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Research Paper

MACAROMOD: A tool to model particulate waste dispersion and benthic impact from offshore sea-cage aquaculture in the Macaronesian region

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ABSTRACT

Uneaten feeding pellets and fish released faeces cause the most severe impact on the benthos beneath aquaculture offshore sea-cages. A modelling tool, 'MACAROMOD', composed of particulate waste dispersion and benthic response, was developed to predict the environmental disturbances of offshore sea-bream (*Sparus aurata*), sea-bass (*Dicentrarchus labrax*) and meagre (*Argyrosomus regius*) aquaculture in the Macaronesian region (oceanic archipelagos in the north-eastern Atlantic). MACAROMOD was tested at 8 sites (7 farms in the Canary Islands and 1 farm in Madeira), hence covering a high variability in oceanographic and environmental conditions. In general, a low percentage of lost pellets was found (3%), while a high rate of pellets were consumed by wild fishes (97%). Considering all studied sites, significant correlations were shown between observed and predicted solid fluxes ($R^2 = 0.89$), and also between solid fluxes and the depositional footprint on the benthos, by taken advantage of observed and predicted values of the ecological status AMBI index ($R^2 = 0.6966$). A flux threshold of 12 kg solids m^{-2} yr^{-1} was predicted as a boundary from which ecological degradation occurs for the study region. MACAROMOD is therefore a valid tool to improve planning and monitoring Macaronesian aquaculture.

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1. Introduction

Global production of fish from aquaculture has grown substantially in the past decades, reaching 97.2 million tonnes in 2013 (FAO, 2013). Aquaculture is the fastest growing animal food producing sector and currently accounts for 33.7% of the global food fish consumption (FAO, 2013). However, the negative consequences that aquaculture may have on natural systems are an increasing cause of environmental concern (Holmer, 2010). Sea-cage aquaculture may change the physical and chemical environmental conditions, leading to changes in the density, species richness, and overall abundances of benthic organisms (Edgar et al., 2010; Machias et al., 2004; Riera et al., 2013). There are many forms of wastes produced by marine fish cage aquaculture; however, particulate waste, in the form of uneaten feeding pellets and fish released faeces, is considered the primary source of ecological impact on the benthic community (Beveridge, 2004; Riera et al., 2011, 2014; Vezzulli et al., 2003). This material, which generally settles on the seabed near the cages, may exceed the carrying capacity of the environment (Kalantzi and Karakassis, 2006; Papageorgiou et al., 2010; Telfer et al., 2009).

Worldwide efforts are underway to develop more sustainable farming techniques (Troell et al., 2003), ensuring conservation of coastal ecosystems in areas with aquaculture development. Current technologies, i.e. modelling, provide powerful and reliable management tools to integrate aquaculture into a broader context of integrated coastal zone management (ICZM). During the last two decades, sea-cage aquaculture particulate waste modelling has rapidly developed from several research-based models (Gowen et al., 1989; Findlay and Watling, 1994; Hevia et al., 1996; Pérez et al., 2002) to well-established and professionally-used tools (Cromey et al., 2002a; Stigebrandt et al., 2004). Nowadays, these models are cost-effective tools, which are been widely used to assist in the prediction of impacts (e.g. SEPA, 2005). Regulatory authorities are increasingly turning to predictive models to make informed decisions when licensing new marine fish farms and granting con-

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sents to discharge waste (Chamberlain and Stucchi, 2007; Dudley et al., 2000; Henderson et al., 2001; Read et al., 2001; Dapueto et al., 2015). However, these tools have not yet been widely used because (i) a calibration and a posterior validation is necessary depending on different variables, such as local-scale oceanographic conditions or culture characteristics, and (ii) a minor fraction of these models have successfully linked solids accumulation with benthic impacts, which in turn provides an estimation of possible environmental impacts derived from fish farm activity.

Among the aquaculture particulate waste dispersal models coupled with benthic impact estimation, DEPOMOD (Depositional modelling) (Cromey et al., 2002a) is renowned for its extensive use. This model is well balanced in terms of interface, data requirements and performance, and is routinely used by the SEPA (Scottish Environment Protection Agency), as a modelling tool to set discharge consents based on maximum farmed biomass for salmon farms in Scotland. This model has been lately adapted for Atlantic cod (*Gadus morhua* L.) farming in N Atlantic Ocean (Cromey et al., 2009) and for sea-bream (*Sparus aurata*) and sea-bass (*Dicentrarchus labrax*) farming in the E Mediterranean Sea (Cromey et al., 2012). However, these models have been built for specific geographical areas, and thus have been parameterized with data to suit environments and fish species from particular regions; these tools are of limited applicability outside their boundaries (Pérez et al., 2014). This is the case of the Macaronesian region, which comprises several archipelagos in the NE Atlantic Ocean off the coast of Europe and Africa, including the Azores, Madeira, the Canary Islands and Cape Verde (Fig. 1). Maritime and environmental characteristics remain similar among the archipelagos, volcanic origin (Longhurst, 2007) and highly influenced by the Azores Current. This current flows eastward from the Gulf Current to supply the eastern Atlantic subtropical boundary region.

The aim of the present study was to develop and validate a model capable of predicting the dispersion and benthic impact of particulate waste from offshore sea-cage aquaculture of sea-bass, sea-bream and meagre in the Macaronesian region (henceforth MACAROMOD). It is well recognized that algorithms, which describe the advection, dispersion and accretion of particles in most deposition models are valid across a wide range of environments, if the model boundary conditions are adequately described (Keeley et al., 2013). Thus, it is possible to transfer the well-established and tested depositional model DEPOMOD to other geographical regions with minor alterations. On the contrary, relationships between depositional fluxes and ecological responses can be strongly influenced by physical environmental properties, i.e. sand *vs* mud, flow regimes, local macrofaunal assemblages, which are site-specific (Keeley et al., 2013). Thus, it was necessary to (i) obtain data related to growing (species-specific food and faeces settling velocities, percentage of uneaten food, among others) and environmental conditions (e.g. currents, dispersion coefficients and food consumption by wild fishes) needed for model parameterization, (ii) derive a benthic response using a semi-empirical relationship between modelled fluxes and a benthic index, and (iii) model validation, so MACAROMOD may be used as a tool to help in decisions for planning and monitoring Macaronesian aquaculture.

2. Material and methods

2.1. Study sites

This study was conducted around eight sea-cage fish farms, seven at the Canary Islands and one in Madeira (Table 1). The Azores and Cape Verde archipelagos were not included, because sea-cage aquaculture was not developed at the time of this study. Site notation is given as: *A_B_c*, where *A* is the archipelago name (C = Canaries and M = Madeira), *B* is the island name (GC = Gran Canaria, M = Madeira and T = Tenerife) and *c* is the site reference number (1–8). This anonymous site reference system is used, as the data were collected under a confidentiality agreement. Four sites were used to derive a benthic response relationship under varying particulate waste flux rates (kg m^{-2} $year^{-1}$) and four sites were used for model validation (particle tracking and benthic response). Data used to derive benthic response relationships (sites *C_T_1*, *C_T_2*, *C_T_3* and *C_T_4)* was obtained from annual compilation monitoring programs during 5 years (2006–2010). Data for model validation was obtained from sampling field surveys during 2012 (sites *C_T_5*, *C_T_6* and *C_GC_7*) and 2013 (*M_M_8*).

Coastal environmental conditions greatly varied among the studied aquaculture facilities, encompassing most of the coastal ecosystems in the Macaronesian region. Thus, this implies that the model output is realistic, considering the high coastal and oceanographic variability in the study area. Continuous currents throughout the entire year are present at all studied aquaculture facilities, ranging from <5 cm s^{-1} on the surface and >20 cm s^{-1} on the bottom layer (Riera et al., 2015). The benthic habitats are mainly comprised by sandy unvegetated seabeds, with sparse *Cymodocea nodosa* and *Caulerpa prolifera* meadows on the surroundings of the aquaculture facilities (>500 m from cages). Sediments were mainly composed by fine and medium-sized sands, with scarce content of very fine-grained sediments, e.g. silt/clay. No subtidal rocky substrate is present beneath the farms.

2.2. Model structure description

The model general structure is that initially developed for DEPOMOD (Cromey et al., 2002a) and further adapted to Mediterranean conditions for MERAMOD (Cromey et al., 2012). The model is assembled by 4 modules: (i) grid generation, (ii) particle tracking, (iii) re-suspension, and (iv) benthic faunal response (benthic impact) (Fig. 2). A grid containing information on depth, sea cages and sampling stations positions for the area of interest is initially required. In contrast to the original model (DEPOMOD) and later versions, MACAROMOD offers a larger grid domain of 999 × 999 cells. This is useful for covering extensive areas and, consequently, additive effects from adjacent farms may be quantified without decreasing model resolution. Given wastage rates of fish food and faeces from the bioenergetics model, hydrodynamic data, individual settling velocity for wasted food and faeces for different culture species and wild fish waste consumption, initial deposition of particles on the seabed are predicted with the particle-tracking component. An important innovation in this module, based on the results of this study, is the possibility to determine cage particles starting position, both in the horizontal and vertical axis. A re-suspension model (Cromey et al., 2002b) then redistributes particles according to near-bed current flow fields to predict net solids accumulated. Finally, an impact assessment is provided by correlating model predictions (e.g. solids fluxes as g m^{-2} y^{-1}) with the benthic faunal indicator of environmental impact AMBI (AZTI's Marine Biotic Index) (Borja et al., 2000).

Sensitivity analysis is an important procedure for model development, used to increase confidence in the model and its predictions, by studying how the variation in the output of a model can be apportioned to different sources of variation, and how the given model depends upon the information. In this study, model sensitivity analysis was not performed because underlying equations and algorithms are equal to those already tested for DEPOMOD and MERAMOD, hence, its sensitivity to parameters changes is already known and taken into consideration in the model parameterization, adaptation and validation procedures.

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