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Predicting the occurrence of rocky reefs in a heterogeneous archipelago area with limited data

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ABSTRACT

The lack of spatial distribution data on marine habitats often presents an obstacle to their protection. The Annex I of the Habitats Directive (European Council Directive 92/43/EEC) lists habitats that are important in biodiversity protection and should be maintained (or restored) to a favourable conservation status. The habitats listed should be protected within an ecological network of protected areas, the *Natura 2000* network. However, in the past the establishment of the marine *Natura 2000* network has been largely based on insufficient knowledge on the distribution of the habitats. Annex I habitat type reefs are defined as formations of hard compact biogenic or geogenic substrata, which arise from the seafloor in the sublittoral and littoral zone. As obtaining marine data is time-consuming and costly, the bathymetric and substratum data needed for their identification on a larger scale are often scarce. Furthermore, the use of data may be limited due to e.g. national security reasons. This study identifies reefs in a complex archipelago area in the northern Baltic Sea using the best, although limited, data currently available. In the area reefs are elevated rocky outcrops and the associated algal communities and blue mussel beds are vital in maintaining biodiversity in the relatively species poor Baltic Sea. In addition to identifying the physical reef structures, an estimate of their ecological value is obtained by modelling the distribution of four key species occurring on reefs. The results are encouraging, as 55 out of 68 of the potential reefs ground-truthed were confirmed to be reefs. Furthermore the number of predicted species occurring on the reefs, correlated significantly with the number of species observed. The presented maps serve as a valuable background for more detailed mapping of the species diversity occurring on reefs as well as for monitoring their ecological status. Map-based information on important habitats is essential in conservation and marine spatial planning to minimize human impact on marine ecosystems.

1. Introduction

With the drive towards more responsible use of marine resources in the recent decades, the spatial element of marine management has become ever more important. Management strategies, including spatial zonation of activities, have become the preferred way to minimize human impact on marine ecosystems. One of the core tools of spatial management is the establishment of interconnected networks of marine protected areas (MPAs) to ensure that species and habitats are maintained within their natural range. In Europe, the protection of marine habitats and species is largely implemented under the Habitats and Birds directives (Council Directive 92/43/EEC and Directive 2009/147/EC, respectively), which stipulate the formation of an ecological network of protected sites encompassing the terrestrial and marine habitats occurring in Europe (*Natura 2000* network).

Annex I of the Habitats Directive lists habitats important in biodiversity protection but these are mainly large physical habitats, defined by topographical and geomorphological attributes, but some biological formations are also included (e.g. biogenic reefs). In addition, typical species and communities associated with the habitats in the different European seas have been identified to broaden the habitat descriptions (European Commission, 2007).

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Furthermore, national interpretations of the pan-European habitats provide additional specifications on the habitat characteristics, including lists of typical species (Airaksinen and Karttunen, 2001).

Effective reserve design and management policies depend on spatial data availability, enabling more direct management of human activities (Costello et al., 2012). However, obtaining spatial data on seabed habitats is challenging and costly, and consequently most of the seabed globally remains unmapped. The requirement for spatial data on marine Annex I habitats in the subtidal has led to various GIS and statistical modelling efforts on existing data. The primarily physical nature of the habitats enables the use of topographical and geological attributes to map potential habitats. GIS analyses based on bathymetry and coastal morphology have been used to identify e.g. potential reefs (Diesing et al., 2009) and Large Shallow Inlets and Bays (Bekkby and Isaeus, 2008). However, in many cases the datasets required for the analyses may be incomplete, lacking e.g. the accuracy needed for reliable analysis, or their use may be limited due to national legislation (e.g. the Territorial Surveillance Act in Finland).

As the diversity of species and communities occurring in Annex I habitats are key aspects contributing to their ecological value, incorporating species information to the habitat maps increases their usability from the management perspective. Species distribution modelling is a tool that is used in conservation and spatial planning, especially in the terrestrial environment (Elith and Leathwick, 2009), but also increasingly in the marine realm (Robinson et al., 2011). Species distribution models (SDMs) provide a means for linking full coverage environmental data to point data on species occurrence, producing probability maps of species distribution. In recent years, many extensive marine habitat mapping projects have been ongoing in European countries (e.g. Connor et al., 2006; Buhl-Mortensen et al., 2011; Dorschel et al., 2011), resulting in better data availability on marine biodiversity. Also the geographical cover and resolution of available GIS layers of the physical environment has improved due to e.g. remote sensing techniques and advanced modelling techniques (Brown et al., 2011; Micallef et al., 2012).

According to the habitat description, reefs are formations of hard compact biogenic or geogenic substrata, which arise from the seafloor in the sublittoral and littoral zone (European Commission, 2007). The Annex I reefs include a range of such different habitats as biogenic reefs constructed by polychaetes (Hendrick and Foster-Smith, 2006; Rabaut et al., 2008), corals (Howell et al., 2011) or bivalves on soft substrata, to outcrops of hard substrata formed by bedrock, cobbles and boulders. This study focuses on the reefs formed by hard substrata.

In terms of biodiversity, rocky reefs often support a zonation of benthic communities, important in maintaining marine biodiversity. This is also true in the northern Baltic Sea although the species diversity is lower in comparison to more marine environments due to low salinity (e.g. Nielsen et al., 1995; Rinne et al., 2011). In the Baltic Sea, the shallow sublittoral is dominated by ephemeral green and brown algae (e.g. Kiirikki, 1996). A key species on the reefs is the perennial brown algae *Fucus vesiculosus* L. that forms a belt below the ephemeral algae. It is an important food source for many invertebrates (Engkvist et al., 2000; Wikström and Kautsky, 2007) also creating refuge for many invertebrate and fish species (e.g. Kautsky et al., 1992). Occurring among the *Fucus* belt, but mainly below it, a variety of red algae are important habitat builders (Eriksson and Bergström, 2005) that may facilitate e.g. mussel colonization (Westerbom et al., 2008). Many of the perennial red and brown algae respond negatively to the eutrophication effects of the Baltic Sea (e.g. Kangas et al., 1982; Berger et al., 2003) and thus may be used as indicators of the ecological status of the reefs (Eriksson and Bergström, 2005; Carstensen et al., 2008). For example, the number of late-successional algal species has been found to correspond negatively to eutrophication (Carstensen et al., 2008). Also the bivalve *Mytilus edulis* L. is often found within the algal communities and attached to *Fucus*, but it also forms dense beds below the algal zone (optimally 5–8 m, Westerbom et al., 2002). The mussel beds have been found to support diverse communities of associated fauna (Koivisto and Westerbom, 2010) and they are also an important food source for diving birds (Nyström et al., 1991).

This study aimed to map the occurrence of the Annex I habitat reefs in a geographically complex area where detailed full-cover data on substratum are lacking and detailed information on bathymetry is unavailable due to national legislation. This is done by examining the link between geological features and bottom topography derived from an existing coarse resolution bathymetric model and using the observed linkages to identify potential rocky reefs outside the extent of existing geological data. As the species diversity occurring on a reef is a key aspect in defining its conservation value, an estimate of the ecological value of the reefs is produced by modelling the distribution of the key component species.

2. Material and methods

2.1. Study area

The study was carried out in the highly heterogeneous archipelago region in south-western Finland, northern Baltic Sea (Fig. 1). The Baltic Sea is non-tidal and the low salinity (varying between 4.0 and 6.2 within the study area) and the ice that covers the northern Baltic Sea in the winter create a challenging environment for the biota. The archipelago acts as a transition zone between the coast and open sea, creating gradients of wave exposure, salinity, water quality and clarity, all generally decreasing towards the mainland (Jumppanen and Mattila, 1994; Suominen et al., 2010). The outer archipelago is rocky and exposed, while the innermost parts are sheltered and shallow, and often have softer sediments in combination with reed vegetation. The resistant Precambrian crystalline rocks and fault tectonics create complex topographic features in the area (Winterhalter et al., 1981; Kaskela et al., 2012). Average depth is about 20 m, but deep elongated channels located in bedrock fracture zones can reach depths of 100 m, whilst small skerries and subsurface rock outcrops are scattered throughout the area. The patchy seabed substratum distribution, with rock outcrops, gravel, sand and clays of different ages, forms one of the most diverse seabed areas within the Baltic Sea (Häkkinen, 1990; Kaskela et al., 2012).

2.2. Identifying potential reefs

2.2.1. Data

Only 41% of the study area is covered by detailed (scale ≥1:20,000) seabed substratum survey data (Fig. 1), interpreted from acoustic-seismic survey lines situated approximately 500 m apart and verified by sediment sampling (e.g. Häkkinen, 1990). In the remainder of the study area a coarse scale (1:1,000,000) seabed substratum type data layer, covering the whole Baltic Sea (Winterhalter et al., 1981), was used for background information, but it does not capture the true heterogeneity of the study area. Both datasets were reclassified to the following marine geological categories: 1) Mud, 2) Clay and silt, 3) Hard clay (varved clay that is exposed, often a thin sand layer on top), 4) Sand and gravel 5) Complex seabed (till), 6) Rock and boulders.

As no detailed bathymetric data were available for the study area, 20 m cell size bathymetric model covering the extent of the geological and species distribution modelling area (Fig. 1) was

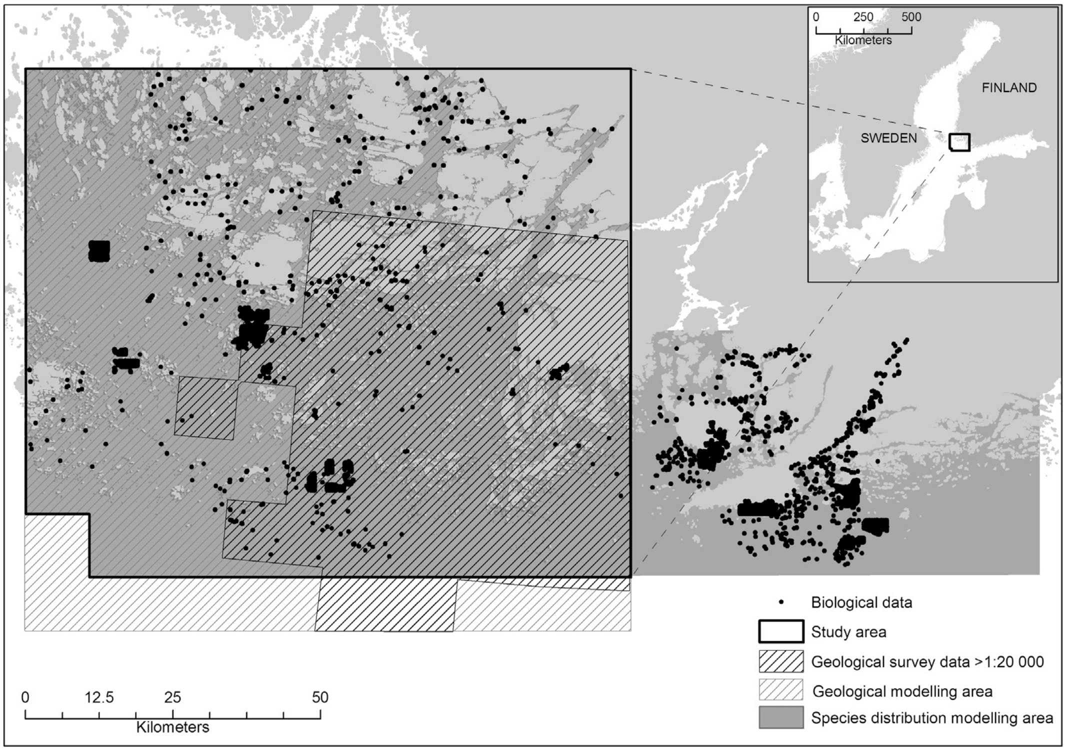

Fig. 1. The study area with the extents of geological survey data, geological modelling area, distribution modelling area and locations for biological data.

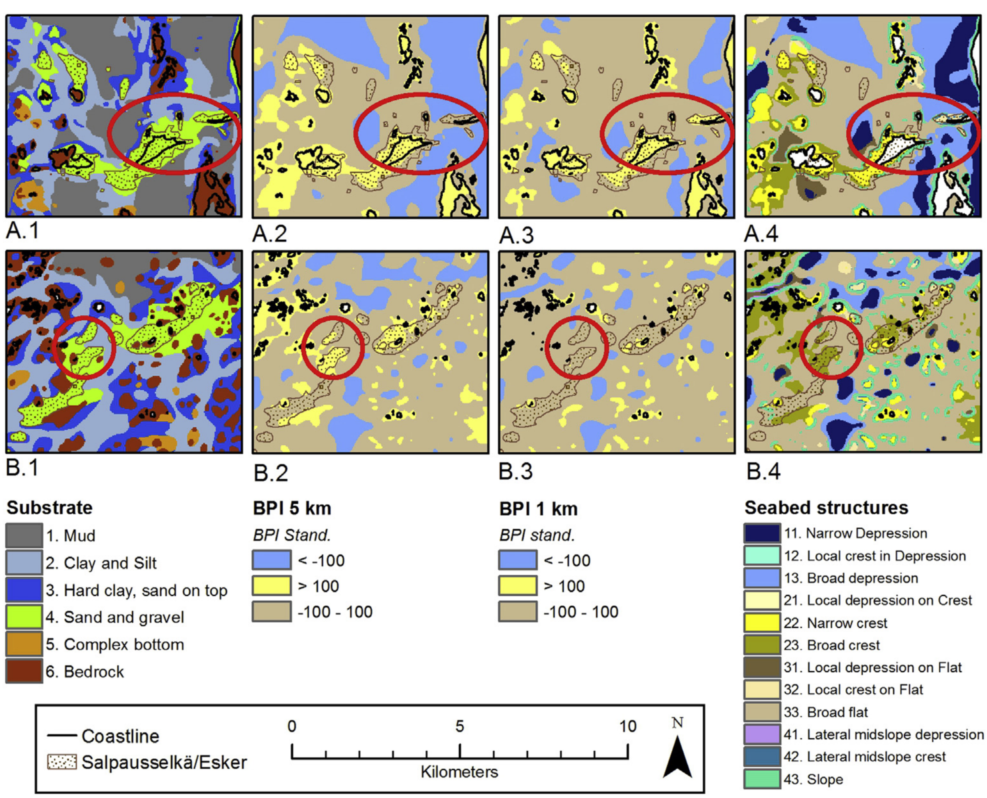

Fig. 2. The Bathymetric position index (BPI) values with neighbourhood sizes of 1 km and 5 km were combined with slope and classified into seabed structures. The combination of neighbourhood sizes represents a satisfactory compromise between the BPI values and a visual comparison with substratum distribution. Particular interest has been on esker and Salpausselkä formations and BPI values above 100, i.e. elevated structures. The areas outlined with red emphasize that in addition to structures that stand out with both neighbourhoods there are structures that coincide with esker data but are distinguished only from either local (A.2 and B.2) or broad (A.3 and B.3) neighbourhood. Both marine and terrestrial substratum data were used for visual comparison where available.

produced using the ArcGIS 9.2 “Topo to raster” algorithm (Stock et al., 2010). Contour lines for shoreline, elevation and bathymetry, point data for bathymetry and polygon data for lakes (1:50,000) in the National Land Survey of Finland Topographic Database were used as primary input data for the model. In addition, navigational chart data for submerged and surface rocks and skerries as well as reed stands were used to complement the primary elevation data. Further offshore (Finnish Exclusive Economic Zone, EEZ), the very coarse IOW (Das Leibniz-Institut für Ostseeforschung Warnemünde) Baltic Sea bathymetry dataset was used (Seifert et al., 2001). A terrestrial elevation model, generated from contour lines in the Topographic Database dating from the end of the 1990s with 25 m cell size, was available from the NLS (© National Land Survey of Finland, license no. 13/MML/12).

2.2.2. Analysis

The bathymetric and elevation models were combined to form a continuous digital elevation model (DEM), with 25 m cell size, covering the geological modelling area (Fig. 1). Features raised from the surrounding environment were identified using the ArcGIS extension Benthic Terrain Modeller (BTM). BTM classifies topographically distinct structures based on the Bathymetric Position Index (BPI), which compares the elevation of a cell with the mean elevation of surrounding cells within a specified radius (see Wright et al., 2005; Lundblad et al., 2006). Multiple BPI surfaces with varying radii (BPI^{1km}, $BPI^{2.5km}$, BPI^{5km}) were compared to geological maps to find the best fit with known geomorphic features e.g. esker formations. Based on the visual comparison between BPI surfaces and geomorphic features the optimal neighbourhood sizes in this analysis for small, local features was BPI^{1km} and for broad features BPI^{5km} (Fig. 2). The classification of seabed structures primarily follows that described in Lundblad et al. (2006), with the addition of a “Broad Crest” category (Table 1).

The identified classes of elevated seabed structures were compared with the existing 1:20,000 seabed substratum data (e.g. Häkkinen, 1990) (Fig. 1) to identify the main substratum for each crest type and slope. There are three large terminal moraines, called the Salpausselkä formations that cut across the seafloor of the study area, occasionally forming islands. Additionally, some eskers continue subsurface. These glacial formations are known to consist primarily of sand and till, and are often covered with thick layers of clays (Häkkinen, 1982, 1990). As the primary substratum types of the Salpausselkä area are known to differ from the surrounding rocky areas, the comparison was done separately for these areas (Fig. 3, hereafter referred to as Salpausselkä and rocky areas). All elevation classes, that were rocky in >50% of the cases, were classified as potential reefs. The results of the comparison were then extrapolated to the areas where no detailed geological data were available (59% of the study area). The potential reefs were classified according to their minimum depth to 5 classes; >15 m deep, 10–15 m, 5–10 m, 0.5–5 m and emerging.

Table 1
Threshold values used in seabed structure classification. Bathymetric Position Index (BPI) value references 1 standard deviation as 100 grid value units.

Structures	BPI^{5km}	BPI^{1km}	Slope
1.1 Narrow depression	≤ -1	≤ -1	
1.2 Local crest in depression	≤ -1	≥ 1	
1.3 Broad depression	≤ -1	$-1 < x < 1$	
2.1 Depression on crest	≥ 1	≤ -1	
2.2 Narrow crest	≥ 1	≥ 1	
2.3 Broad crest	≥ 1	$1 < x < 1$	
3.1 Local depression on flat	$-1 < x < 1$	≤ -1	≤ 5
3.2 Local crest on flat	$-1 < x < 1$	≥ 1	≤ 5
3.3 Broad flat	$-1 < x < 1$	$-1 < x < 1$	≤ 5
4.1 Lateral midslope depression	$-1 < x < 1$	≤ -1	>5
4.2 Lateral midslope crest	$-1 < x < 1$	≥ 1	>5
4.3 Slope	$-1 < x < 1$	$-1 < x < 1$	>5

2.3. Species distribution modelling

2.3.1. Data

A total of 9986 point samples were extracted from drop-video, ROV- and scuba-diving transect data collected as part of the Finnish Inventory Program for the Marine Environment (VELMU) during 2004–2011. In all data, depth, bottom substratum and coverage (%) of all identifiable taxa occurring in the field of view were recorded. The dataset is a combination of stratified random sampling (stratification according to depth and exposure) and grid sampling, mainly with 100 m interval, producing relatively large areas with high sampling effort (Fig. 1). Only samples shallower than 30 m were included.

The environmental variables used in species distribution modelling included depth, slope, wave exposure, percentage hard substrata, Secchi depth, salinity and concentrations of nitrogen and phosphorus. Slope (degrees) was calculated from the bathymetric model. Wave exposure was extracted from a wave exposure index grid covering the Finnish territorial waters, calculated using the Simplified Wave Model (SWM) (Isæus, 2004).

As no geological data was available for the whole study area, the coverage of hard substrata (bedrock, boulders and cobbles) was modelled using the substratum data recorded in the biological surveys. To avoid unwanted effects of spatial autocorrelation, grid sampled data were reduced to a random subsample of 10% of the data. Transect data were randomly sampled to 30 m minimum distance between samples. This resulted in 2060 records that were divided into a model training (70%) and a test (30%) dataset. A Random Forest model (Breiman, 2001; Cutler et al., 2007) was created using the ModelMap package (Freeman et al., 2012) in R (R Development Core Team, 2012). Predictor variables included in the model were depth (from the field data), wave exposure (from the exposure model), bottom curvature (calculated from the depth model) and distance to nearest rocky shore. Rocky shores were derived from CORINE Land Cover (Finnish Environment Institute, 2009), and the distance to rocky shores was calculated using the Euclidean Distance function in ArcGIS. The model explained 43.9% of the variance in the hard bottom percentage, and the mean of squared residuals was 0.09. Pearson correlation between the predicted and observed values was 0.65 and the root mean square deviance was 0.31. Prediction error was smaller than differences in values of hard bottom where a species was present or absent, thus the layer was considered adequate for use in SDMs.

Raster layers (100 m cell size) were created for Secchi depth and water quality parameters (total phosphorus content (μg^{-1} L), total nitrogen content (μg^{-1} L) and salinity (psu)) by interpolation (Inverse Distance Weighting) between records extracted from the national water quality database. Long-term average (1999–2008) values of high-summer (July–August) observations were used to describe the general status of the sea.

2.3.2. Analysis

Species distribution modelling was carried out using Maxent, version 3.3.3e. Maxent is a machine-learning method that uses presence-only data to predict species occurrence (Phillips et al., 2006; Elith et al., 2011) and has performed well in comparisons with other modelling techniques (Elith et al., 2006; Monk et al., 2010; Reiss et al., 2011; Poulos et al., 2012). To account for the spatial bias in the survey data, we used all biological sampling points as a background (Phillips and Dudík, 2008; Phillips et al., 2009; Elith et al., 2011).

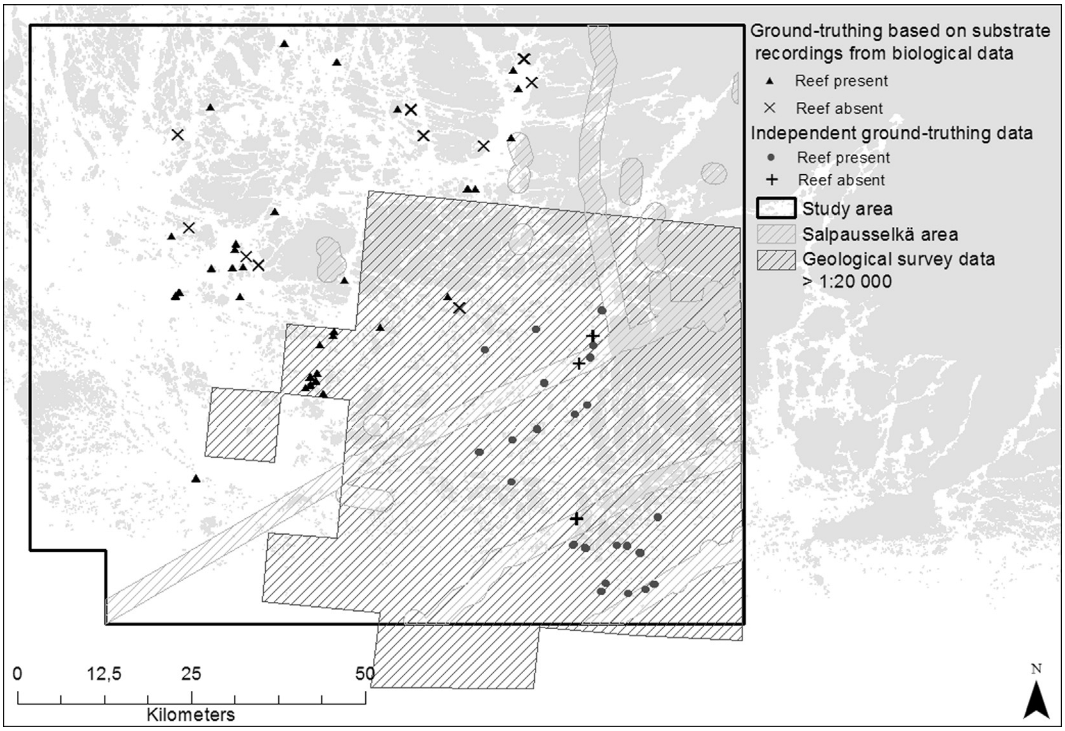

Fig. 3. The ground-truthing sites. The Salpausselkä area as well as the area with detailed geological data, are also shown.

The modelled area includes the whole south-western archipelago region with available biological data, extending further than the study area (Fig. 1). The modelled species were *Fucus vesiculosus*, *Furcellaria lumbricalis* (Huds.) J.V.Lamour, *Phyllophora pseudoceranoides* (S.G. Gmel.) Newroth et A.R.A. Taylor and the bivalve *Mytilus edulis*. These are all listed as typical species to reefs in the Finnish national description of the Annex I habitats (Airaksinen and Karttunen 2001). Furthermore, the modelled algal species are among the perennial algae regarded as sensitive to eutrophication in the Baltic Sea and thus their occurrence may reflect the ecological quality of the reefs (Blomqvist et al., 2012). *Phyllophora pseudoceranoides* was modelled as a species complex with *Coccotylus truncatus* (Pall.) M.J. Wynne et J.N. Heine, as the two species are difficult to distinguish. For *Fucus* and *Mytilus*, which often reach high coverage, only observations exceeding 10% cover (*Fucus*) and 50% (*Mytilus*) were regarded as presences.

All environmental layers were resampled to 20 m cell size and restricted to a maximum depth of 30 m. Biological data were divided into a training (70%) and a test (30%) dataset. Field measured values for depth and % hard substratum were used in the model building. For other variables, values were obtained from the rasters. The correlation between predictor variables was tested, but no strong correlations (correlation coefficients > 0.7) were found. All variables were initially included in the model but only the variables that significantly increased model performance were kept in the final models. The regularization multiplier (e.g. Phillips and Dudik, 2008) was set to 3 in the *Furcellaria* and 2 in the *Phyllophora/Coccotylus* models, as visual inspection of the response curves showed over-fitting to some variables. The default regularization multiplier 1 was used for *Fucus* and *Mytilus*.

Model performance was evaluated on the test data using area under the curve (AUC, Swets, 1988) and true skill statistic (TSS, Allouche et al., 2006). AUC is a threshold-independent measure describing the discriminative ability of the models, with values between 0 and 1 ($1 =$ perfect discrimination and $0.5 =$ no better than random; e.g. Freeman and Moisen, 2008). TSS reflects the rate of false positive and false negative predictions ($\text{TSS} = \text{sensitivity} + \text{specificity} - 1$), but is not as sensitive to frequency of presence points (prevalence) as the commonly used Kappa (Allouche et al., 2006). TSS values >0.6 are considered good, 0.2–0.6 fair to moderate, and <0.2 poor (Jones et al., 2010 and references therein).

The resulting raster layers describing the predicted probability of occurrence were converted into binary presence/absence maps, using the equal training sensitivity and specificity threshold (e.g. Jiménez-Valverde and Lobo, 2007) from the Maxent default output. The binary maps were intersected with the physical reefs. This was done separately for all species, producing four separate shapefiles e.g. "Reefs with *Fucus*", Reefs with *Mytilus*" etc. These shapefiles were converted into raster layers and summed together (in Raster calculator), to produce a layer that showed the number of species predicted to occur on each reef.

2.4. Ground-truthing

As the biological data were used only in species distribution models describing the ecological value of the potential reefs, the occurrence of the potential reefs structures was ground-truthed using the substratum recordings from the dive-transects coinciding with the potential physical reefs (42 transects, Fig. 3). In addition, an independent dive-transect dataset collected in 2012 was used for ground-truthing (26 transects). Out of the 68 ground-truthing transects, 38 were within the extent of the detailed geological data and 30 transects were outside. All transects were on emerging reefs. Transects were placed perpendicular to the shoreline, covering the depths where vegetation occurred. Coverage of both bottom substratum and species were recorded. A potential reef was considered an actual reef if the substratum on transect was bedrock, boulders or stones (larger than 60 mm in diameter). Only the independent dataset was used for evaluating the number of predicted species against the number of species

Table 2
Seabed substrate distribution in the study area according to marine geological data.

Seabed substrate	Study area (tot)		Rocky area		Salpausselkä area	
	km^2	%	km^2	%	km^2	%
1 Mud	514	17	459	17	55	12
2 Clay and silt	1031	33	889	34	142	31
3 Hard clay	693	22	595	23	98	21
4 Sand and gravel	118	4	28	1	90	19
5 Complex seafloor	121	4	103	4	18	4
6 Rock	611	20	554	21	57	12
Total	3088	100	2628	100	460	100

observed (including erect perennial algae and *Mytilus*). The transects varied in the number of predicted species. Pearson correlation was calculated between the number of species predicted and the number of species observed.

3. Results

3.1. Identification of potential reefs

The dominant substrata within the study area were rock and different kinds of clays. Sand and gravel were typical around the offshore continuations of the Salpausselkä formations, where rocky areas were less common (Table 2). The proportion of sand within the Salpausselkä area was higher (19%) than in the area surrounding it (1%). There were some rock outcrops (12%), but their proportion was smaller than in other areas (21%). Thus the division into subareas of rock and sand was relevant for this study. Altogether 12 different types of seabed structures were identified from the study area. Seven structure types were considered to represent elevated structures (structures 1.2, 2.1, 2.2, 2.3, 3.2, 4.2 and 4.3 in Table 1.), covering 27% of the seafloor.

The comparison between the detailed geological data and the seabed structures revealed that in the rocky area, the primary material of elevated structures was rock and boulders both when measured in area coverage and in abundance (Table 3). Of all the elevated features, narrow crests, broad crests and local crests on flat were selected as potential reefs from the seabed structures, as the majority of them were rocky (80%, 62% and 52%, respectively, Table 3). Thus, these structures were regarded as potential reefs throughout the study area, also where detailed geological data were not available. In the Salpausselkä area, the main substratum type of crests in area coverage was sand. However, in abundance the most common material was rock, suggesting that smaller elevations were often of rock and larger elevations were sand. Only narrow crests were rocky in over 50% of the cases, and thus they were regarded as potential reefs across the whole Salpausselkä area. In addition to sand and rock, local elevations in the Salpausselkä area were often composed of clay and silt as well as hard clay (Table 3).

Potential reefs were mainly located in the exposed outer archipelago, where the proportion of water compared to land is high and the islands are small (Fig. 4). Most of the potential reefs (59%) also extend above the surface, forming small islets or islands (Fig. 4a). Of the fully submerged structures, 22% of the reefs extend to a depth of 0.5–5 m, 9% of 5–10 m, 3% of 10–15 m and 7% of deeper than 15 m at their shallowest point.

3.2. Species distribution modelling

All distribution models showed moderate to high accuracy according to AUC, with values varying between 0.79 and 0.95 (Table 4). The TSS values for the models of *Fucus* and *Furcellaria* showed good performance and moderate for *Coccotylus/Phyllophora* and *Mytilus*. The most important variables in the *Fucus* and *Furcellaria* models were depth and hard bottom percentage; both prefer high coverage of hard bottom, with *Fucus* occurring in shallow depths (mainly 1–3 m according to the response curves) and *Furcellaria* slightly deeper (3–10 m). Secchi depth was also an important variable for *Furcellaria*, with the highest probabilities at intermediate Secchi depths (1.5–3 m). Depth was the most important variable also for the *Coccotylus/Phyllophora* complex. Other important variables for the two species were wave exposure (the two species showing preference to high exposures), percentage of hard substratum and Secchi depth, with preference to lower Secchi depths. The percentage of hard substratum was the most important variable for *Mytilus*, followed by depth (maximum probability at 10 m, but occurring in depths of 0–30 m) (Table 4). The presence/absence maps for the species are shown in Fig. 5.

Out of the 9305 rocky crests that were identified in the topographical analysis, 21.8% had one of the modelled species present, 17.4% had high probability for the occurrence of two species, 18.9% for three species and 11.8% for all four species (Fig. 4b). According to the models, it was mainly the smallest rocky crests that had no predicted species presences (29.8% of all reefs) and the species numbers were highest on larger elevations that also reached the surface (Fig. 4).

Table 3
Elevated seabed structures studied against substrate distribution.

Rocky area	Substrate distribution, % of areal coverage						Substrate distribution, abundance %					
Structure	Mud	Clay	H. Clay	Sand	Complex	Rock	Mud	Clay	H. Clay	Sand	Complex	Rock
1.2 Local crest in depression	14	29	51	0	0	6	9	21	49	2	2	17
2.1 Local depression on crest	2	75	23	0	0	1	10	77	8	2	0	3
2.2 Narrow crest	0	5	18	1	4	72	1	3	8	2	3	84
2.3 Broad crest	1	1	26	1	3	59	2	9	23	2	4	60
3.2 Local crest on flat	8	11	38	2	4	37	3	11	27	1	6	52
4.2 Lateral midslope crest	5	9	46	1	3	36	4	10	32	2	3	48
4.3 Slope	9	27	36	1	4	23	13	23	26	1	3	33
Total of row	2	14	29	1	3	49	7	15	24	1	4	49
Salpausselkä area												
1.2 Local crest in depression	0	14	86	0	0	0	0	33	67	0	0	0
2.1 Local depression on crest	0	89	11	0	0	0	0	80	20	0	0	0
2.2 Narrow crest	0	2	30	25	7	36	1	3	12	20	7	57
2.3 Broad crest	0	2	18	68	1	11	1	7	21	18	4	48
3.2 Local crest on flat	0	4	47	15	13	20	2	5	30	15	7	41
4.2 Lateral midslope crest	1	12	35	10	10	33	2	5	34	12	6	41
4.3 Slope	9	25	34	15	3	14	10	25	27	10	3	25
Total of row	2	6	25	46	3	17	5	15	25	14	4	37

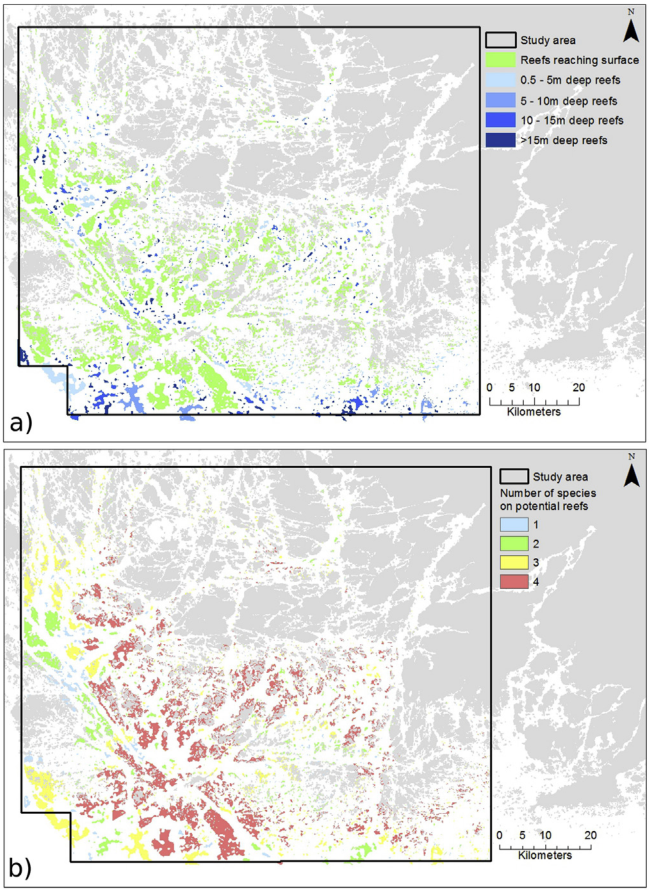

Fig. 4. The identified reefs classified according to a) depth at shallowest point of the reef and b) the number of species predicted present on the reefs by models.

3.3. Ground-truthing

Out of the 68 ground-truthing dive-transects on potential reefs, 55 were actual reefs (81%) (Fig. 3). However, often the substratum became sand or gravel at the deepest end of the transects. Only four of the 38 ground-truthing sites within the extent of the detailed geological data were not actual reefs (89% success rate). The four sites that could not be regarded as actual reefs had gravel and sandy substratum, two of them in the Salpausselkä area (and one close by). Outside the detailed geological data, 9 out of 30 transects (70% success rate) were not actual reefs and most of the misclassified elevations had mixed substrata of sand, gravel and stones.

Only the actual reefs confirmed using the independent ground-truthing dataset (23 transects) were used for evaluating the species composition on the reefs. *Mytilus* was very common throughout the transects, as well as many red algal species, especially *Furcellaria lumbricalis*. In contrast, *Fucus* was absent from many of the ground-truthed sites. On the transects where the number of observed perennials was less than predicted, high coverage of annual filamentous species were recorded (*Cladophora glomerata* (L.) Kütz., *Pylaiella littoralis* (L.) Kjellm., *Ceramium tenuicorne* (Kütz.)). There was a weak but significant correlation between the number of predicted species and the number of recorded perennial species (Pearson's correlation coefficient = 0.45, $p = 0.03$).

Table 4
The variables used in modelling of the species, their importance (% contribution to the model) and model performance (AUC and TSS values). The number of presence records for each species in shown in brackets after the species name.

	Fucus > 10% cover (210)	*Furcellaria (474)*	*Phyllophora/ Coccotylus (141)*	*Mytilus* > 50% cover (1356)
Variable				
Depth	58.4	33.4	32.8	38.6
Hard bottom %	27.9	22.4	14.4	46.5
Exposure	7.2	8.2	16.7	2.2
Secchi	6.5	21.7	14	12.8
Slope		7.7	1.4	
Salinity		0.4	9.7	
N tot		0.4	4.7	
P tot		5.8	6.3	
Model performance				
AUC (test)	0.95	0.86	0.87	0.79
TSS	0.69	0.67	0.51	0.43
Equal training sensitivity and specificity threshold	0.29	0.38	0.32	0.44

4. Discussion

Mapping reef habitats at a level of accuracy sufficient for supporting management decisions is challenging in a heterogeneous archipelago with varying topography and a mosaic of substrata. The convoluted network of islands with the associated long shoreline, shallow waters and navigational hazards presented by submerged outcropping rock make bathymetric and geological mapping time consuming and full coverage is difficult to obtain. In this study we were able to show that extrapolating from existing sources of geological data available in a subarea was a successful way of identifying potential reef structures in an area without high resolution seabed mapping data. Further, we have been able to attribute some ecological value to the potential reef formations through the use of SDMs, enabling a preliminary assessment of their comparative conservation value. Both results contribute valuable, previously unavailable spatial information on one of the key habitats in need of protective measures.

4.1. Identification of potential reef structures

The comparison of structures identified in the BPI analysis and the existing geological data, allowed for the identification of structures likely to be rocky also outside the extent of the detailed geological data. As expected, the modelling results were more accurate within the area where detailed geological data were available than in the area outside (89% and 70% success respectively). However, when considering the size and the heterogeneity of the area, as well as the general change in the environment from the outer archipelago to the inner parts, the accuracy of the modelling can be considered good. Previous knowledge also supported the separation into areas dominated by crystalline bedrock and the areas dominated by moraine features (the Salpausselkä area). This proved to be successful, as elevations with exposed sand were typical only in the Salpausselkä area. However, some structures in the Salpausselkä area were relatively evenly distributed between two or three substratum classes, leading to uncertainty when assigning them to certain substrata. This was also reflected in the ground-truthing results, as the predictions were more uncertain within the Salpausselkä area.

Generally, there were many potential reefs identified in the study area. Ground-truthing confirmed most of the potential reefs as actual reefs, but it also highlighted the zonation of substrata present on most reefs where outcropping bedrock and boulders grade into sedimentary habitats along the elevated features. This suggests that in many areas the reefs were not as large as identified by the analysis and the largest reefs identified were, in fact, larger

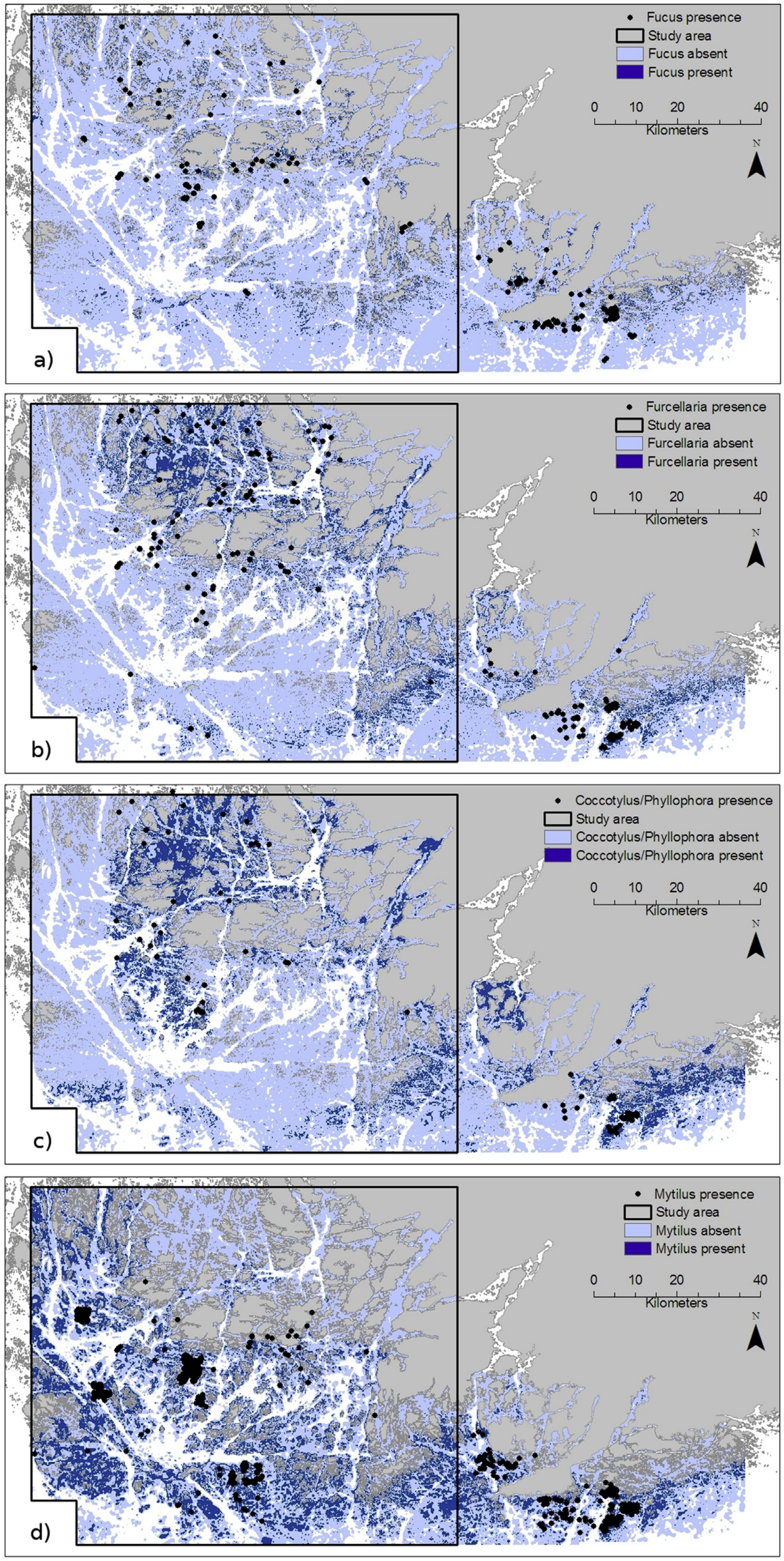

Fig. 5. Presence locations and the modelled presence/absence for a) *Fucus vesiculosus* (>10% cover), b) *Furcellaria lumbricalis*, c) *Phyllophora pseudoceranoides/Coccotylus truncatus* and d) *Mytilus edulis* (>50% cover). Areas deeper than 30 m are shown in white. Predicted presence for *Fucus* is concentrated close to shallow shores and is therefore not clearly visible on the map.

reef complexes with sedimentary substrata in between. As the definition of reefs does not include any information on required size or height for a reef (European Commission, 2007), the selection of scale for the analysis needs to be done case-specifically, based on previous knowledge on the scales of variation in the study area, as well as the scale of the underlying data. Here the scale for the analysis was chosen based on the best fit between the geological data and previous knowledge on the esker formations as the separation between the moraine features and rocky outcrops was considered a key issue when identifying reefs from other elevations in the Archipelago Sea. A more detailed scale analysis would have detected more fine scale variation in the area (e.g. many separate reefs within the areas now identified as large reef complexes) but, on the other hand, missed some important larger features (e.g. eskers and larger reefs). Furthermore, a finer scale analysis would have required even finer scale geological data to find the match between the structures and substratum. Nevertheless, the relatively high success rate in finding reefs shows that biologically relevant entities can be obtained by using geological and bathymetric data, even on a coarser scale.

Most of the rocky outcrops in the study area break the surface to form small islands on the surface. According to the habitat descriptions (European Commission, 2007), the intertidal area is included in a reef if it continues subtidally without interruption, i.e. also the submerged part of shore is a reef. However, in the non-tidal Baltic Sea, reefs that break the surface are classed as underwater parts of Boreal Baltic islets and small islands albeit hosting, in fact, similar communities as reefs. In the study area, the completely submerged reefs were mainly in the outermost archipelago or along the deeper trenches. They were also generally smaller as typically the emerging reefs formed larger complexes with many small islands breaking the surface.

4.2. SDMs and ecological value of the reefs

Species distribution modelling and calculating the number of modelled perennial species occurring on potential reefs provided a useful way of estimating the ecological value of the reefs, as the number of species modelled correlated significantly with the number of species observed. The number of species was also higher on larger elevations that often reached the surface several times, forming many islands. Evidently, the larger areas also covering a wider depth range are likely to have more species occurring on them, but this observation also offers some interesting insights from the conservation perspective. The suitable habitats for species dependent on hard substrata are likely to be better connected to each other within the larger elevations including many islands than between e.g. two smaller elevations separated by deeper trenches. Thus, the identified reef complexes as a whole may be of high conservation value. However, further studies are required to better estimate the connectivity between and within reefs and larger reef complexes.

The main distribution of the modelled red algae (*Coccotylus/Phyllophora* and *Furcellaria*) was predicted to the inner and middle archipelago, but there were areas with high probability of occurrence also in the outer archipelago. Thus the species were also captured as occurring on the outer reefs. Although it is possible that the concentration towards the inner and middle archipelago reflects the true distribution, it is likely that the result somewhat highlights the spatial bias between dive-transects and drop-video sampling. There are more diving sites in the northern parts of the area than in the outer archipelago, and it is possible that these species, usually occurring in low coverages, remained unnoticed in the drop-videos (e.g. covered by filamentous or drift algae typical to the area). In the ground-truthing dive transects, the species occurred regularly also in the outer archipelago. These kinds of shortcomings of the model cannot be detected from the accuracy measures (e.g. AUC) as they only reflect the recorded species observations against the predictions. The result emphasizes the need for balanced sampling designs and methods with equal detection probabilities across survey areas. More structured distribution survey effort is required if species distribution models are to be created for management needs.

On some of the reefs that were predicted suitable for all the predicted species, annual species dominated and only low coverages of perennial species were found. Some of the reefs had only annual species, despite the fact that suitable substratum was available, thus decreasing the correlation between the number of species predicted to occur on a reef and the number of perennials observed. This confirms the findings that despite the lower nutrient concentrations in the outer Archipelago Sea in comparison to the inner parts, the eutrophication effects are evident in the area and large amounts of filamentous algae occupy many of the reefs (unpublished data from the VELMU program). The absence of *Fucus* from the sites where it was predicted to occur may be due to large scale disappearance of the species from the area in the late 1970's (Rönnberg et al., 1985) and its inability to recolonize the areas where it used to occur due to competition from filamentous algae (Berger et al., 2003, pers. comm. with Martin Snickars, Åbo Akademi University). If the eutrophication status will improve as a result of effective management measures, the perennial species may be able to thrive in the areas otherwise suitable for their occurrence and the ecological status of the reefs will improve.

4.3. Conclusions

Although spatial data on habitat distribution are recognised to be of central importance, in many cases sufficient resources for extensive marine surveys (Connor et al., 2006; Buhl-Mortensen et al., 2011) may be lacking. Furthermore, the availability of existing high-resolution data layers is sometimes restricted due to commercial or military sensitivity, e.g. in this study, the most detailed data on bathymetry and bottom substratum existing in the area were not available. Although higher resolution environmental variables and full-coverage data would probably have further improved the results, this study shows that high accuracy can be achieved by combining existing and available knowledge on the geomorphological and geological elements. 81% of the ground-truthed potential reefs were actual reefs and also the species number proved successful in providing knowledge on the ecological value of the reefs. Although the EU definition for reefs does not unambiguously include biological elements, the habitat is included in Annex I of the Habitats Directive due to their high value in biodiversity conservation and the unique biological communities that they host. Thus, from the conservation and spatial management perspective, the inclusion of ecological attributes to the habitat maps is especially important. Nevertheless, the uncertainties compounded by interpolations, modelling and generalizations used during the mapping procedure need to be considered when using the maps for management purposes.

This study has provided new valuable information on the occurrence and characteristics of reefs that can be used to achieve efficient protection of these important habitats. Although results are promising, dedicated surveys and better access to environmental data layers are needed to further improve the accuracy of the maps.

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