Journal of Environmental Management 158 (2015) 24–35

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Bioeconomic analysis of the environmental impact of a marine fish farm

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ARTICLE INFO

Article history:
Received 16 December 2013
Received in revised form
27 January 2015
Accepted 22 April 2015
Available online 25 May 2015

Keywords:
Bioeconomic model
Environmental impact
Managerial practice
Impact indicator
Settled matter
Spain

ABSTRACT

The evaluation of the environmental impact of aquaculture installations is nowadays a common social demand in many countries. The usual scientific approach to this question has been to assess the outcome from an ecological perspective, focussing on the effects produced on benthos or the water column and interactions with marine flora and fauna. In this paper, a bioeconomic model is developed to extend this traditional approach, to determine both the amount of total settled matter, its dispersion on the ocean floor and impacts on the marine ecosystem, while also taking into account other social considerations such as discounted net profits and investment returns. The model was applied to the case of off-shore gilthead seabream production in a coastal area of the Canary Isles archipelago, where the tidal current is predominant. Cage emissions and the degree of degradation of seagrass meadows on the seabed were taken as ecological impact indicators, while the net present value (NPV) for a specific time period was used as an economic indicator. By analysing the simulation results obtained by the bioeconomic model, we were able to determine the combination of production volume and harvest quantity which yields the greatest economic efficiency for different levels of degraded area.

1. Introduction

In the last decades, the world aquaculture production has greatly increased, diversified, intensified and advanced technically. In particular, from a modest 0.6 million tons in 1950, the annual production has reached 79 million tons in 2010, excluding plants and non-alimentary products, and although it has slowed in the last years, it maintains a healthy annual growth rate of 6% (FAO, 2012). It is expected that its contribution to economy and society will increase in the future.

This spectacular growth of aquaculture has aroused controversy related to negative impacts of this activity on the environment, and its sustainability has been questioned (Read et al., 2001). Fish farming produces emissions (feed waste, faeces, medicines and pesticides) which originate undesirable effects on wildlife populations, such as the transmission of diseases through the ingestion of contaminants or escaped fish, in addition to other negative effects on the ecosystem (Read and Fernandes, 2003). Other types of social impacts are generated by the installation, such as the visual impact made on areas with high landscape value. But, of all the environmental outcomes of the development of aquaculture, the one that has caused most controversy is that of the enrichment in organic matter, as reflected in the proliferation of studies concerning this issue (Cho and Bureau, 2001; Islam, 2005; Olsen et al., 2008; Hall, 2011; Byron and Costa-Pierce, 2013). The accumulated organic matter stimulates overproduction of bacteria, who transform the composition, structure and functions of sediments. Some of the effects are: decay on the oxygen concentration, increase of oxygen demand, perturbations on the common cycles of nutrients, provoking changes in the biomass and diversity of marine species.

Concerned by the environmental effects of aquaculture installations, some institutions and researchers have developed indicators for environmental management in certain areas (Fezzardi et al., 2013) and recommended the implementation of Best Management Practices for the production of specific species and culture system (Boyd, 2003; MacMillan et al., 2003; Collins et al., 2007). The objective of these practices is to achieve environmental respectful productions, which are availed by official certifications and eco-labels.

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http://dx.doi.org/10.1016/j.jenvman.2015.04.034
0301-4797/

In parallel to these recommendations, many scientific papers have proposed in the two last decades mathematical models to explain and forecast the waste emission processes and effects produced by aquaculture installations (Gillibrand and Turrel, 1997; Cromey et al., 1998, 2002; Carroll et al., 2004; Stigebrandt et al., 2004; Chou et al., 2004; Aguado-Giménez and García-García (2004); Machias et al., 2006; Holmer et al., 2008; Borja et al., 2009; Cromey et al., 2009). In general terms, these models are based on equations that take into account the volume of emissions from aquaculture farms, and their dispersion and impact on the marine environment.

Most aquaculture models by now address the problem exclusively from an ecological standpoint and ignore productive and economic aspects, although these are also of vital importance. All these factors are tightly related, since there are mechanisms of an economic nature that lead farmers to consider the environmental effects of their decisions (Asche et al., 1999). In particular, if farm management practices are prejudicial to the environment, production can be compromised by increased fish mortality rates or reduced quality. For example, eutrophication processes and the heightened presence of algae, bacteria and viruses, as a result of inadequate practices in aquaculture installations, have been documented (Gilbert et al., 2002; San Diego-McGlone et al., 2008). The growth of some cultivated species, such as shrimp, has been reduced by 5–10% a year as a result of disease and environmental damage (Tacon, 2002). Improvements in the technology used in aquaculture, such as greater efficiency of the food supplied, can also lead to higher environmental quality (Tveterås, 2002). Environmental impacts that are generated by aquaculture installations but which do not directly affect production can also influence the economic results of the farm, following the imposition of environmental cost internalisation mechanisms, in the form of stricter regulations and/or higher taxes.

The aim of this paper is to perform a joint analysis of the environmental and economic impacts of aquaculture. To do so, a bioeconomic model is presented from which the following forecasts are obtained:

a) The emission and dispersion of total matter from aquaculture cages and its impact on benthos.
b) The economic results in different scenarios, according to the management strategy adopted regarding questions such as the final fish size and the annual production volume.

This approach provides an instrument with which producers can simulate management strategies taking into account both their own constraints and the environmental restrictions imposed by regulatory authorities. As a case study, the model was applied to the conditions found in the culture of gilthead seabream in the vicinity of the Canary Islands (Spain). The results obtained concerning the economic profitability and the environmental impact arising from different management strategies in aquaculture in this region can serve as a guide for optimum management of such an installation.

The rest of this paper is organised as follows. Section 2 reviews previous models of the impact of aquaculture. Section 3 then presents the bioeconomic model proposed, which, unlike the most of previous models, considers the productive, ecological and management activities of aquaculture, detailing each of these components. The following section then applies the model to the case study of gilthead seabream culture in a specific area near the Canary Islands. Section 5 provides an analysis of the results, followed by a discussion and some final conclusions.

2. Modelling emissions from aquaculture farms

Three fundamental approaches have been taken to the construction of mathematical models of the emission of nutrients from aquaculture farms. The first is embodied in studies that describe the processes related to these emissions. These studies aim to quantify the fraction of supplied food that is released to the environment, as dissolved organic matter, as particulate organic matter or as nutrients, mainly nitrogen and phosphorus. Various mathematical models have been developed to estimate emissions from different cultivation methods of species and locations, for example McDonald et al. (1996), Kaushik (1998), Lupatsch and Kissil (1998), Cho and Bureau (1998), Stigebrandt (1999), Nordvarg and Hakanson (2002), Papatryphon et al. (2005), Chamberlain and Stucchi (2007), Yokoyama et al. (2009) and Piedecausa et al. (2010).

A second perspective focuses on the growing concern caused by phenomena of hypernutriphication or eutrophication of water masses, such as the degradation of benthos, which have motivated various studies of the dispersion of excreted products. Most organic matter dispersion models are based on a simple transport mechanism to calculate the horizontal displacement of the particulate compounds with respect to depth, velocity and direction of the current. Gowen et al. (1989) pioneered the use of this technique to calculate dispersion, using forecasts of the volumes of uneaten pellet food and the faeces released from fish culture farms on the basis of their settling velocity on the seabed. This model was applied by Gillibrand et al. (2002), who developed a model to predict the enrichment of nutrients and the benthic impact of fish farms in coastal lagoons. Pérez et al. (2002) adapted the same model to integrate it within a geographic information system and predict the environmental impact of organic matter waste. Other studies, such as Gowen et al. (1989), extended the original model by introducing true bathymetry and a current velocity gradient that accounts for depth.

In the third approach, various studies have sought to establish standards for monitoring aquaculture installations, to preserve environmental conditions in and around them, by identifying relationships between the emission of nutrients and organic matter and their impact on the environment. Most of these studies focused on the impact on water quality and on the accumulation of sediment on the seabed, although others have considered interactions with pelagic and benthic marine communities. Chou et al. (2004) analysed the changes in chemical parameters of seabed sediment provoked by waste from aquaculture installations, using a statistical model of situations of hypoxia or anoxia. In this respect, Aguado-Giménez and García-García (2004) studied the evolution, over a year, of chemical parameters in the sediment near several fish farms. Other authors such as Machias et al. (2006) have analysed the interaction between the emissions from the net pens in oligotrophic waters and local fisheries, while Holmer et al. (2008) and Borja et al. (2009) focused on indicators to assess the effects of aquaculture on benthos.

In other studies, models have been proposed that integrate the different processes found in the aquaculture-environmental installation system. Gillibrand and Turrel (1997) and Cromey et al. (1998) developed mathematical models to estimate release dispersion rates from fish farms and their impact on the environment, regarding both water and benthos quality. During the last ten years, more sophisticated models have appeared, such as DEPOMOD, developed by Cromey et al. (2002), which include hydrographic data to model the re-suspension of particulates and the changes in the benthic community in salmon culture farms. Other versions of this model are CODMOD (Cromey et al., 2009) and MERAMOD (Carroll et al., 2004), which extend the applicability to cod and gilthead seabream (or seabass) cultures, respectively.