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Ecological niche modelling of the distribution of cold-water coral habitat using underwater remote sensing data

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ABSTRACT

Despite a growing appreciation of the need to protect sensitive deep sea ecosystems such as cold-water corals, efforts to map the extent of their distribution are limited by their remoteness. Here we develop ecological niche models to predict the likely distributions of cold-water corals based on occurrence records and data describing environmental parameters (e.g. seafloor terrain attributes and oceanographic conditions). This study has used bathymetric data derived from ship-borne multibeam swath systems, species occurrence data from remotely operated vehicle video surveys and oceanographic parameters from hydrodynamic models to predict coral locations in regions where there is a paucity of direct observations. Predictions of the locations of the scleractinian coral, *Lophelia pertusa* are based primarily upon ecological niche modelling using a genetic algorithm. Its accuracy has been quantified at local (~25 km^2) and regional scales (~4000 km^2) along the Irish continental slope using a variety of error assessment techniques and a comparison with another ecological niche modelling technique. With appropriate choices of parameters and scales of analyses, ecological niche modelling has been effective in predicting the distributions of species at local and regional scales. Refinements of this approach have the potential to be particularly useful for ocean management given the need to manage areas of sensitive habitat where survey data are often limited.

1. Introduction

A goal in ecology, conservation planning, evolution, biogeography, climate change scenarios and invasive-species studies is the ability to predict where a species is likely to occur without extensive direct observations (Peterson et al., 2003, Fleishman et al., 2001, Peterson et al., 2002b, Anderson et al., 2002, Segurado and Araújo, 2004). Ecological niche modelling predicts the locations of suitable habitat for a species based on occurrence records and physical environmental parameters (Anderson et al., 2002, Anderson et al., 2003, Peterson, 2001, Pulliam, 2000, Mc Nyset, 2005, Austin, 2002). The predictions rely on an understanding of the factors influencing species distributions at multiple spatial scales and are proving to be an innovative tool for an initial exploration of questions related to species ecology, distribution and management.

Numerous studies have focused on developing quantitative models of species' niches and species–environment relationships with the objective of predicting species' distributions. Some have used geographic information system (GIS) based techniques (Store and Jokimaki, 2003, Zhao et al., 2006), statistical methods such as Ecological Niche Factor Analysis (ENFA) (Hirzel et al., 2006, Hirzel et al., 2002), multiple regression analysis and other generalised linear and additive models (Guisan and Zimmermann, 2000, Guisan et al., 2002, Zaniewski et al., 2002), generalised dissimilarity models; maximum entropy (Elith et al., 2006), genetic algorithms (Stockwell and Noble, 1991), neural networks (Recknagel, 2001, Guisan and Zimmermann, 2000); multivariate adaptive regression splines; BIOCLIM (Beaumont et al., 2005) and classification techniques (Guisan and Zimmermann, 2000, Pesch et al., 2007). A common approach of all these techniques is to include georeferenced species occurrence data combined with environmental variables to develop a map which predicts a species' potential distribution within a given geographic range. The areas of predicted presence ecologically resemble those areas where the species is known to occur. Primary occurrence data for predictive models may, for example, be derived from collections of museum specimens (Lim et al., 2002, Wiley et al., 2003), along with records compiled from atlas collections (Peterson, 2001) and data derived from interviews with local fisherman (Gass and Willison, 2005). Other occurrence records are gathered from data collected during field sampling. The environmental variables

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belong to a subset of variables that may influence the species' ecological niche. Generally, they do not include other influences (e.g. food webs, environmental conditions) that are changing with time. The resulting partial ecological niche model consists of a map of the species' potential geographic distribution.

Within the framework of partial ecological niche modelling, there are still challenges arising from the use of ad hoc data collections from poorly-designed experiments or opportunistic sampling, or the types, distributions and correlations of environmental data used for the independent variables in the predictive models (Stockwell and Peters, 1999). In addition, there are often no objective criteria for assigning the weighting that an independent variable contributes to a prediction, so there are many combinations of variables that result in many models which satisfy the data. These challenges are especially pertinent to benthic habitat studies in deep waters where the expense and logistics of data collection require that species occurrence records are limited to ecosystem hotspots, leaving much of the seafloor unexplored. This paucity of direct observations of a species in remote areas poses considerable difficulties for an understanding of benthic habitats.

In this study we present an approach to partial ecological niche modelling of cold-water coral habitats along the Irish continental slope in the northeast Atlantic Ocean. We focus on cold-water corals because they are representative of sensitive deep-water ecosystems with a global distribution.

Our approach to the partial ecological niche modelling uses the well-established Genetic Algorithm for Rule-Set Prediction (GARP) developed by Stockwell and Noble (1991), based upon a genetic algorithm (Holland, 1975). GARP has predicted single and multiple species distributions across diverse regions and taxa (Peterson and Cohoon, 1999, Peterson et al., 2002a, Anderson et al., 2002, Anderson and Martinez-Meyer, 2004, Peterson et al., 2003). It has predicted distributions of marine and freshwater fish species (Wiley et al., 2003, Mc Nyset, 2005) but it has not previously been applied to species in deep sea benthic environments. Its ability to assess a wide range of possible model predictions based upon sparse species presence-only data was an attractive feature to address the challenges of partial ecological niche modelling in the deep ocean. We have used it to predict the spatial distribution of cold-water coral habitat based upon species occurrence records derived from ROV video imagery, terrain parameters derived from multibeam swath acoustic bathymetry data and oceanographic parameters derived from hydrodynamic model predictions.

In this study, we address the following questions: (i) can GARP models predict cold-water coral habitat in local areas (~25 km^2) and regions (~4000 km^2) from available environmental parameters?, (ii) how accurate are the predictions?, (iii) which combinations of environmental parameters produce the most accurate predictions?, and (iv) which analyses scales improve the accuracy of the model predictions?

2. Cold-water coral habitats

Scleractinian, azooxanthellate reef framework-forming cold-water corals have a global distribution (except for polar regions) and are particularly well studied in the northeast Atlantic (Schroeder, 2002, Reed, 2002, Mortensen et al., 2001, Freiwald et al., 1999, Fosså et al., 2002, Taviani et al., 2005, Rogers, 1999). In the northeast Atlantic, *Lophelia pertusa* and to a lesser extent, *Madrepora oculata* are the principal reef-forming scleractinian corals with a third species *Desmophyllum cristagelli* commonly observed associated with dead coral framework (Freiwald, 2002). The high degree of complexity associated with cold-water coral reefs represents a habitat for diverse associated fauna (Jensen and Frederiksen, 1992) including fish, crustaceans, echinoderms, mollusks, polychaete and sipunculan worms and other macrofauna.

The occurrence of *L. pertusa* in Irish waters has been associated with clusters of carbonate mounds in water depths predominantly between 400 and 1000 m at the Porcupine Seabight (De Mol et al., 2002; Huvenne et al., 2005). Porcupine Bank (Wheeler et al., 2005, Olu-Le Roy et al., 2002, Van Weering et al., 2003) and Rockall Trough (Van Weering et al., 2003, Kenyon et al., 2003). Cold-water corals can occur as individual colonies but where conditions are favourable, colonies coalesce to form reef structures covering several kilometres.

L. pertusa thrives under specific environmental conditions of which factors such as water depth, water movement, temperature and food supply are considered crucial. The lower temperature limit of *L. pertusa* in the northeast Atlantic Ocean is the 4 ° C isotherm while the upper temperature limit has been recorded at 12 °C; the depth range for their occurrence is ~100 m to 1500 m and the evidence at present suggests that physical oceanography may partly explain the distribution of *L. pertusa* along the continental margin (White et al., 2005, Thiem et al., 2006). Corals are non-vagile benthic animals and cannot seek out their own food so they rely on the local current regime to supply an abundance of small food particles (Mortensen et al., 2001, Frederiksen et al., 1992, Reed et al., 2006). The corals are typically associated with topographic highs such as carbonate mounds, moraine ridges and iceberg plough-mark levees where current acceleration enhances food supply to the suspension feeders (Thiem et al., 2006, Gage and Tyler, 1991). Internal tidal mixing at the continental slope is thought to influence the distribution of the scleractinian corals by promoting increased bottom mixing and sediment re-suspension at carbonate mounds (Genin et al., 1986). Permanently or episodically strong currents prevent the settlement of fine-grained detritus, provide food particles to the coral polyps and possibly exchange waters carrying larvae and gametes (Frederiksen et al., 1992, Roberts et al., 2003).

Cold-water corals encountered in the study areas (Fig. 1) take the form of 'thickets' typically occurring on the upper flanks of carbonate mounds where they are well positioned to receive maximum exposure to currents along mound slopes and over the top of the mound; this allows the corals to orient their polyps to the direction of currents carrying suspended food particles. The lower-mound flanks tend to exhibit few living corals and are dominated by extensive coral debris. Corals are generally absent from the flat seabed between mounds with the exception of isolated colonies occurring on boulders, sand ripples or in rough bathymetric depressions (e.g. channels) (Mortensen and Buhl-Mortensen, 2004b, Mortensen and Buhl-Mortensen, 2004a, Hovland et al., 2005).

3. Methods

It is generally recognised that many benthic fauna show a particular affinity for certain types of terrain (e.g. Wilbur, 2000, Džeroski and Drumm, 2003). Recent developments in swath acoustic multibeam systems have made it possible to acquire full coverage high resolution bathymetric data of the seafloor. These data can be processed to produce seafloor terrain attributes that are useful environmental variables for the definition of a habitat in shallow water (Kenny et al., 2003, Kostylev et al., 2001) and deep water (Dartnell and Gardner, 2004, Lundblad et al., 2006). We have used seafloor terrain attributes including slope, terrain complexity (rugosity and bathymetric position index), aspect and curvature to help define the partial ecological niche (Wilson et al., 2007).

Slope may serve as a proxy for current kinematics at mounds and hence the supply of food to suspension feeding organisms (Wilson et al., 2007). Closed current circulation patterns such as Taylor column formation can be generated that promote the retention of organic matter over a bank (White et al., 2005). Topographically complex surfaces have been investigated to understand why they exhibit increased species diversity (Kostylev et al., 2005, Johnson et al., 2003). Terrain rugosity is defined as the ratio of surface area to planar area