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A global integrated analysis of open sea fish farming opportunities

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ABSTRACT

The present work develops and implements at the global scale an innovative methodological approach to identify opportunities for farming seven fish species in offshore zones. The proposed methodology is based on a three-step approach integrated by: i) the biological suitability, to identify areas with optimal conditions for fish growth; ii) the structural suitability, to identify adequate areas for the integrity and durability of the cages; and iii) the operational suitability to evaluate the possibility of carrying out the operational and maintenance activities. The integration of these three complementary aspects, allowed the mapping of suitable zones for farming each fish species. It is shown, that the main potential zones for fish farming are concentrated in South America (South Pacific and South Atlantic Ocean), Africa (North Atlantic Ocean), Mediterranean Sea, Japanese and Chinese Seas and Oceania. The unprecedented global analysis presented by this work, considering comprehensive aspects other than only the biological requirements, provides guidelines to assist future studies in marine management.

1. Introduction

Over the last two decades, the rapid growth of aquaculture production has increased the average consumption of fish and by-products globally. The contribution of aquaculture reached a milestone in 2014, when aquaculture sector contributions exceeded the supply of fish per catch (FAO, 2016a), and therefore, it is expected to be the main source of aquatic animal food in the next few years (Ottinger et al., 2016). This situation and the continuous overexploitation of marine and coastal resources has encouraged intensification in the search for new opportunities in open seawaters. Furthermore, recent technological advances in offshore cages allow the development of aquaculture operations in the open sea (Benetti et al., 2010). The expansion of this activity in the marine environment has been contemplated in public policies at the international, national and regional levels. For instance, the European Commission's Blue Growth strategy supports the sustainable growth of marine-related activities, one of its main axes being the expansion of offshore aquaculture (European Commission, 2017).

Main challenges for the aquaculture sector expansion in the marine environment are linked to the industry establishment and the location of aquaculture farms (Angel and Freeman, 2009; Byron et al., 2011; Soto et al., 2008). GIS-based suitability models are frequently used for identifying areas for aquaculture facilities (Stelzenmüller et al., 2017), taking advantage of multi-criteria evaluation (MCE) methods. The literature provides several studies based on MCE to recognize suitable zones for fish farming in specific coastal regions, most of them focused on species growth. Dapueto et al. (2015) and Pérez et al. (2005) evaluated the suitability of offshores zones for locating fish cages for farming seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*), based on criteria of water quality, legal constraints and social and economic factors. Aspects related to the infrastructure and the operations and maintenance (O&M) activities were addressed through a constraint mask and submodels of relative importance by stakeholder weight assignment, taking into account significant wave height (Hs) and criteria related to bathymetry.

However, studies at larger scales remain less frequent (Stelzenmüller et al., 2017) and face a barrier due to the availability of appropriated and homogeneous long-term data series at both the temporal and spatial resolution (Fisher and Rahel, 2004). Consequently, few contributions have been implemented at global scale. Kapetsky et al. (2013) conducted, in a technical paper, the status and potential of offshore aquaculture development of all maritime nations, considering Cobia, Atlantic salmon and Blue mussel. Based on sea surface temperature and some constraint criteria, feasibility potential zones, according to their technical (using depth and current velocities) and economical features, were identified and compared with current

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aquaculture production by country. More recently, Gentry et al. (2017) evaluated the general potential for the growth of 180 species (120 fish and 60 bivalves) across locations, based on biological, common environmental and human-use constraint factors. In most of the studies, long-term data series are not considered. Furthermore, although the integration of aspects related to the cage resistance and O&M activities with biological factors are essential to identify development opportunities for the open sea aquaculture industry, they are not widely recognized.

Therefore, for mid-term maritime planning of aquaculture developments, a holistic view on the global potential and opportunities for farming commercial and promising fish species worldwide is required. In this context, this work aimed at developing an integrated analysis of offshore aquaculture suitability at a global scale, taking simultaneously into consideration the biological conditions for growth of different commercial fish species, the structural resistance of offshore cages and the feasibility for O&M activities. For this purpose, potential zones were identified according to the temporal and spatial dynamics of physic-chemical and met-ocean factors to meet fish, cage and operational requirements.

2. Material and methods

This study analyzed, at the global scale, the opportunities for marine fish farming between the coastline and the isobate of 700 m, using a combination of validated statistical information and reanalysis (20–30 years) at temporal (hourly, daily and weekly) and spatial resolutions (0.25°), according to the availability of homogeneous data (Table 1). Seven marine fish species with high commercial potential and/or a large farming trajectory in the aquaculture industry were selected for this study (Table 2). The identification of suitable zones for aquaculture of these species was based on the integration of three aspects related to farming opportunities: the biological suitability, the structural suitability for offshore cages and the operational suitability for O&M activities (Fig. 1).

2.1. Biological suitability

Selection of suitable areas for the seven fish species considered in this work (Table 2) was based in the analysis of two limiting factors for fish growth: temperature and salinity. Based on previous works (unpublished data), two different parameters, mean value and the exceedance time percentage for a specific reference threshold, were calculated for both variables, at each 0.25° grid cell. Optimum ranges for salinity and temperature for each species were established according to scientific literature (*cf.*Table 2). The suitability assessment for each cell was based on the fulfillment of two criteria for both variables: 1) the mean value for the whole data series should remain within the optimum range and 2) percentage of time that both variables exceed the higher threshold of temperature and the lower threshold of salinity, respectively, should not be higher than 30% through the study period. A map with areas that fulfilled these conditions was generated.

2.2. Structural suitability

Ocean currents (velocity, m/s) and 50-year return period significant wave height (Hs^{50}, m) were the variables used to recognize suitable areas for the cages, considering the resistance parameters for a generic cage in three different environmental scenarios (Table 3), based on the Standard Norge (2009). In the first case, two parameters and the corresponding criteria were considered for current velocities: the mean velocity and the exceedance time percentage for the reference threshold (Table 3). For the wave height, the calculation of Hs^{50} used the Peak Over Threshold (POT), assuming the frequency as a Poisson process and the intensity by Generalized Pareto Distribution (GPD), based on the developed by Cañellas et al. (2007). The structural suitability assessment for each cell was based on the joint fulfillment of three criteria: 1) mean velocities must remain below the threshold, 2) percentage of time that current velocities exceed the threshold should be lower than 30%, and 3) Hs^{50} values must remain below the corresponding thresholds. Based on those criteria, a final map of suitable cells was generated for each scenario.

2.3. Operational suitability

Feasibility assessment for O&M activities was carried out according to fulfillment of wave height (Hs, m) criteria for three different scenarios (see thresholds in the Table 3). As for some of the previous variables, the mean and the exceedance time percentage were the two parameters selected to analyze the operational suitability, using the same criteria (mean below the threshold and < 30% of exceedance time). Finally, a map considering the different scenarios was proposed.

2.4. Farming suitability

Considering the high exposure scenario for structural and operational suitability (Currents ≤ 1.5 m/s; Hs^{50} ≤ 5 m; Hs ≤ 3 m) and the biological suitability, suitable areas were integrated into a farming suitability map for each of the seven fish species. Then, for graphical purposes, a combined map for all the species was delivered in order to facilitate the global analysis in different geographic zones. Finally, more detailed maps were generated for some relevant zones for offshore aquaculture.

All analyzes and maps were performed in MATLAB R2014b (Mathworks, 2014) and ArcGIS 10.1 (ESRI, 2015) software.

3. Results

3.1. Biological suitability

The distribution of suitable areas in Fig. 2 follows a pattern according to the climatic zones, where the subtropical ones concentrated

Table 1
Summary of data sources, resolutions and available periods.

Variables	Information sources	Temporal resolution	Spatial resolution	Available period
Salinity (PSU)	Copernicus: Marine Service Information (European Union), 2016GLOBAL_REP_PHYS_001_013	weekly	0.25°	1993 to 2013
Water temperature (°C)	Donlon et al., 2012 OSTIA SST	daily	0.25°	1985 to 2013
Currents (V,m/s)	NCAR (National Center for Atmospheric Research Staff) (Eds), 2016 CFSR	hourly	0.25°	1979 to 2010
Waves (Hs,m)	Reguero et al., 2012 GOW - IH Cantabria	hourly	0.25°	1979 to 2010
Bathymetry (m)	Amante and Eakins, 2009 Etopo1	punctual	0.017°	2015