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Sustainable use of marine resources through offshore wind and mussel farm co-location

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ABSTRACT

Marine Spatial Planning (MSP) can offer significant benefits in terms of economic conservation strategies, optimizing spatial planning and minimizing the impact on the environment. In this paper, we focused on the application of *multi-criteria evaluation* (MCE) technique for co-locating offshore wind farms and open-water mussel cultivation. An index of co-location sustainability (SI) was developed based on the application of MCE technique constructed with physical and biological parameters on the basis of remote-sensing data. The relevant physical factors considered were wind velocity, depth range, concerning the site location for energy production, and sea surface temperature anomaly. The biological variables used were Chlorofill-a (as a measurement of the productivity) and *Particle Organic Carbon* (POC) concentration, in order to assess their influence on the probable benefits and complete the requirements of this management framework. This SI can be easily implemented to do a first order selection of the most promising areas to be more specifically studied in a second order approach based on local field data.

1. Introduction

1.1. Scientific background

Offshore wind farms are widely spread in Denmark, however, their growth has proven to limit the allowable space for aquaculture sites. Therefore the environmental authorities, to enhance sustainability, improve marine space utilization and reduce costs, are encouraging to move the aquaculture facilities between the wind farms (Foteinis and Tsoutsos, 2017). The coexistence of this complementary use of marine space, which has been first investigated by Buck et al. (2008), is possible for both limited depths found in the Danish coastal waters and also for higher depths found in other offshore sites, where the monopiles are substituted by semisubmersible structures. In this case, the aquaculture lines have to cope with the structure moorings, which recently have been investigated (Benassai et al., 2014a,b, 2015). The co-locating strategy of aquaculture and offshore wind farms arises from the increase in local biodiversity, species abundance and biomass that have been found in artificial reefs used as foundations for offshore wind farms (Alexander et al., 2016; Gimpel et al., 2015; Stelzenmüller et al., 2016). To do this, specific co-management strategies are needed that are either more results-oriented (e.g., for integrating technical knowledge of the two sectors) or more process-oriented (e.g., for establishing new linkages between different groups) (Michler-Cieluch and Krause, 2008). Typically, the synoptic and mesoscale characteristics of some remote sensing sensors have been exploited to infer information about the environment and its changes and, therefore, to support decision-makers to take the correct action for Marine Spatial Planning (MSP). Some authors showed that the main factor explaining growth variation was phytoplankton availability, as permitted by the current speed (Camacho et al., 1991). The actual amount of phytoplankton available to the mussels depends on the water flow through the mussel ropes (i.e. current speed) and the Chl-a concentration. Different levels of Chl-a content and water current speed, which influence phytoplankton availability, coupled with proper salinity and temperature conditions, affect mussel growth.

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Other potential stressors that can impact bivalves include dissolved oxygen and POC concentrations. The Baltic Sea, in particular the Danish and Norwegian Fjords, are characterized by high levels of hypoxia due to on-shore slow circulation currents, a shallow bottom, and excess of nutrients such as nitrogen, phosphorus and organic carbon. Enhanced eutrophication not only reduces water clarity but also causes a shift in phytoplankton species composition from high quality (e.g., diatoms) to low quality species (e.g., cyanobacteria). This shift in species composition can have a rippling effect up the food chain and cause a decrease in natural fish stocks due to the decrease in zooplankton biomass. This condition may increase the hypoxia and cause the decline of seagrass and macrophyte concentration. During the preliminary physical analysis, the factors influencing the aquaculture sustainability are chosen among the conditions leading to more enhanced growth rates, which are governed by food availability and phytoplankton dynamics (Winter, 1978; Soniat and Ray, 1985). An upwelling index, associated to high productivity areas, is linked with the increase in sea surface Chl-a concentrations (Valavanis et al., 2004), so areas with high Chl-a concentrations present also an increase of nutrients available to photo-synthesisers. The oceanographic processes such as upwelling, gyres or eddies, which can transport cold, nutrient-rich water from below the pycnocline to the euphotic zone where photosynthesis takes place are typical of autotrophs organisms associated with low SST (Sea Surface Temperature). The spatial integration of SST anomaly and Chl-a normalized may detect areas of productive processes such as upwelling and gyres (Valavanis et al., 2004). The analysis of climatological (long-term) time series allows the identification of persistently productive regions, independent on short-term variability.

1.2. Marine Spatial Planning as a tool to implement ecosystem-based conservation strategies

This study confirms that MSP is a key framework for delivering conservation strategies in marine environment, provided that it reduces conflicts between different uses of marine space and limits the possible undesirable effects, such as the restriction of activities in the coastal area.

Today this ecosystem approach has become widely accepted as a strategy for integrated management of resources that promotes conservation and sustainable use (Douvere, 2008).

In this study, we use MSP as a tool to achieve a sustainable use of marine resources in coastal areas, where multiples activities occur and space is a limiting factor. Following Benassai et al. (2014c, 2011), who proposed the development of a *Sustainability Index* (SI) for the co-location of aquaculture cultivation in marine areas of offshore wind farms, we selected the optimal sites for a sustainable offshore aquaculture on the basis of physical–chemical parameters driving autotrophic production, coupled with other biological environmental factors (i.e. Chl-a, POC) that can fuel increases in microbial biomass and productivity.

2. Study area and data source

2.1. Site characterization

The study area used as a test site to implement the co-locating management was identified in the Danish portion of the Baltic Sea and in the western part of the Danish North Sea (Fig. 1), where many offshore wind farms are already installed and many projects are in construction or in the planning stage. Marine aquaculture along the Baltic Sea and the Denmark coast is an advantageous tie-in-strategy to optimize the great potential to sustainably develop offshore wind farms that are supported by strong and stable winds. For instance, in the Danish portion of the Baltic Sea and in the western part of the Danish coast the average wind speed ranges between 7 and 10 m/s with higher values in the Northern zones. Persistent winds, together with shallow water columns (depth less than 40 m) are important factors influencing the feasibility of developing an offshore wind farm (Benassai et al., 2014c).

However, the social and environmental conditions of the coastal areas should always be considered, especially during the planning stages. In the North Sea these planned structures compete with shipping, recreational activities, cables and pipelines, military exercises, and fisheries (Wirtz et al., 2003).

The circulation in the coastal area under study, consisting in the Southern and Eastern North Sea, from the German Bight into the Skaggerak, is influenced by the Jutland current in the Northern part of Denmark which branches into two currents, one staying in the North Sea and the other entering the Skagerrak. In the Kattegat the influence of oceanic circulation is weaker than in the North Sea since dominating factors are river run-off and larger atmospheric variability above land (Becker, 1996).

The South-Eastern part of the North Sea is influenced by the shallow water column and the strong tidal current which transports high nutrient and sediment loads. In general the North Sea circulation pattern is cyclonic, so that German Bight waters, which are nutrient-rich due to river discharge in relatively shallow waters, are transported towards North along the Jutland west coast, into the Skagerrak and even spilled into the Kattegat.

2.2. Data source and modelling

Topography was interpolated from ETOPO1 high-resolution (1 arc-minute) digital elevation model. Fig. 1 evidenced a North Sea average of about 100 m deep, with a maximum depth higher than 200 m in the Skagerrak (between Denmark and Norway) and depths of few meters (lower than 20–25 m) in the Southern Bight (51–54° N). In particular the western part of the Kattegat presents relatively shallow depths (10–20 m) whereas the eastern part has a north–south trench with depths higher than 40 m and more (Carstensen and Conley, 2004). With regard to wind speed at 10 m a.s.l., the MERRA (*Modern Era Retrospective-analysis for Research and Application*), a NASA reanalysis for the Era satellite using the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5 DAS), was used. The original data was on the GEOS-5 grid with 2/3 degree longitude and 1/2 degree latitude resolution and covers the period 01/10/2006–31/10/2016. This dataset, although with a relatively low resolution, is the only public data covering the study area.

The SST (Fig. 4) and relative anomaly (SSTa) (Fig. 5) in the North Sea were obtained by Aqua MODIS (*Moderate Resolution Imaging Spectroradiometer*) satellite observations with a resolution of 4 km pixel^{-1}. The SSTa pattern shows North Sea regions with warmer or colder temperature than the long-term average for a given year (from October 2015 to October 2016).

The chlorophyll-a (Chl-a) concentration in the ocean indicates the presence and concentration of phytoplankton, and is related to oceanic primary production. Fig. 6 shows interannual averaged (from 2006 to 2016) MODIS/Aqua satellite detected Chl-a concentrations with a resolution of 4 km pixel^{-1}, calculated using an empirical relationship derived from in situ measurements of Chl-a and blue-to-green band ratios of in situ remote sensing reflectances (Rrs).

POC concentration, obtained by MODIS/Aqua observations at the same resolution was reported for the same 10 years averaged dataset in Fig. 7.