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A coupled biogeochemical-Dynamic Energy Budget model as a tool for managing fish production ponds

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HIGHLIGHTS

- A coupled biogeochemical-DEB model was developed for semi-intensive fishponds.
- Different management scenarios were simulated in order to optimize fish production.
- The model reproduced fishpond dynamics reasonably well.
- Scenarios were evaluated using the Analytical Hierarchical Process methodology.
- Doubling stocking densities and improving fish feeds were identified as the best management options.

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ABSTRACT

The sustainability of semi-intensive aquaculture relies on management practices that simultaneously improve production efficiency and minimize the environmental impacts of this activity. The purpose of the present work was to develop a mathematical model that reproduced the dynamics of a semi-intensive fish earth pond, to simulate different management scenarios for optimizing fish production. The modeling approach consisted of coupling a biogeochemical model that simulated the dynamics of the elements that are more likely to affect fish production and cause undesirable environmental impacts (nitrogen, phosphorus and oxygen) to a fish growth model based on the Dynamic Energy Budget approach. The biogeochemical sub-model successfully simulated most water column and sediment variables. A good model fit was also found between predicted and observed white seabream (*Diplodus sargus*) growth data over a production cycle. In order to optimize fish production, different management scenarios were analysed with the model (e.g. increase stocking densities, decrease/increase water exchange rates, decrease/increase feeding rates, decrease phosphorus content in fish feeds, increase food assimilation efficiency and decrease pellets sinking velocity) to test their effects on the pond environment as well as on fish yields and effluent nutrient discharges. Scenarios were quantitatively evaluated and compared using the Analytical Hierarchical Process (AHP) methodology. The best management options that allow the maximization of fish production while maintaining a good pond environment and minimum impacts on the adjacent coastal system were to double standard stocking densities and to improve food assimilation efficiency.

1. Introduction

To turn aquaculture into a more productive activity with improved profit margins, fish farmers worldwide have been intensifying production (World Bank, 2006). Intensification implies that fish are cultivated at high densities and using formulated feeds, which increases the ecological footprint of this activity (Folke et al., 1998). The lower environmental risks of semi-intensive aquaculture (Banas

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et al., 2008; Bosma and Verdegem, 2011), together with the increasing demand of consumers on food safety and on cultivated species welfare, have brought semi-intensive aquaculture products back into the front scene (SEACASE, 2010). Nevertheless, this industry has been struggling with economic difficulties as a result of high production costs (e.g. labor, energy and land costs) and low productivity. A low profitability together with the increasing market competition with low-price intensive aquaculture products (SEACASE, 2010), may seriously compromise the economic viability of this activity.

Some of the solutions that have been proposed to increase the competitiveness of semi-intensive aquaculture include product diversification and the optimisation of fish production for traditionally cultivated species (SEACASE, 2010). When cultivating a new species, as is the case for the white seabream — *Diplodus sargus* (Cejas et al., 2003; Sá et al., 2006), which is the object of the present study, optimization becomes even more relevant due to the inexistence of management protocols. In aquaculture systems, optimized faming procedures imply that not only production is maximized but also that sound environmental conditions are maintained within fishponds and in the receiving coastal waters. But how can this be achieved?

The common approach uses a trial-and-error strategy based on current knowledge for traditionally cultivated species. In Portugal, where the present study was conducted, experimental white seabream farming protocols follow the guidelines defined for a well-established semi-intensive Mediterranean species – the gilthead seabream (*Sparus aurata*) – which belongs to the same fish family (Sparidae).

In fact, the first experimental white seabream production trials in semi-intensive earth ponds were performed at stocking densities of 1.5 kg m^{-3} (Serpa et al., 2007b), which corresponds to the standard density for commercial gilthead seabream production in Portugal (SEACASE, 2010). Recent studies however revealed that doubling gilthead seabream densities has no major environmental impacts in the adjacent coastal waters (Ferreira et al., 2010), therefore, new trials are required to assess if white seabream productivity enhancement is also feasible from the environmental point of view.

Another key variable for the optimization of white seabream production in semi-intensive systems is water exchange rates (Brambilla et al., 2007; Hopkins et al., 1993). So far, water management in experimental production ponds is based on water quality standards for cultivated Mediterranean species. This implies that whenever pond environmental conditions deteriorate, water exchange rates are increased as a strategy for improving dissolved oxygen levels and reducing the concentrations of potentially toxic compounds like ammonia and nitrites (Brambilla et al., 2007; Burford and Lorenzen, 2004), which potentiates the pollution risks for adjacent marine waters. On the other hand, under sound environmental conditions, water exchange rates are commonly reduced to minimize energy costs (SEACASE, 2010) and the adverse impacts of effluent discharges (Páez-Osuna, 2001a,b; Primavera, 2006). In either situation, the variation of water exchange rates is often managed intuitively, as in other semi-intensive systems (Giovannini and Piedrahita, 1994).

As regards to nutrition, so far the white seabream is currently being fed with rations optimized for gilthead seabream (Cejas et al., 2003; Sá et al., 2006), which are supplied at standard feeding rates (Serpa et al., 2007b, 2013). As the feeding requirements of these two Sparidae species are most likely to diverge as a result of their different feeding regimes (Aksnes et al., 1997; Figueiredo et al., 2005; Leitão et al., 2007), current white seabream feeding rates might possibly lead to situations of over- or underfeeding. The lower food assimilation efficiency by cultivated white seabream (75%) has also been reported to cause growth constraints (Serpa et al., 2013), which points out for the need to develop species-specific diets. Aside from fulfilling the species nutritional and bioenergetics demands, new feed formulations will have to adjust pellet sinking rates (Serpa et al., 2013) to the white seabream feeding behavior, in order to improve current food conversion rates (1: 3.7; Serpa et al., 2007b) and to minimize the amount of solid wastes (Piedecausa et al., 2009 and nutrient loadings, particularly phosphorus (Ferreira et al., 2010; SEACASE, 2010), resulting from undigested, un-utilized and uneaten feeds (Black, 2001; Islam, 2005; World Bank, 2006).

As testing different management options in the field is extremely time consuming and often unfeasible, ecological models appear as powerful tools to assist in this task due to their potential to reproduce fishpond dynamics. However, most fishpond models have been specifically designed to address nitrogen (Burford and Lorenzen, 2004; Hargreaves, 1997; Jiménez-Montealegre et al., 2002; Kochba et al., 1994) phosphorus (Montoya et al., 2000) or oxygen dynamics (Culberson and Piedrahita, 1996; Meyer and Brune 1982), whereas less effort has been made towards the development of more comprehensive models using coupled pelagic–benthic-fish models (Lefebvre et al., 2001; Li and Yakupitiyage, 2003; Nath et al., 1999; Piedrahita et al., 1984).

The purpose of the present study was to develop a mathematical model capable of reproducing fishpond dynamics in order to simulate different management scenarios: i) increase of stocking densities; ii) decrease/increase of water exchange rates; iii) decrease/increase of fish feeding rates, iv) decrease of phosphorus content in fish rations; v) increase of food assimilation efficiency and vi) decrease of food pellets sinking velocity. The final goal of this work was to evaluate which scenarios would lead to maximum white seabream production with minimum impacts for the environment.

2. Material and methods

2.1. Description of the system

Data for model calibration was collected during a 2-year white seabream growth trial, carried out in the earth ponds of an Aquaculture Research Station located in the Ria Formosa lagoon (Southeast Portugal). In May 2003, a rectangular earth pond with a surface area of 450 m^2 and an approximate volume of 650 m^3 was stocked with 3000 juveniles of white seabream. Seawater was supplied to the fishpond at rates varying from 25 to 100 m^3 h^{-1}. The pond was equipped with aerators (FORCE-7; 1.5 hp) in order to maintain dissolved oxygen above critical levels for fish survival (range: 6.3 to 9.6 mg l^{-1}). Fish were fed daily with commercial food pellets containing 51% of total protein, 29% fat and 1.2% total P, at 1.2% body wet weight per day in the first production year, and 0.8% in the second year. Daily ration varied throughout the experiment, between 0.83 and 11.7 kg d^{-1}, according to fish biomass and feeding response (Serpa et al., 2007b).

2.2. Model development

The coupled model described herein was built on a biogeochemical and a fish growth model described in previous works (Serpa et al., 2012, 2013). The biogeochemical model reproduced the cycles of the elements that are more likely to negatively affect fish production and cause undesirable environmental impacts due to their excess (e.g. nitrogen and phosphorus), or deficit (e.g. oxygen). The fish growth model is based on the Dynamic Energy Budget theory to simulate white seabream growth as a function of the amount of food supplied and water temperature (Serpa et al., 2013). In the present work both models were coupled as described below.

Coupling consisted in using the outputs of the DEB model as inputs for the biogeochemical model, and vice-versa (Fig. 1). In the biological model, not all the food supplied was available to fish due to pellets sedimentation and decay (Serpa et al., 2013). Uneaten food was assumed to be an extra source of particulate organic matter (POM) to pond sediments, settling at velocities of 0.035 ± 0.030 m s^{-1}. After reaching the bottom, uneaten food was directly integrated in the