, whereas in open water the approach previously developed in FARM (e.g. Ferreira et al., 2007) was used, with the additional module for biodeposition described in Silva et al. (2011).

The main methodological innovations were the simulation of growth for gilthead, and the implementation of the diagenesis component. These are described in more detail below.

2.1. Individual model for gilthead bream

Several models already exist for individual growth of gilthead bream (e.g. Brigolin et al., 2010; Hernández et al., 2003; Libralato and Solidoro, 2008); therefore where possible, we drew on formulations already tested by those authors. However, we required an explicit simulation of feeding (see below), and we additionally needed to fraction the various components of metabolism in order to simulate growth at different current speeds.

The individual growth model developed (AquaFish) is based on net energy balance, and uses a similar rationale (i.e. maximum simplicity) to the AquaShell model developed for bivalves (Ferreira et al., 2010; Silva et al., 2011). By contrast to organically extractive shellfish aquaculture, finfish are fed (dry feed pellets in the West but often trash fish in SE Asia)—one of the key indicators of finfish aquaculture is the feed conversion ratio, or FCR, so the feed supplied must be accounted for in the model.

Another key difference in simulating feeding is that a concentration-based approach, as is normally used in shellfish models, is not appropriate, since gilthead (and other fish species such as salmon and bass) eat a 'meal'; this is best thought of by considering that in the wild, gilthead thrive on a diet of discrete prey items such as mussels, crustaceans, and smaller fish.

2.1.1. Feeding and digestion

Elliott and Persson (1978) derived various equations to represent food consumption and gastric evacuation in fish. We have used a similar approach in developing a feeding model, following also from the equations given in Franco et al. (2006).

The maximum food intake (g DW pellets d^{-1}) into the fish stomach is calculated based on allometry (Brigolin et al., 2010), and the temperature effect (f_θ) on feeding (Eq. (1)) follows Hernández et al. (2003):

$$f_\theta = D\left(e^{\alpha(\theta_m-\theta)} - e^{\beta(\theta_m-\theta)}\right) \tag{1}$$

where (values from Hernández et al., 2003):

θ	water temperature (°C)
θ_m	maximum lethal temperature = 32.9 °C
α	temperature function parameter = –0.12 $°C^{-1}$
β	temperature function parameter = −0.15 $°C^{-1}$
D	temperature adjustment parameter = 4.93.

Feeding is a function of stomach volume, converted to dry mass of feed pellets, and of stomach 'fullness'; the feeding rate is reduced through the application of a satiation coefficient as the animal's stomach capacity is reached. Fish stomach capacity has been studied by e.g. Knight