Biological Conservation 143 (2010) 230–238

Contents lists available at ScienceDirect

Biological Conservation

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

Towards a spatially explicit risk assessment for marine management: Assessing the vulnerability of fish to aggregate extraction

Vanessa Stelzenmüller *, Jim R. Ellis, Stuart I. Rogers

Centre for Environment, Fisheries and Aquaculture Science (Cefas), Pakefield Road, Lowestoft NR33 OHT, UK

ARTICLE INFO

Article history:
Received 30 September 2008
Received in revised form 14 September 2009
Accepted 7 October 2009
Available online 4 November 2009

Keywords:
GIS
Indicator kriging
Marine spatial planning
Random simulations
Sensitivity index
Vulnerability

ABSTRACT

Management of human activities in the marine environment increasingly requires spatially explicit risk assessments that link the occurrence and magnitude of a pressure to information on the sensitivity of the environment. We developed a marine spatial risk assessment framework for the UK continental shelf assessing the vulnerability of 11 fish and shellfish species to aggregate extraction. We calculated a sensitivity index (SI) using life-history characteristics and modelled species distributions on the UK shelf using long-term monitoring data and indicator kriging. Merging sensitivity indices and predicted species distributions allowed us to map the sensitivity of the selected fish to aggregate extraction. The robustness of the sensitivity map was affected primarily by widespread species with a low to medium level of sensitivity, while highly sensitive species with more restricted distributions had a limited effect on the overall sensitivity. The highest sensitivity in the case study occurred in coastal regions, and where nursery and spawning areas of four important commercial species occur. To test the framework, we overlaid the estimated sensitivity map with the occurrence of aggregate extraction activity in inshore waters, including sediment plume estimations, to describe species vulnerability to dredging. We conclude that our spatially explicit risk assessment framework can be applied to other ecosystem components and pressures at different spatial scales and it is therefore a promising tool that can support the sustainable development of marine spatial plans.

1. Introduction

Many human activities have a direct or indirect effect on marine ecosystems. To ensure sustainable development in the marine environment it is necessary to develop planning tools that move from a sectoral to an integrated approach to marine management (Douvere, 2008). A basic requirement for marine spatial plans is a clear understanding of both the spatial and temporal distributions of human pressures and ecosystem components (species, habitats, etc.), and the effects of human pressures on the marine environment at meaningful ecological scales (Zacharias and Gregr, 2005; Eastwood et al., 2007). Integrated ecosystem-based management also needs to evaluate cumulative and interactive effects of multiple human activities (Evans and Klinger, 2008; Halpern et al., 2008a).

Spatially explicit risk assessments that link information on the sensitivity of the environment to the occurrence of a pressure are fundamental to the implementation of spatial management (Hope, 2006). In general, Ecological Risk Assessments (ERAs) comprise the formulation of the problem, followed by analyses and characterisation of risk (Hope, 2006). The 'problem formulation' phase consists of the development of assessment endpoints, conceptual models and a plan for analyses. The 'analysis phase' requires data to determine the occurrence of adverse effects, and the extent to which the ecosystem is exposed to the stressor(s). In the last phase, past or future risks are estimated and interpreted with the help of both quantitative and qualitative approaches. Thus the final product is an estimate of the probability or likelihood of adverse ecological effects. Quantitative risk assessments rely on mathematical models to predict the response of the ecological receptor to a changing environment. In contrast, qualitative approaches use ecosystem attributes combined with ecological receptors and stressors (Astles et al., 2006).

In marine spatial planning, any ERA must address the location-specific characteristics and interactions that define that ecosystem (Woodbury, 2003). There are currently very few examples of spatial risk assessments in marine ecosystems, and many risk assessments often neglect spatial relationships (Woodbury, 2003; Hope, 2006).

Early attempts to assess marine environmental sensitivity were undertaken for different shore types in relation to the potential impacts of oil spills (Gundlach and Hayes, 1978). More recently, biological and life-history traits and information on species intolerance have been integrated in sensitivity assessments (Bremner et al., 2006; Hiscock and Tyler-Walters, 2006). Other approaches

* Corresponding author. Tel.: +44 1502 527779; fax: +44 1502 513865.
E-mail address: vanessa.stelzenmuller@cefas.co.uk (V. Stelzenmüller).

0006-3207/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biocon.2009.10.007

to assess sensitivity have used species attributes (Williams et al., 1994; Furness and Tasker, 2000) together with spatial information on species occurrences, for example to gauge the potential impacts of offshore wind farms on seabirds (Garthe and Hüppop, 2004).

Comprehensive spatial information on species distributions is often based on the predictive modelling of available data. Spatial modelling is an important component of ecological modelling and is becoming widely used in applied ecology and conservation where understanding the spatial distributions is required (Jørgensen, 2008). Commonly used spatial modelling techniques to predict species occurrences in the marine environment include regression models (Eastwood et al., 2003; Vaz et al., 2008) and geostatistical methods (Stelzenmüller et al., 2005). Recent studies have also combined regression and Geographical Information System (GIS) techniques (Pittman et al., 2007) or geostatistics and GIS (Stelzenmüller et al., 2007). In the context of marine conservation or impact assessment, where predicted species occurrences have been required, the geostatistical tool indicator kriging has been used successfully for less frequently sampled species (Stelzenmüller et al., 2004). Indicator kriging was introduced by Journel (1983) as a spatial prediction method that is suitable for highly skewed data, such as those from fisheries and other field surveys.

Here we developed a spatial risk assessment framework for the UK continental shelf to assess the vulnerability of 11 fish and shellfish species to aggregate extraction. We calculated a sensitivity index (SI) based on seven factors reflecting species' potential vulnerability to aggregate extraction. We used indicator kriging to predict the probability of occurrence for each of the case-study species using a long-term dataset (>10 years) collected from beam trawl surveys operating within the 60 m depth boundary over extensive parts of the English and Welsh continental shelf. Using GIS methods we modelled and mapped the average sensitivity (and its uncertainty) to aggregate extraction by combining the calculated species sensitivity indices with the probabilities of species occurrence. In the final step of our framework, we compared the occurrence of planned and licensed aggregate extraction off the southeast coast of the UK to the modelled sensitivity in order to describe the vulnerability of the area and highlight the potential applications and importance of such an approach. Ultimately, we discuss how this framework might be used to assess the risk of multiple human pressures and serve as a tool for the development of sustainable marine spatial plans.

2. Material and methods

2.1. Study area and species included

We limited the study area to within the 60 m depth contour, the maximum depth for aggregate extraction activities (Fig. 1). Our criteria to select fish and shellfish species for the analysis were that they (i) are likely to be affected by aggregate extraction, (ii) have an appropriate catchability by the survey trawl, and (iii) are of commercial and/or conservation interest. We included cod (*Gadus morhua*), whiting (*Merlangius merlangus*), plaice (*Pleuronectes platessa*), sole (*Solea solea*), turbot (*Psetta maxima*), spotted ray (*Raja montagui*), thornback ray (*Raja clavata*), edible crab (*Cancer pagurus*), lobster (*Homarus gammarus*), queen scallop (*Aequipecten opercularis*) and scallop (*Pecten maximus*).

2.2. Sensitivity index (SI)

Environmental effects of marine aggregate extraction on the seabed include the removal of sediment and the resident fauna, resulting in changes to the nature and stability of sediments. Other direct effects include the exposure of underlying strata, increased turbidity and redistribution of fine particulate material (Desprez, 2000; Newell et al., 2004; Boyd et al., 2005; Robinson et al., 2005; Cooper et al., 2007). There are several potential impacts of marine aggregate extraction on commercial fisheries (e.g. loss of fishing grounds, increased steaming time, displacement of effort, exposure of boulders that may damage trawl nets, etc.), but the effects on fish are not well described in the literature (Newell et al., 1998; Desprez, 2000). Potential effects include loss of habitat, changes in the availability of prey, and an increased vulnerability to predators in turbid waters. The increased turbidity may also affect egg and larval stages through elevated exposure to re-suspended contaminants. Furthermore, there may be important impacts on the suitability of the seabed as a nursery ground (including post-larval habitat) or as a spawning ground, particularly for demersal egg-laying teleosts (e.g. herring) and oviparous elasmobranchs which deposit eggs on geological or biological features on the seabed.

For each of the selected fish and shellfish species we calculated a sensitivity index (SI) reflecting the species sensitivity to aggregate extraction based on the approach developed by Furness and Tasker (2000) and Garthe and Hüppop (2004). In this context, 'sensitivity' is the degree to which fish or shellfish species respond to a pressure, and 'vulnerability' is the probability or likelihood that a component will be exposed to a pressure to which it is sensitive (Zacharias and Gregr, 2005).

The sensitivity index sums the scores of seven different factors derived from species attributes which are most responsive to the impacts associated with aggregate extraction. We scored each factor on a 5-point scale from 1 (low) to 5 (high). The factors included are described below.

2.2.1. Geographical distribution

In a GIS we superimposed the locations of survey trawl catch data (presence/absence; see detailed description of survey data below) on a 2 nm by 2 nm grid. For each species we calculated a spatial distribution ratio as the number of cells with presence data/total number of grid cells (27,213) and scored 1 for >0.03, 2 for >0.02–0.03, 3 for >0.01–0.02, 4 for >0.005–0.01, and 5 $\leqslant$ 0.005, so that species with patchy or restricted distributions had the highest sensitivity score.

2.2.2. Threat status

We derived for each species a status of threat from the IUCN red list published in 2007 (www.iucnredlist.org) and the OSPAR (2007) list of Threatened and/or Declining Species and Habitats. The scores were distributed as follows: 1 = not on a list, 2 = lower risk, 3 = vulnerable, 4 = endangered, 5 = critically endangered.

2.2.3. Importance for fisheries

This factor reflected the economic importance (£) of the species in commercial fisheries. For each species we multiplied the average price per tonne of fish landed in the UK by UK vessels from January to August 2007 (taken from the UK Sea Fisheries Statistics (2007)), by the total weight of fish landed to yield a total value (£/1000). We distinguished five categories and scored as follows: 1 = <£2291, 2 = £2292–£5363, 3 = £5364–£10,966, 4 = £10,967–£15,346, and 5 = >£15,347.

2.2.4. Habitat vulnerability

The habitat vulnerability factor reflected the proportion of the habitat vulnerable to aggregate extraction. We distinguished the habitat categories in terms of distance from shore (estuary, inshore, inner shelf, outer shelf, slope), and substratum (sand, mud, shelf gravel, and rock), and calculated the species habitat diversity (HD) as the total number of habitat combinations that a species