



A predictive approach to benthic marine habitat mapping: Efficacy and management implications

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ABSTRACT

The availability of marine habitats maps remains limited due to difficulty and cost of working at sea. Reduced light penetration in the water hampers the use of optical imagery, and acoustic methods require extensive sea-truth activities. Predictive spatial modelling may offer an alternative to produce benthic habitat maps based on complete acoustic coverage of the seafloor together with a comparatively low number of sea truths. This approach was applied to the coralligenous reefs of the Marine Protected Area of Tavolara - Punta Coda Cavallo (NE Sardinia, Italy). Fuzzy clustering, applied to a set of observations made by scuba diving and used as sea truth, allowed recognising five coralligenous habitats, all but one existing within EUNIS (European Nature Information System) types. Variable importance plots showed that the distribution of habitats was driven by distance from coast, depth, and lithotype, and allowed mapping their distribution over the MPA. Congruence between observed and predicted distributions and accuracy of the classification was high. Results allowed calculating the occurrence of the distinct coralligenous habitats in zones with different protection level. The five habitats are unequally protected since the protection regime was established when detailed marine habitat maps were not available. A SWOT (Strengths-Weaknesses-Opportunities-Threats) analysis was performed to identify critical points and potentialities of the method. The method developed proved to be reliable and the results obtained will be useful when modulating on-going and future management actions in the studied area and in other Mediterranean MPAs to develop conservation efforts at basin scale.

1. Introduction

Habitat mapping is a prime necessity for environmental planning and management since it can provide an inventory of environmentally sensitive areas, identify hot spots of ecodiversity, detect changes in biotic cover, allow boundary demarcation of multiple-use zoning schemes, and help quantifying ecosystem services (Bianchi et al., 2012; Ichter et al., 2014). On land, high quality habitat maps are obtained thanks to aerial photography, satellite imagery and an array of multi-spectral and hyperspectral sensors while ground-truthing can be achieved by means of field surveys (Sankey et al., 2017).

In the sea, light attenuation in the water column limits the use of optical methods to the intertidal or shallow depths (Kachelriess et al., 2014). Acoustic methods (such as single- or multibeam echosounders and side scan sonar) supply the best alternative, as sound can reach greater depths (Mayer, 2006).

Acoustic methods can discriminate between reefs and sedimentary areas but give little information on the biotic communities inhabiting these substrata (Markert et al., 2013). The analysis of backscatter images is promising in this respect (Lamarque and Lurton, 2017), but requires a large amount of sea-truthing to associate acoustic regions (or facies or classes) to different biotic assemblages (van Rein et al., 2011). Field surveys for sea-truthing are more expensive than on land, as they require purposely equipped vessels and autonomous or remotely operated videos and scuba diving (Clements et al., 2010). Scuba diving provides the most accurate method to describe and identify benthic communities living on reefs (Bianchi et al., 2004) but has severe limitations in term of operational time and/or depth (Parravicini et al., 2010). All these constraints explain the paucity of detailed marine habitat maps. Spatial distribution models (Guisan and Zimmermann, 2000) applied to the marine ecosystems can represent an alternative to predict the distribution of marine communities on the basis of physical

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attributes such as depth or distance from coast. Physical parameters can be more easily obtained, and require a reduced number of sea-truthing surveys (Martín-García et al., 2013). Spatial distribution models allow obtaining large-scale and efficient mapping also when sea-truthing data are limited. They showed effective in understanding the distribution of benthic organism categories (Holmes et al., 2008), subtidal rocky habitats (Mielck et al., 2014) and seagrass beds (Kelly et al., 2001).

Coralligenous reefs are endemic Mediterranean habitats and important coastal ecosystems for distribution, biodiversity, biomass, and role in the carbon cycle (Laubier, 1966; Bianchi, 2001). They represent an iconic submerged seascape (Bianchi et al., 2005; Giaccone, 2007), exhibit great structural and functional complexity (Paoli et al., 2016, 2018), and provide multifarious ecosystem services to humans (Paoli et al., 2017), but are vulnerable to either global or local impacts (Gatti et al., 2015a, 2015b, 2017; Montefalcone et al., 2017). Coralligenous reefs have therefore been included among the ‘special habitat types’ that should be assessed under the Marine Strategy Framework Directive of the European Union (Bavestrello et al., 2016).

Coralligenous reefs are characterised by a basal bioconstructed layer mostly formed by calcareous red algae (Oprandi et al., 2016) and typically exhibit a canopy of erect macroalgae or sessile invertebrates that grow in dim light conditions and in relatively calm waters, typically between 20 and 120 m (Ballesteros, 2006). They are therefore too deep for optical methods but their distinct assemblages cannot be distinguished by acoustics. The habitat classification developed by the European Nature Information System EUNIS (Davis et al., 2004; Tunesi et al., 2006) recognises 15 such habitat types, differentiated by depth, exposure, substrate, and characteristic and accompanying species (Bellan-Santini et al., 2002). EUNIS habitats characterised by macroalgae are called ‘associations’, those characterised by macroinvertebrates are called ‘facies’. However, in the European Red List of marine habitats, Mediterranean coralligenous habitats are classified as Data Deficient (Gubbay et al., 2016), thus evidencing the urgent need for thorough investigations and accurate monitoring plans (Ballesteros, 2008; Sartoretto et al., 2017).

In this paper, the coralligenous habitats of a Marine Protected Area have been mapped through a predictive model applied to a set of underwater observations, made by scuba diving and used as sea truth, and to acoustic data offering a complete coverage of the seafloor. Results allowed: i) calculating the surface area occupied by each of the distinct coralligenous habitats identified; ii) quantifying their occurrence in zones with different level of protection; and iii) discussing management implications. The application of the spatial prediction method has been criticized through a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis (Gao and Peng, 2011).

2. Material and methods

2.1. Study area

The study area is represented by the coastal marine tract located around Tavolara Island, in NE Sardinia, Italy (Fig. 1).

From a geomorphological perspective, high cliffs, interrupted by narrow coastal plains and coastal lagoons, compose the mainland (Rovere et al., 2013). Two major islands characterise the continental shelf: Tavolara and Molara. From a lithological perspective, the entire study area is composed of granitic bedrock of Hercynian origin (304–251 Mya). The only exception is Tavolara Island, composed almost entirely of Jurassic (201–145 Mya) limestone. Seafloor morphology is similarly characterised by granitic inselbergs and limestone pinnacles and further complicated by beachrocks that run parallel to the coastline at various depths (Orrù and Pasquini, 1992).

Since 1997, Tavolara and Molara, together with most of the surrounding region, have been included in the Marine Protected Area of ‘Tavolara - Punta Coda Cavallo’, extending for about 15,000 ha and divided in three zones subjected to different levels of protection (Rovere

et al., 2013): zone A (no entry – no take), of ca 600 ha, is limited to a small site at the south-east of Tavolara and the islet of Molarotto to the east of Molara; zone B (general reserve, human activities strictly regulated), of ca 3400 ha, is split in four parts around Tavolara, Molara and Molarotto, Capo Ceraso, and Capo Coda Cavallo; zone C (partial reserve or buffer zone, most human activities allowed but regulated) comprises the remaining ca 11,000 ha, between Capo Ceraso to the north and Cala Finocchio to the south (Fig. 2).

Most infralittoral bottoms of the Marine Protected Area are covered by an extensive seagrass (*Posidonia oceanica*) meadow (Navone and Bianchi, 1992; Gattorna et al., 2006), whereas rocky outcrops of different nature (granite, limestone, beachrock conglomerate) harbour distinct epibenthic communities according to depth and slope (Navone et al., 1992; Bianchi et al., 2010).

2.2. Data sources

Early acoustic surveys in the Marine Protected Area of Tavolara - Punta Coda Cavallo were carried out in 1989 using single beam echo sounders (Elac Laz 5100, 60 kHz, and Furuno 612, 100 kHz) and side scan sonar (Klein 150 kHz), and allowed producing a first geomorphological map at the scale of 1:25000 (Navone et al., 1992). In 2011, a new seabed survey was carried out using multibeam (Kongsberg-GeoSwath Plus 250 kHz) and side scan sonar (Klein 3900–445/900), which allowed perfecting and updating the previous map (Deiana et al., 2013; Rovere et al., 2013). From these surveys, detailed bathymetry and georeferenced information about potential coralligenous reef occurrence were obtained (the full set of acoustic data is available at the Marine Protected Area of Tavolara - Punta Coda Cavallo: www.amptavolara.com). Only rocks between 25 m and 55 m (maximum depth explored) were considered in this study (Fig. 2).

Direct observations by scuba diving (Bianchi et al., 2010) were used as sea-truths of acoustic surveys and provided the relevant biological information. Positioning accuracy of divers was in the order of a few tens of metres, which is considered adequate at the scale 1:25000 of the final map (Rovere et al., 2013). Dives were carried out in 21 sites (capital letters A to U in Fig. 2). Depending on local morphological complexity, up to 6 stations were surveyed in each site, differing for depth, slope and proximity of the sedimentary bottom. In total, 57 stations were surveyed, each station consisting of a reef portion of about 2 m² (Gatti et al., 2012). Diving surveys allowed realising an inventory of 59 conspicuous sessile species (Table 1).

2.3. Species clustering

A presence-absence matrix of 59 species × 57 stations was used to classify different species groups by means of cluster analysis (Halkidi et al., 2001), using specifically a fuzzy clustering technique (Dunn, 1974; Bezdek, 1981). Fuzzy *c*-mean (FCM) is an unsupervised clustering algorithm that has been widely applied since the introduction of the fuzzy set concept (Zadeh, 1965; Rezaee et al., 1998).

FCM is able to determine the grade of membership for each object in the cluster, starting from the identification of the most characteristic point in each cluster, which can be considered as the ‘centre’. In the specific case, the centre is represented by the typical species composition of each coralligenous habitat. In particular, FCM minimizes within-cluster variance D_v (distance or square error) expressed as:

$$D_v = \sum_{k=1}^K \sum_{x_j \in S_k} |x_j - C_k|^2$$

where C_k is the mean point of all points in the cluster k , K is the number of clusters, S_k is the set of points in the k_{th} cluster, and x_j is the standardized vector for site j (Sadri and Burn, 2011). The FCM algorithm identifies an initial set of k groups and then calculates the mean point, or centroid, of each set. The next step is the construction of a new partition by associating each point with the closest centroid. Then, the

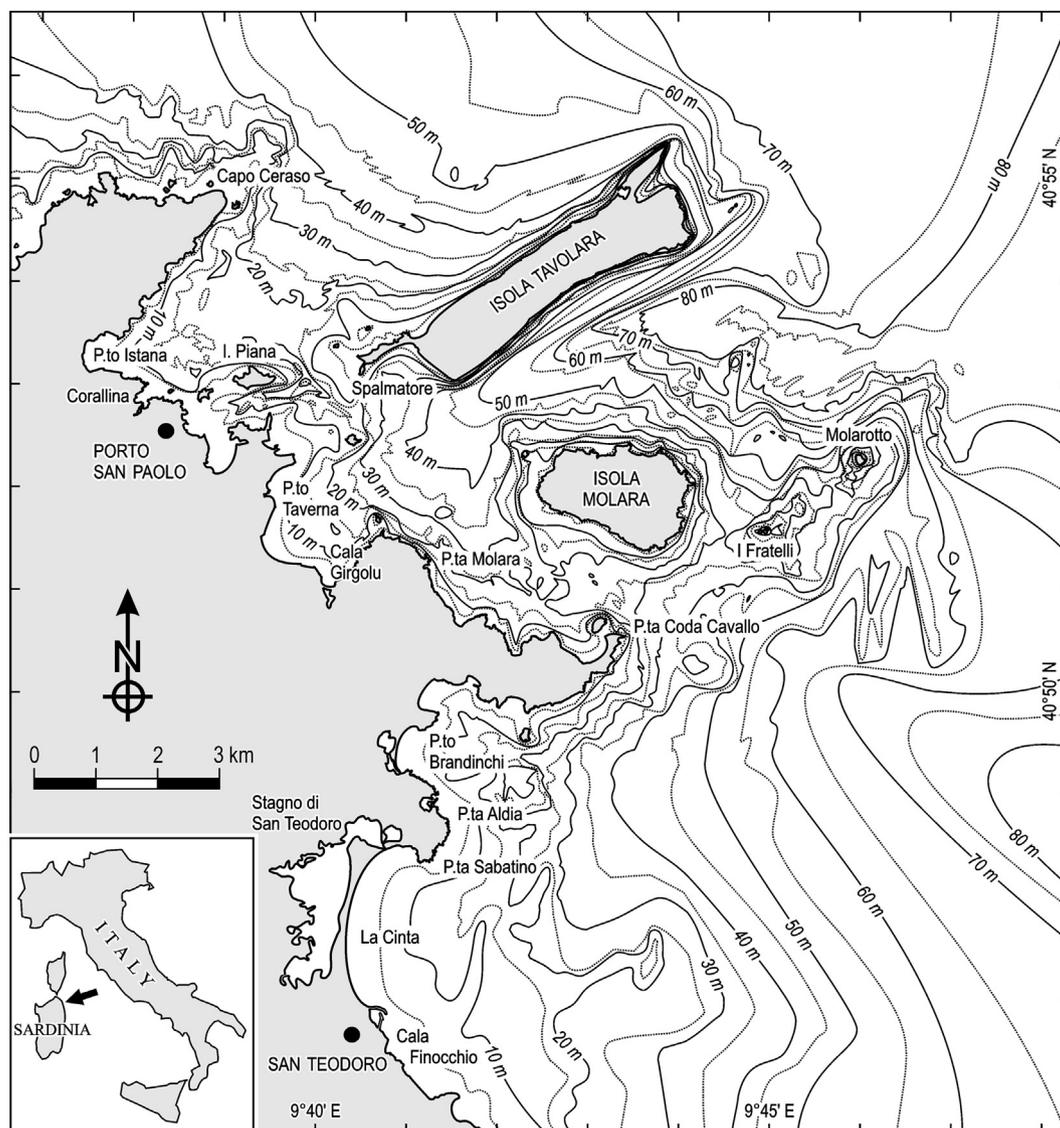


Fig. 1. Study area with main site names and depth contours (every 5 m). Inset: arrow indicates the geographical position of the study area in NE Sardinia.

centroids are recalculated for the new clusters, and the algorithm is repeated by alternate applications of these two steps until the centroids do not change anymore: clusters are therefore defined (Sadri and Burn, 2011).

One of the main features of fuzzy clustering methods is that data points can be assigned to more than one cluster with different degrees of membership (De Oliveira and Pedrycz, 2007), thus evaluating the probability that the input belongs to each cluster. As a consequence, fuzzy clustering can outperform the so called 'hard clustering methods', in which a data point is univocally assigned to a single cluster. This feature is particularly helpful when clusters are not well separated, the borders of the clusters are not sharp, and clusters overlap such as in many environmental applications (Chuang et al., 1999; Gorsevski et al., 2003; Budayan et al., 2009). The degree of belonging of a site i to the k th cluster is equal to the inverse of the distance of site i to the centroid of the cluster. Each station is assigned to the cluster with which it has the highest degree of membership. These coefficients are normalized so that the sum of memberships of one site of interest to all different clusters is unity (Ayvaza et al., 2007).

A clustering toolbox developed for Matlab® was here used for the FCM analysis (Balasko et al., 2005). The optimal values for the number of the clusters have been assessed by determining the compactness and

separation of the clusters: validity indices such as partition index (SC), separation index (S), and Dunn's index (DI) have been calculated (Budayan et al., 2009). SC is the ratio of the sum of compactness and separation of the clusters. The compactness is represented by the mean of the distance between the points and the cluster centroid, weighted by the membership coefficients, whereas the separation is estimated by the sum of the distances from a cluster centroid to all other cluster centroids. SC measures the overlapping of the fuzzy clusters, and greater values are optimal. S is again represented by the ratio of the compactness to the separation, separation being here defined as the minimum distance between the cluster centres. DI is a classical index to identify compactness and separation, and it is calculated as the ratio of the shortest distance between the two point belonging to each other cluster and the largest distance between the two points belonging to the same cluster (Balasko et al., 2005; Kim et al., 2011).

Species groups resulting from fuzzy clustering has been equated, whenever possible, to coralligenous habitats listed in EUNIS (Tunesi et al., 2006).

2.4. Habitat modelling

Each rock between 25 m and 55 m within the study area, as

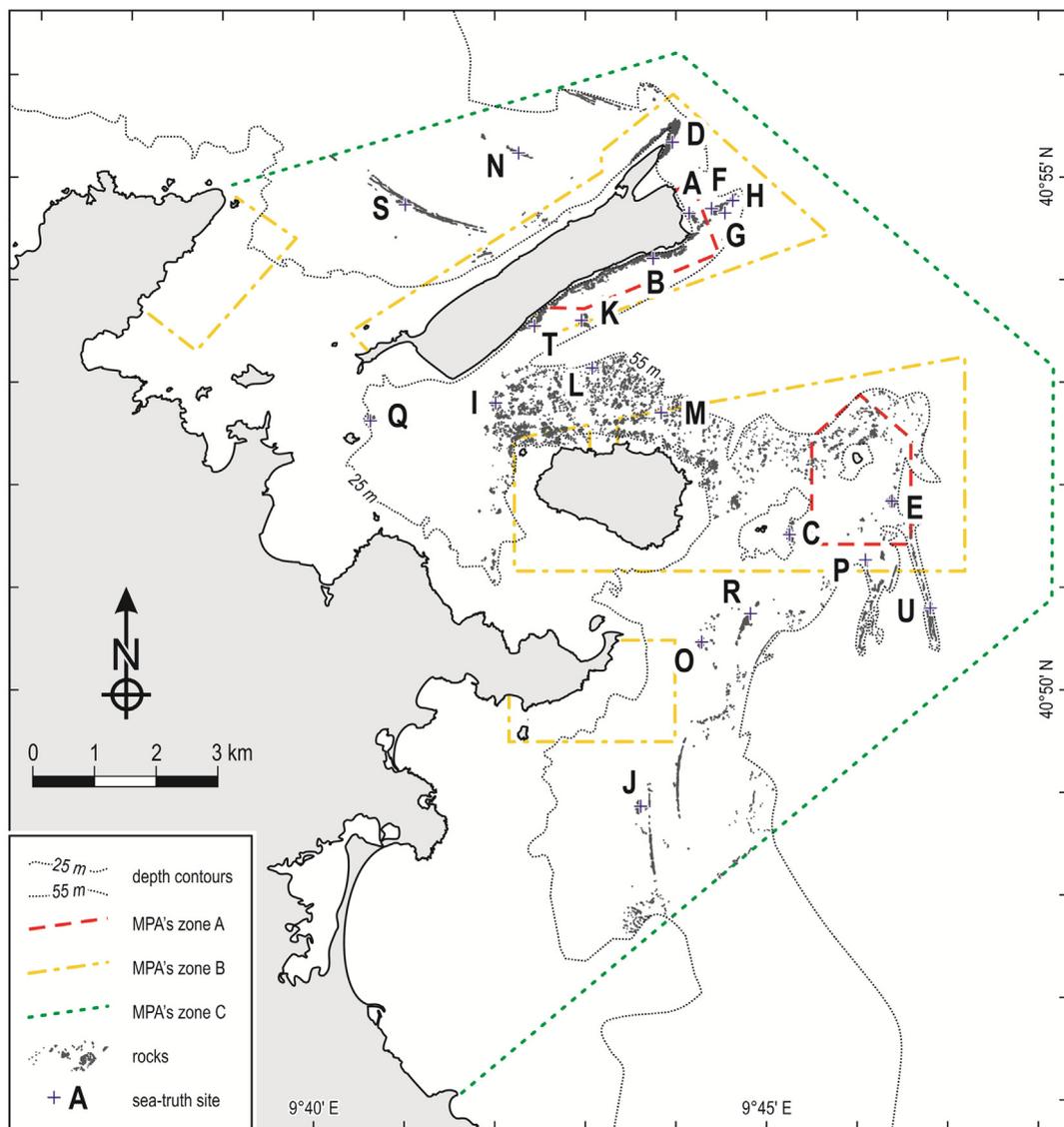


Fig. 2. Prediction area within the depth contours of 25 m and 55 m and the borders of the Marine Protected Area of ‘Tavolara - Punta Coda Cavallo’. The distribution of sea-truth sites is indicated, as well as that of the rocks likely to harbour coralligenous assemblages, and therefore targeted by predictions.

resulting from geomorphological maps produced with acoustic data, was taken into account to assess a number of physiographical features applied as explanatory variables for prediction (Table 2). Explanatory variables were calculated by means of the analysis of shapefiles relative to depth, coastline, substrate lithology, and rocks distribution. Predictive variables were calculated taking into account the centroid of each polygon. Maps of the predictor variables are reported as supplementary material (Appendix A).

Species group distribution with regards of physiographical features was predicted by means of random forest (RF) classification (Breiman, 2001). The algorithm is based on classification tree methodology and is able to model a response variable from a number of explanatory variables by subdividing a dataset into subgroups. This can be represented as a binary tree, a hierarchical structure formed by nodes and edges, the latter representing a sort of information flow between adjacent nodes. In particular, subgroups originate from recursive partitions based on decision rules that allow each part to be divided successively into smaller data portions. This is achieved by two means: (1) a random selection of explanatory variables is chosen to grow each tree and (2) each tree is based on a different random data subset, created by bootstrapping (Efron, 1979). Finally, the optimal ‘splitting’ in comparison with real data is identified and selected as a predictor. The data portion

used as a training subset is known as the ‘in-bag’ data, whereas the rest is called the ‘out-of-bag’ data. The latter are not used to build the tree, but provide estimates of generalization error, which always converges as the forest size increases (Breiman, 2001). The number of trees needs to be sufficiently high since the mean square error is calculated from prediction with the test dataset averaged over all trees (out-of-bag error). With this approach, the presence probabilities of all five species groups are predicted at the same time, and the procedure assesses a presence once the predicted probability is higher than an automatically calculated threshold. Results are represented by maps of presence probability distribution since in many cases more than a species group has been detected on a site.

The rank importance of each explanatory variable is accounted for in terms of changes in mean square error estimated by leaving a variable out of the model. After the most relevant variables were identified, the following step consisted of studying the nature of the dependence between the response variable and each explanatory variable. Partial dependence plots were used to illustrate the relationships between individual explanatory variables and predicted probabilities obtained from RF (Hastie et al., 2001). Univariate partial dependence plots are a tool to identify, for each considered variable, the range of optimal values expected to increase the presence probability (Marini et al., 2015;

Table 1

List of sessile conspicuous species observed during sea-truth dives and used to identify different coralligenous habitats in the Marine Protected Area of Tavolara – Punta Coda Cavallo.

Ochrophyta
<i>Arthrocladia villosa</i> (Hudson) Duby, 1830
<i>Cystoseira zosteroides</i> C. Agardh, 1820
<i>Dictyopteris polypodioides</i> (A.P. De Candolle) J.V. Lamouroux, 1809
<i>Nereia filiformis</i> (J. Agardh) Zanardini, 1846
<i>Sporochmus pedunculatus</i> (Hudson) C. Agardh, 1820
Rhodophyta
<i>Acrosymphyton purpuriferum</i> (J. Agardh) Sjöstedt, 1926
<i>Kallymenia spathulata</i> (J. Agardh) Codomier ex P.G. Parkinson, 1980
<i>Lithophyllum stictaeforme</i> (J.E. Areschoug) Hauck, 1877
<i>Mesophyllum lichenoides</i> (J. Ellis) Me. Lemoine, 1928
<i>Osmundaria volubilis</i> (Linnaeus) R.E. Norris, 1991
<i>Peyssonnelia squamaria</i> (S.G. Gmelin) Decaisne, 1842
<i>Phyllophora crispa</i> (Hudson) P.S. Dixon, 1964
<i>Rodriguezella strafforelloi</i> F. Schmitz ex J.J. Rodríguez y Femenías, 1895
Chlorophyta
<i>Codium bursa</i> (Olivi) C. Agardh, 1817
<i>Dasycladus vermicularis</i> (Scopoli) Krasser, 1898
<i>Flabellia petiolata</i> (Turra) Nizamuddin, 1987
<i>Halimeda tuna</i> (J. Ellis & Solander) J.V. Lamouroux, 1816
<i>Palmophyllum crassum</i> (Naccari) Rabenhorst, 1868
Porifera
<i>Acanthella acuta</i> Schmidt, 1862
<i>Agelas oroides</i> (Schmidt, 1864)
<i>Aplysina cavernicola</i> (Vacelet, 1959)
<i>Axinella cannabina</i> (Esper, 1794)
<i>Axinella damicornis</i> (Esper, 1794)
<i>Axinella polypoides</i> Schmidt, 1862
<i>Axinella vaceleti</i> Pansini, 1984
<i>Axinella verrucosa</i> (Esper, 1794)
<i>Clathrina clathrus</i> (Schmidt, 1864)
<i>Cliona viridis</i> (Schmidt, 1862)
<i>Dysidea avara</i> (Schmidt, 1862)
<i>Haliclona cratera</i> (Schmidt, 1862)
<i>Phorbas tenacior</i> (Topsent, 1925)
<i>Sarcotragus foetidus</i> Schmidt, 1862
<i>Sarcotragus spinosulus</i> Schmidt, 1862
<i>Scalarispongia scalaris</i> (Schmidt, 1862)
<i>Spirastrella cunctatrix</i> Schmidt, 1868
<i>Spongia lamella</i> (Schulze, 1879)
Cnidaria
<i>Alcyonium acaule</i> Marion, 1878
<i>Alcyonium coralloides</i> (Pallas, 1766)
<i>Balanophyllia europaea</i> (Risso, 1826)
<i>Cladocora caespitosa</i> (Linnaeus, 1767)
<i>Eunicella cavolini</i> (Koch, 1887)
<i>Eunicella singularis</i> (Esper, 1791)
<i>Eunicella verrucosa</i> (Pallas, 1766)
<i>Leptopsammia pruvoti</i> Lacaze-Duthiers, 1897
<i>Paramuricea clavata</i> (Risso, 1826)
<i>Parazoanthus axinellae</i> (Schmidt, 1862)
Annelida
<i>Protula tubularia</i> (Montagu, 1803)
<i>Salmacina dysteri</i> (Huxley, 1855)
Bryozoa
<i>Calpensia nobilis</i> (Esper, 1796)
<i>Myriapora truncata</i> (Pallas, 1766)
<i>Pentapora fascialis</i> (Pallas, 1766)
<i>Reteporella grimaldii</i> (Jullien, 1903)
<i>Rhynchozoon pseudodigitatum</i> Zabala & Maluquer, 1988
<i>Smittina cervicornis</i> (Pallas, 1766)
<i>Turbicellepora incrassata</i> (Lamouroux, 1816)
Chordata
<i>Aplidium conicum</i> (Olivi, 1792)
<i>Halocynthia papillosa</i> (Linnaeus, 1767)
<i>Microcosmus sabatieri</i> Roule, 1885
<i>Polycitor crystallinus</i> (Renier, 1804)

Carlucci et al., 2016). All the 5 explanatory variables have been employed for the RF classification. The analysis was implemented in the randomForest R package (Liaw and Wiener, 2002).

2.5. Model accuracy evaluation

Models performance is usually evaluated by comparing the predictions with a set of validation sites and constructing a confusion matrix or error matrix. Columns in a confusion matrix typically represent the sampled data classified according to the corresponding clustering, while rows represent data classified according to the model. As a consequence, the matrix reports the number of true positive, false positive, false negative and true negative cases predicted by the model. False positives are named commission errors and represent data that belong to a cluster but are labelled as belonging to another. False negatives or omission errors represent data that were left out from classification instead. The proportion of correctly predicted sites obtained from the confusion matrix can be taken as a measure of overall model accuracy (Allouche et al., 2006).

A diagram synthesizing the entire methodological process followed is reported in Fig. 3.

2.6. SWOT analysis

SWOT analysis derives its name from the assessment of the Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T) faced by the studied system. Traditionally, it has been employed for business management as a tool for the evaluation of the performance of industries, companies or organisations (Gao and Peng, 2011; Bull et al., 2016). Nonetheless, SWOT analysis has also been used in the field of environmental management and assessment (Scolozzi et al., 2014, and references therein). The basic idea of a SWOT analysis arises from the perspective that the performance of an agent with respect to a particular objective depends on the way in which the management of that agent interacts with both its internal characteristics and the external context in which the agent is included (Houben et al., 1999; Sevkli et al., 2012).

In this context, the agent is represented by the spatial prediction method for habitat mapping. Strengths and weaknesses are variables that are part of the system and that can be directly modified; in this case they are features of the methodology itself that can ease or hamper the achievement of the study goals, respectively. Opportunities and threats are variables that are external to the system but that can influence it; external variables cannot be directly modified but it is important to keep them under control in order to take advantage from the positive aspects and prevent negative consequences.

SWOT analysis represents a suitable tool to characterise instantly the key variables that affect results from spatial assessment method for habitat mapping application given its ability to represent rationally the influence played by multiple factors on the process under study (Santopuoli et al., 2016). Moreover, it offers the researcher with the possibility to immediately understand and fix critical aspects and to optimise results.

3. Results

3.1. Species clustering

Partition index (SC), separation index (S) and Dunn's index (DI) consistently identified 5 clusters of species as the optimum solution for the presence-absence data set derived from the diving surveys (Fig. 4). These clusters correspond to as many different coralligenous habitats (Fig. 5).

The cluster named CZO was mostly composed by species of brown (*Cystoseira zosteroides*, *Arthrocladia villosa*, *Nereia filiformis*) and red macroalgae (*Osmundaria volubilis*, *Phyllophora crispa*), the only important sessile invertebrate being the sponge *Axinella verrucosa*. It was found between 27 and 43 m depth, on (sub)horizontal elevated substrates, preferentially on granite. This species group can be equated to the Association with *Cystoseira zosteroides* of EUNIS (code A4.261).

Table 2
Explanatory variables considered in the spatial distribution model of coralligenous habitats of the Marine Protected Area of Tavolara – Punta Coda Cavallo.

Name of the variable	Description	Role for coralligenous habitats
Distance from the coast	Minimum distance (km) from the coastline	Proxy for the influence of land
Depth	Depth (m) of the rocky outcrop	Proxy for light penetration
Distance from the nearest neighbour	Minimum distance (km) from other rocks in the area	Proxy for connectivity between habitats
Relative fetch index	Relative distance from coast over 8 different trajectories starting every 45° from each rock	Proxy for water movement
Lithotype	Classification of rock among three categories: granite, limestone, beachrock	Effect of substrate nature on species occurrence

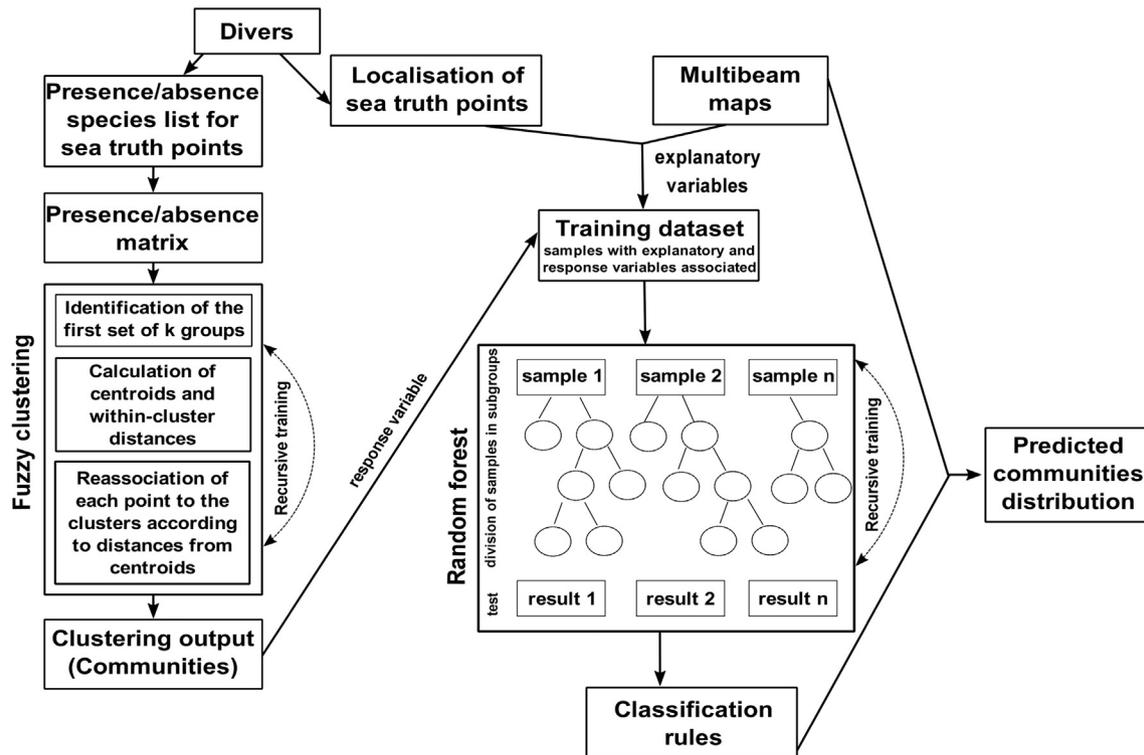


Fig. 3. Diagram of the methodological framework applied to obtain the spatial distribution of different coralligenous communities in ‘Tavolara - Punta Coda Cavallo’ Marine Protected Area.

Cluster APO was essentially made by large sponges, such as *Axinella polypoides*, *Sarcotragus foetidus*, *Spongia lamella*, *Dysidea avara*, *Scalariispongia scalaris* and *Cliona viridis*. The first was the showiest, and this species assemblage could therefore be named Facies with *Axinella polypoides* (which has no EUNIS equivalent at present). It occurred between 25 and 55 m depth, on (sub)horizontal substrates, mostly on granite.

Cluster ECA included both sessile invertebrates (e.g., the gorgonian *Eunicella cavolini*, the sponge *Axinella damicornis*, the scleractinian coral *Leptopsammia pruvoti*, and the bryozoan *Myriapora truncata*) and macroalgae (e.g., the rhodophyte *Acrosymphyton purpuriferum* and the chlorophytes *Halimeda tuna* and *Flabellia petiolata*). This species assemblage was common on vertical walls between 25 and 34 m depth, especially on limestone. It corresponds well to the Facies with *Eunicella cavolini* of EUNIS (code A4.269).

Cluster ESI was comprised of several species belonging especially to cnidarians (e.g., *Eunicella singularis* and *Alcyonium coralloides*), bryozoans (e.g., *Smittina cervicornis* and *Turbicellepora incrassata*), and macroalgae (e.g., *Sporochnus pedunculatus* and *Osmundaria volubilis*). It has been observed on (sub)horizontal substrates of various lithologies between 28 and 54 m depth. The high frequency of the gorgonian *Eunicella singularis* makes it comparable to the Facies with *Eunicella singularis* of EUNIS (code A4.26A).

Finally, cluster PCL was essentially characterised by the large

gorgonian *Paramuricea clavata* and the pseudocolonial serpulid *Salmacina dysteri*, accompanied by species also common in other groups. It occurred between 25 and 53 m, mostly on inclined to vertical limestone rocks, and fully corresponds to the Facies with *Paramuricea clavata* of EUNIS (code A4.26B).

3.2. Habitat modelling

Random forest indicated that the distribution of these five habitats was mainly driven by variations in distance from coast and depth, followed by lithotype (Fig. 6).

Distance from nearest neighbour and relative fetch index resulted less important for the determination of their distribution in the area (< 5% mean decrease accuracy). For this reason, only distance from coast, depth and substrate influence will be discussed in the following paragraphs.

Partial dependence plots showed that short distance from the coast was preferred by CZO and PCL, while APO, ECA and ESI mostly occurred at higher distances from land. In particular, clear thresholds were detected at 0.5 and 1 km from coastline for ECA and APO, respectively (Fig. 7).

Depth occurrence for CZO was bimodal, with peaks at 25–30 m and especially at 45–55 m. APO and ECA occurrence was most probable at greater depths, with sudden increases at 30 m for APO and a continuous

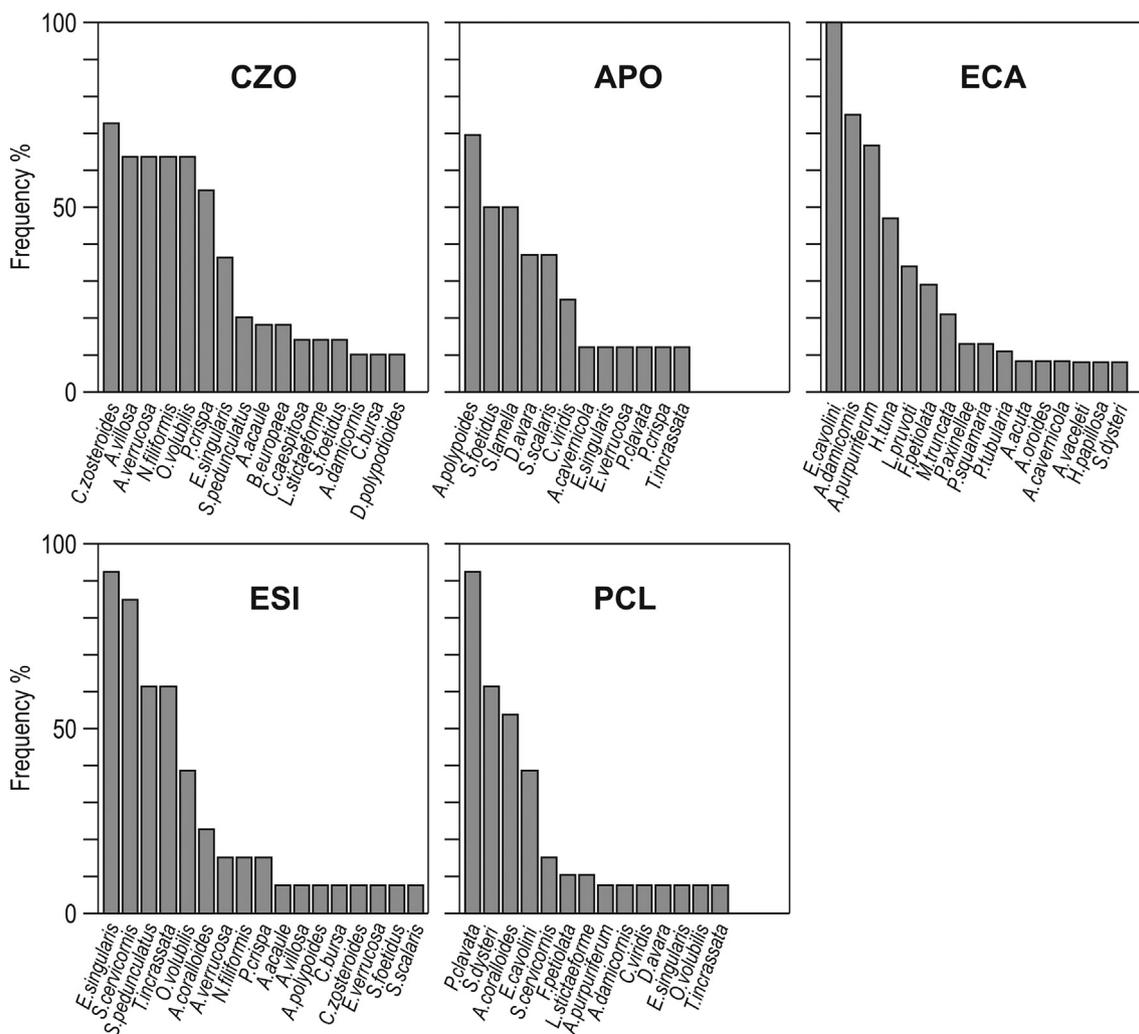


Fig. 4. Species rank-frequency diagrams in the five groups identified by fuzzy clustering, and interpreted as distinct coralligenous communities: CZO = Association with *Cystoseira zosteroides*; APO = Facies with *Axinella polypoides*; ECA = Facies with *Eunicella cavolini*; ESI = Facies with *Eunicella singularis*; PCL = Facies with *Paramuricea clavata*. Species whose frequency was lower than 5% are not represented.

increasing trend for ECA. Comparatively shallower depths were preferred by ESI and PCL, which were more frequent between 25 and 45 m (Fig. 7).

Granite substrate was linked with the presence of CZO and APO, while limestone had an evident positive effect on the presence of PCL. Substrate was not particularly relevant for the distribution of ESI. Only CZO showed a certain preference for beachrocks (Fig. 7).

3.3. Model accuracy evaluation

Accuracy of the model was evaluated through the analysis of the confusion matrix (Fig. 8).

The overall accuracy of the classification reached 89%, with 51 cases predicted correctly. Omission and commission error rates were both low (0.12 ± 0.04 se and 0.10 ± 0.05 se, respectively); the highest omission error rate was showed by ESI (23%), while PCL had the highest commission error rate (25%). The model displayed a better performance in detecting presences instead of absences, being commission errors lower than omission errors for all habitats but PCL.

3.4. Maps of habitat distribution

Distribution maps illustrating the predicted probability of occurrence were produced for each habitat, based on the importance of

explanatory variables and their influences displayed by partial dependence plots. In general, congruence between observed and predicted distribution was good (Figs. 9 to 13).

CZO and ECA exhibited the widest distributions in the area, but the former was expectedly more frequent at higher distance from the coast (Fig. 9) and the latter in coastal sites (Fig. 11). The two habitats might co-occur on granite south of Punta Coda Cavallo and on beachrocks north of Tavolara. APO, ESI and PCL were predicted in rather restricted settings, mostly in the central part of the Marine Protected Area and between Tavolara and Molarra. APO (Fig. 10) was mostly expected around Molarra where rocks are granite; field observations, however, indicated that it was never prevalent (i.e., the most common habitat in the site). ESI (Fig. 12) was expected to occur mostly in the channel between Tavolara and Molarra and on off-shore beachrocks. Finally, PCL (Fig. 13) was expected to occur especially on limestone pinnacles to the east of Tavolara, and secondarily on granitic inselbergs in the seafloor between the two main islands and on deep beachrocks off Molarra.

Based on prediction maps, coralligenous habitats would cover a total of 48.9 ha of seabed within the Marine Protected Area of Tavolara - Punta Coda Cavallo (Table 3).

ECA come out as the most widespread habitat, covering nearly 30% of the total coralligenous habitat extent, followed by ESI, CZO, APO and PCL, in the order. More than half of the total extent of coralligenous habitats (28.3 ha) would be present in zone C, whereas only 5 ha

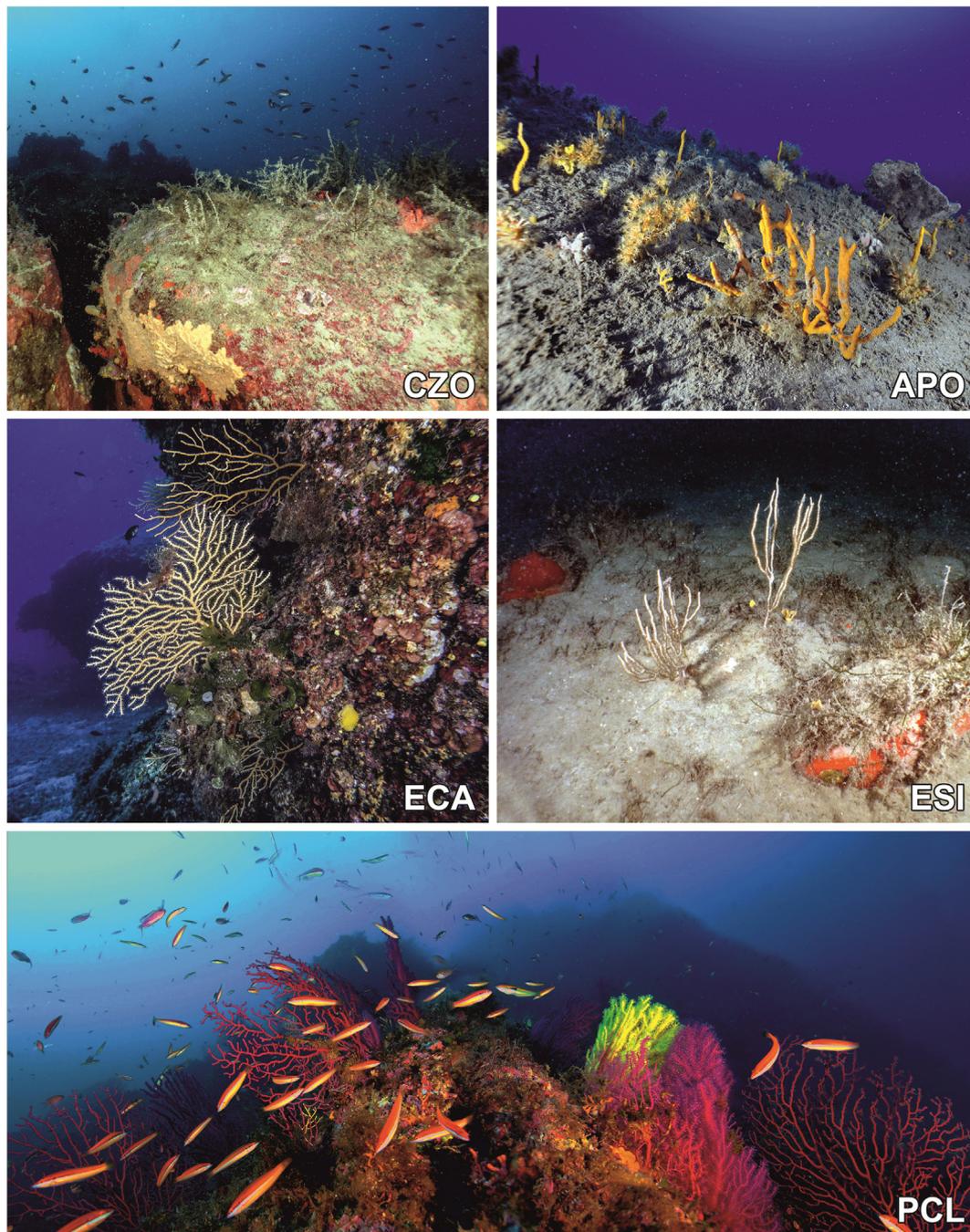


Fig. 5. The five coralligenous communities recognised in the Marine Protected Area of Tavolara - Punta Coda Cavallo. CZO = Association with *Cystoseira zosteroides* (EUNIS equivalent: A4.261); APO = Facies with *Axinella polypoides* (EUNIS equivalent: none); ECA = Facies with *Eunicella cavolini* (EUNIS equivalent: A4.269); ESI = Facies with *Eunicella singularis* (EUNIS equivalent: A4.26A); PCL = Facies with *Paramuricea clavata* (EUNIS equivalent: A4.26B).

(nearly 10% of the total) would be included in zone A, where protection is maximal. The most protected habitats (i.e., those concentrated in zone A) would be ECA and APO, most of CZO would be located in zone C (under the lowest protection regime), and ESI and PCL would be near equally distributed between zones A and B (Fig. 14).

3.5. SWOT analysis

SWOT analysis (Table 4) evidenced robust strengths, among which simplicity and easiness of the method in the face of the high quality of the results should be underlined, which imply interesting opportunities for planning and management.

4. Discussion

Over the last fifteen years, the production of benthic habitat maps has tremendously advanced thanks to the integration of acoustic remote sensing techniques, in situ observations for sea-truthing, and spatial modelling (Lamarche et al., 2016). The present study used abiotic surrogates (rocks at 25–55 m depth) from acoustic data and unsupervised classification (assemble first, predict later) from sea-truth inspections (Calvert et al., 2015; McHenry et al., 2017) to map the distribution of coralligenous reefs, an important Mediterranean habitat that requires management actions (Ballesteros, 2008; Sartoretto et al., 2017), within a Marine Protected Area.

Despite the use of a basic set of explanatory variables and presence-

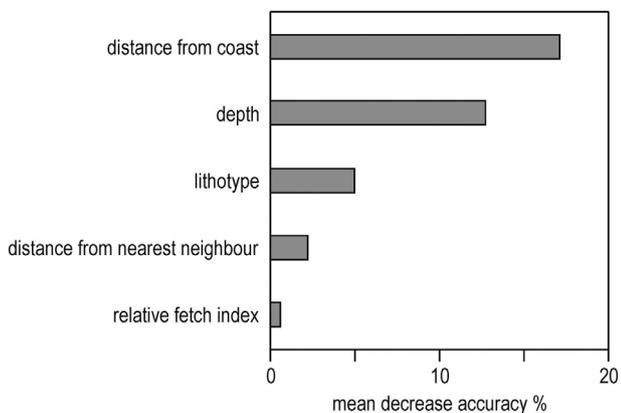


Fig. 6. Importance of the explanatory variables employed. Mean decrease in accuracy is a measure of the accuracy loss in case of exclusion of the variable from the analysis.

absence data only, the model was able to classify correctly the near totality of the coralligenous habitats known in the area studied (Mori et al., 1995; Bianchi et al., 2007), and omission and commission error rates were low, when compared with similar literature reports (Purkis and Riegl, 2005; Palialexis et al., 2011; Tulloch et al., 2013; Zapata-Ramírez et al., 2013). To date, higher accuracy has been obtained only adopting a lower resolution level for habitat prediction, such as sea-grass/sand (Di Maida et al., 2011) or kelp/sponges/sand (Ratray et al., 2013). In this study, the high accuracy of the predictions has been probably achieved thanks to two conditions: 1) the employment of an objective clustering method to identify different habitats, based on algorithms and not on subjective judgements; 2) the application of the

		PREDICTED					row totals	omission error rate
		CZO	APO	ECA	ESI	PCL		
OBSERVED	CZO	11	0	0	0	0	11	0.00
	APO	0	7	0	1	0	8	0.13
	ECA	0	0	10	0	2	12	0.17
	ESI	0	0	1	10	2	13	0.23
	PCL	0	0	1	0	12	13	0.08
column totals		11	7	12	11	16	57	
		commission error rate						
		0.00	0.00	0.17	0.09	0.25		

Fig. 8. Error matrix calculated for classified acoustic information. Sea-truth stations that are classified as correct habitats are located along major diagonal of matrix, while all non-diagonal elements represent errors of omission or commission. CZO = Association with *Cystoseira zosteroides*; APO = Facies with *Axinella polypoides*; ECA = Facies with *Eunicella cavolini*; ESI = Facies with *Eunicella singularis*; PCL = Facies with *Paramuricea clavata*.

random forest technique, widely recognised as one among the most performing, to predict their distribution.

Accuracy of the classification and low error rates, together with

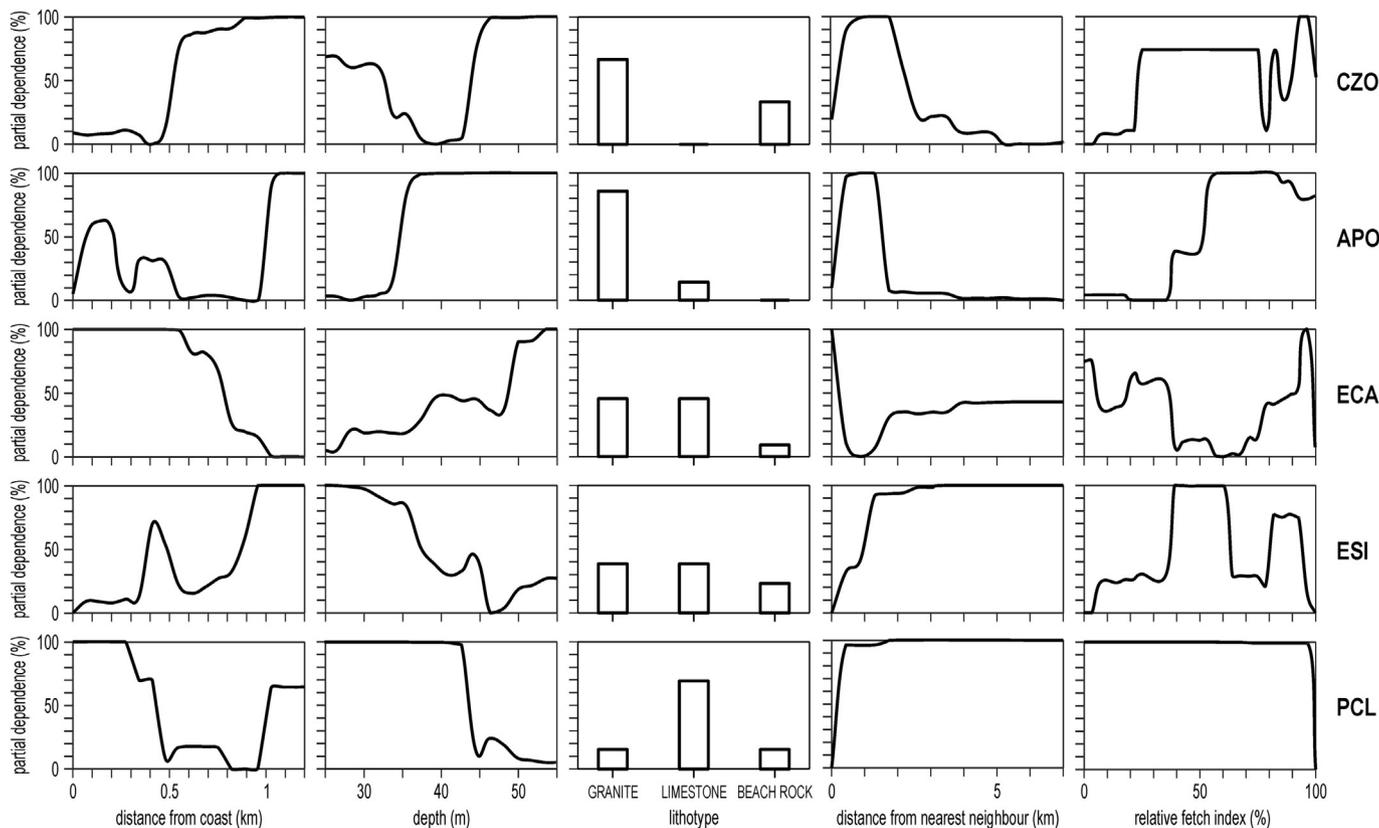


Fig. 7. Univariate partial dependence plots estimated by the random forest model for the explanatory variables distance from coast, depth, substrate typology, distance from nearest neighbour, and relative fetch index. CZO = Association with *Cystoseira zosteroides*; APO = Facies with *Axinella polypoides*; ECA = Facies with *Eunicella cavolini*; ESI = Facies with *Eunicella singularis*; PCL = Facies with *Paramuricea clavata*.

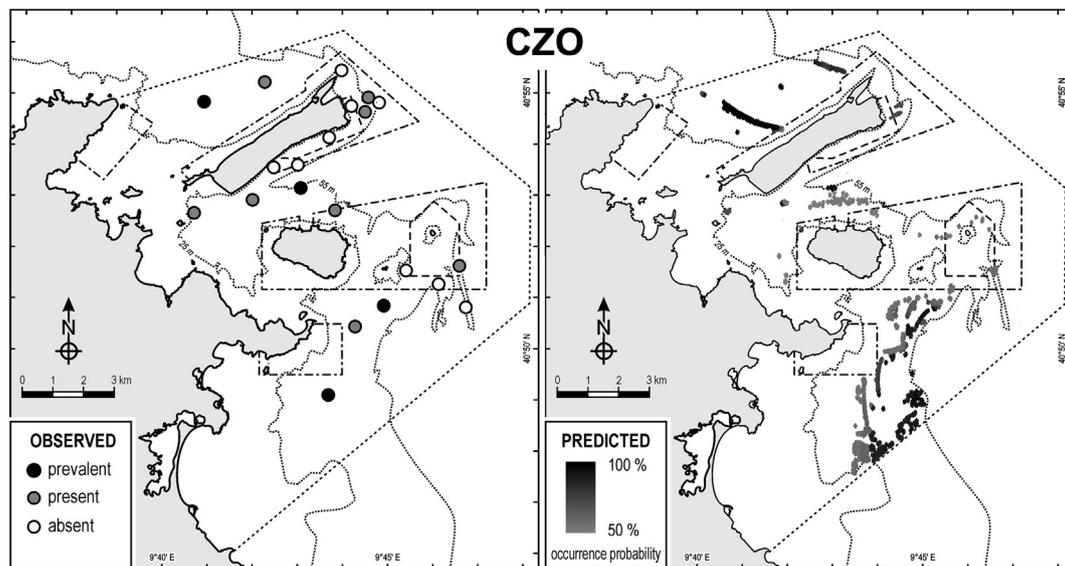


Fig. 9. Observed and predicted distribution of the Association with *Cystoseira zosteroides* in the Marine Protected Area of Tavolara - Punta Coda Cavallo.

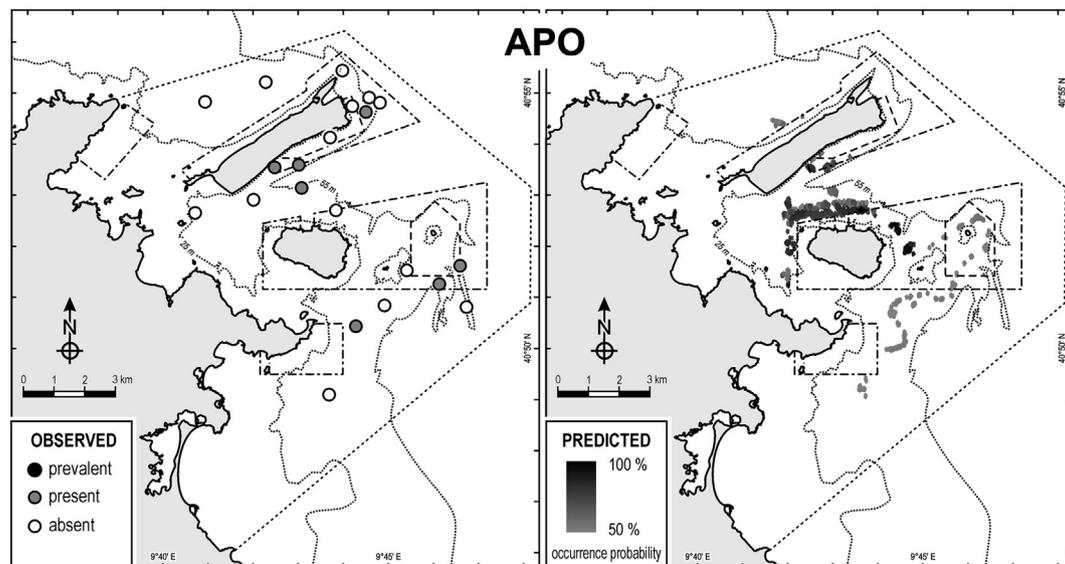


Fig. 10. Observed and predicted distribution of the Facies with *Axinella polypoides* in the Marine Protected Area of Tavolara - Punta Coda Cavallo.

high congruence between observed and predicted occurrences, indicate that the habitat distribution maps obtained in this study were both reliable and effective.

A qualitative evaluation of pros and cons of the applied framework were evaluated through SWOT analysis. Weaknesses and threats essentially depended on data quality and adequate sea-truthing. While improved acoustic technologies are rapidly becoming available to facilitate large-scale data acquisition (Lecours et al., 2015; Strong and Elliott, 2017), interpretation of acoustic data still requires extensive field calibration and costly sea-truthing processes that remain essential (Pergent et al., 2017). The approach adopted in this study, based on: 1) an acoustic dataset distinguishing a number of features of interest at the required spatial resolution (Holmes et al., 2008) and 2) a rapid and cheap field work for sea-truthing (Bianchi et al., 2010), seems therefore particularly promising.

The proposed prediction was based on few and simple explanatory variables that were derived from the main physiographic features of the study area namely: depth, distance from coast, lithotype, exposition to currents and proximity to other rocks. The entire set of explanatory variables was derived from the analysis of geomorphological maps,

which represent one of the basic pieces of information required for the management of marine ecosystems (Bianchi et al., 2012; Young and Carr, 2015).

In the area studied, the distribution of distinct coralligenous habitats resulted mainly driven by distance from coast, depth and lithotype. While depth and lithotype were already expected to be major discriminating factors (Bavestrello et al., 2000; Deter et al., 2012), distance from coast proved the most important. Bracchi et al. (2017) recognised distinct coralligenous morphotypes (rather than habitats) at different distances from coast in the Apulian shelf (SE Italy).

The interplay of different discriminating factors allowed for the coexistence of more than a habitat in sites with complex morphologies, such as, for instance, the high limestone pinnacles east of Tavolara. Substrate slope and elevation from level substrate are important factors for the development of different coralligenous assemblages (Guidetti et al., 2014; Doxa et al., 2016). High-resolution multibeam data coupled with geographic information systems allow calculating slope (Dolan and Lucieer, 2014), which could be introduced as an additional explanatory variable, expected to potentially improve prediction accuracy.

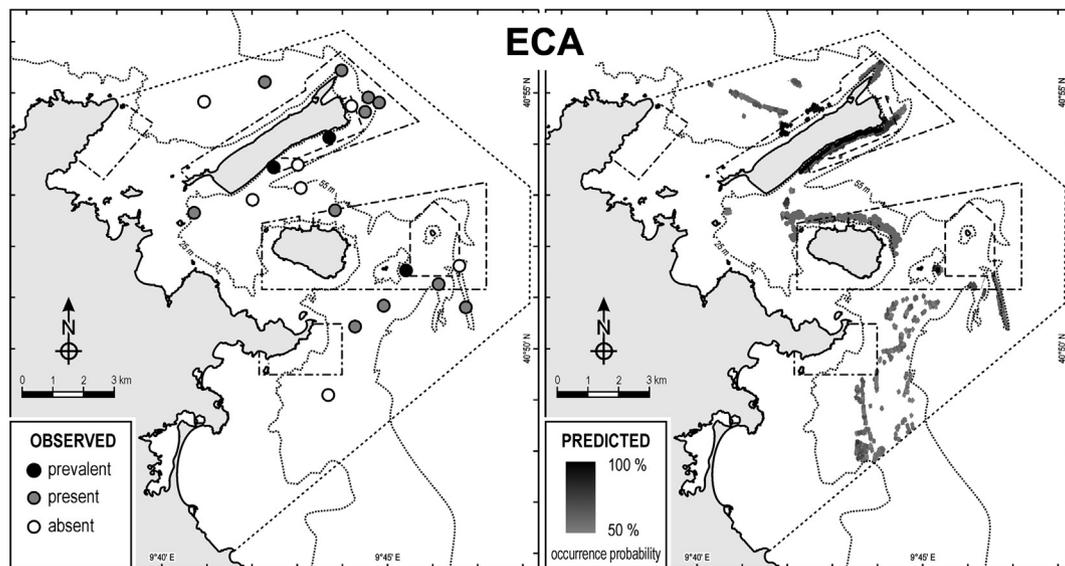


Fig. 11. Observed and predicted distribution of the Facies with *Eunicella cavolini* in the Marine Protected Area of Tavolara - Punta Coda Cavallo.

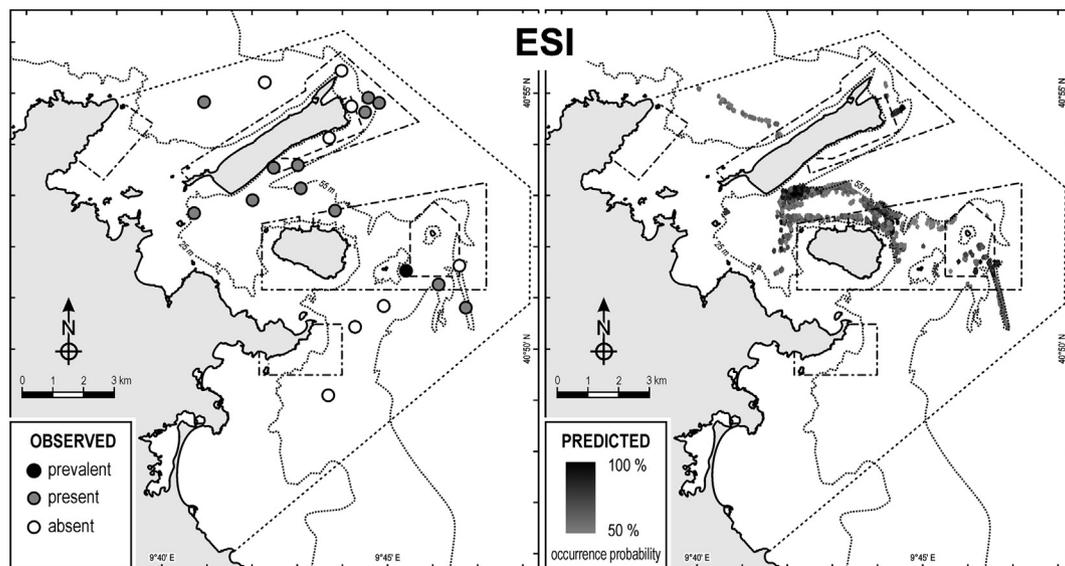


Fig. 12. Observed and predicted distribution of the Facies with *Eunicella singularis* in the Marine Protected Area of Tavolara - Punta Coda Cavallo.

Fuzzy clustering had been already applied to coralligenous epibenthic assemblages by Falace et al. (2015), who identified three coralligenous habitats in the Northern Adriatic Sea. With a similar approach, the present study identified five coralligenous habitats in the Marine Protected Area of 'Tavolara - Punta Coda Cavallo' from the analysis of presence/absence data collected during sea-truth surveys (Bianchi et al., 2007, 2010). Four of these habitats (Association with *Cystoseira zosteroides*, Facies with *Eunicella cavolini*, Facies with *Eunicella singularis*, Facies with *Paramuricea clavata*) corresponded to already existing EUNIS (European Nature Information System) types (Tunesi et al., 2006), while what we called Facies with *Axinella polypoides* has no EUNIS equivalent to date. This habitat is well characterised by the dominance of large sponges in the upper layer, instead of macroalgae or gorgonians as in the majority of the other coralligenous habitats recognised by EUNIS. Beside the distinctive species *A. polypoides*, other commonly found sponges were *Sarcotragus foetidus*, *Spongia lamella*, *Dysidea avara*, and *Scalارسpongia scalaris*. Similar habitats have been already described in other Mediterranean regions (Bedulli et al., 1986; Ben Mustapha et al., 2002; Garrabou et al., 2014; Cánovas Molina et al., 2016), but have not been recognised yet either by EUNIS or in the

handbook for the classification of Mediterranean habitats (Pergent et al., 2007). Sponges in coralligenous reefs are highly diverse (Bertolino et al., 2013) but they have been mainly studied for their role of bioeroders (Cerrano et al., 2001) rather than of canopy-formers. We strongly advocate the opportunity of including the Facies with *Axinella polypoides* in the next revision of EUNIS. Canopy-forming sponges play an important role in benthic-pelagic coupling (Coppari et al., 2016) and may thus be a major component for the functioning of coastal marine ecosystems.

EUNIS classification was born to provide European administrators and scientists alike with a consensus frame for management and conservation (Bianchi et al., 2018), and has recently been employed also for impact assessment (Casoli et al., 2017). Examples of EUNIS-based marine habitat maps are accumulating for the European seas (Diesing et al., 2009; Coggan and Diesing, 2011; Cabral et al., 2015; Victor et al., 2015), thus providing a test to evidence problems and further needs (Galparsoro et al., 2012; Mo et al., 2012). EUNIS habitat classification scheme brings the uniformity required to share management experiences and to search for common solutions; the availability of reliable maps based on EUNIS may therefore have profound implications for

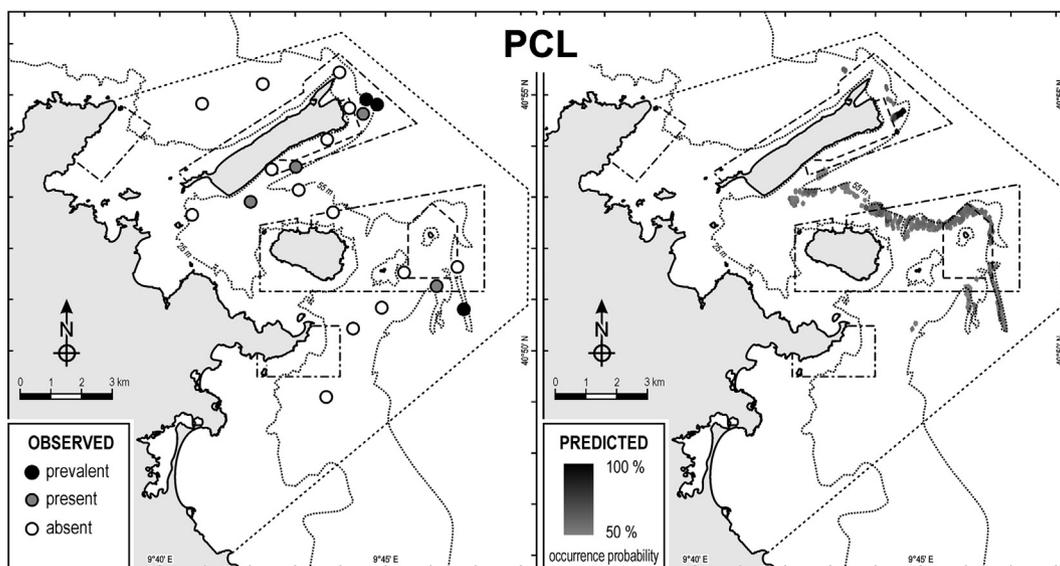


Fig. 13. Observed and predicted distribution of the Facies with *Paramuricea clavata* in the Marine Protected Area of Tavolara - Punta Coda Cavallo.

Table 3

Predicted area occupancy (in ha) of the five coralligenous habitats in the three protection zones of the Marine Protected Area of Tavolara – Punta Coda Cavallo.

	Zone A	Zone B	Zone C	Total
CZO: Association with <i>Cystoseira zosteroides</i> (EUNIS A4.261)	0.1	0.2	8.8	9.1
APO: Facies with <i>Axinella polypoides</i>	0.8	1.5	5.8	8.1
ECA: Facies with <i>Eunicella cavolini</i> (EUNIS A4.269)	3.0	6.7	4.3	14.0
ESI: Facies with <i>Eunicella singularis</i> (EUNIS A4.26A)	0.5	3.3	6.4	10.2
PCL: Facies with <i>Paramuricea clavata</i> (EUNIS A4.26B)	0.6	3.9	3.0	7.5
Total coralligenous habitats	5.0	15.6	28.3	48.9

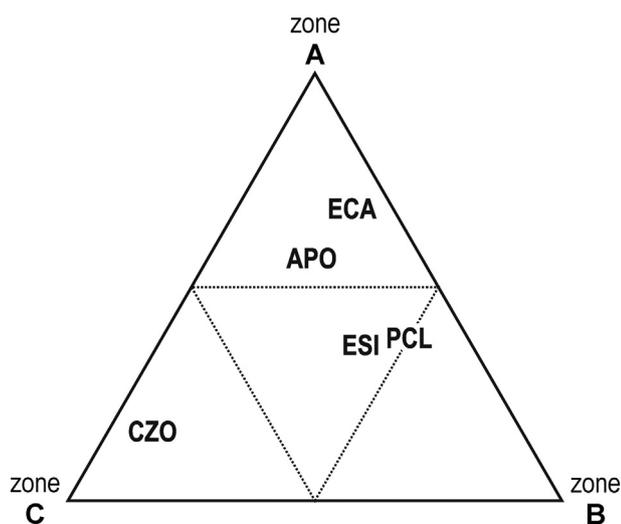


Fig. 14. Triangular diagram of the predicted relative occurrence of the five coralligenous habitats identified in the three protection zones of the Marine Protected Area of Tavolara - Punta Coda Cavallo. Zone A = no entry – no take; zone B = general reserve, human activities strictly regulated; zone C = partial reserve or buffer zone, most human activities allowed but regulated. CZO = Association with *Cystoseira zosteroides*; APO = Facies with *Axinella polypoides*; ECA = Facies with *Eunicella cavolini*; ESI = Facies with *Eunicella singularis*; PCL = Facies with *Paramuricea clavata*.

planning and decision-making (McHenry et al., 2017).

In the case of the Marine Protected Area of ‘Tavolara - Punta Coda Cavallo’, prediction maps allowed for the first time evaluating the level of protection of five coralligenous habitats, four of which EUNIS classified. Results showed that the five habitats are unequally protected: the highest protection level has been granted to habitats corresponding to ‘animal forests’ (i.e., having a canopy of sessile invertebrates, such as gorgonians or sponges), the lowest to the habitat with a macroalgal canopy. While animal forests exert a major appeal towards underwater tourism (Paoli et al., 2017), macroalgal-dominated coralligenous habitats are typically associated with a basal layer rich in encrusting calcified rhodophytes (Gatti et al., 2012). Thus, the current zonation scheme of the Marine Protected Area of Tavolara - Punta Coda Cavallo apparently aims at conserving the aesthetic value of the seascape (Bianchi et al., 2012), rather than the importance of bioconstructional processes (Bianchi, 2001). Representativeness is one of the main criteria to drive conservation efforts (Asaad et al., 2017), and it seems therefore judicious that these two important ecological aspects should at least equally considered.

The protection regime of the Marine Protected Area of Tavolara - Punta Coda Cavallo was established long before detailed marine habitat maps of the region were available. The method developed in the present study, and the results obtained, will be of help when modulating ongoing and future management actions in the area. Similar applications in other Mediterranean Marine Protected Areas are encouraged to develop consistent conservation efforts at basin scale.

5. Conclusions

Coralligenous reefs represent important habitats that are still insufficiently known (Gubbay et al., 2016). This condition creates the emergency need for the assessment of rapid and efficient tools able to accomplish to the European Marine Strategy Framework Directive requirements and to establish appropriate management strategies. The approach adopted in this study proved successfully to that scope.

The spatial distribution of coralligenous habitats in the Marine Protected Area of Tavolara - Punta Coda Cavallo MPA has been mapped through the application of fuzzy clustering and random forest techniques. Fuzzy clustering identified five coralligenous habitats in the Marine Protected Area of Tavolara - Punta Coda Cavallo from the analysis of qualitative information collected in 57 stations by scuba diving in 21 sites (Bianchi et al., 2010). Four of these habitats corresponded to already existing EUNIS types (Davis et al., 2004), while the

Table 4

SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of the predictive habitat mapping applied to the coralligenous reefs of the Marine Protected Area of Tavolara – Punta Coda Cavallo.

Strengths	Weaknesses
A limited amount of information is required to predict distribution patterns. Explanatory variables are simple and can be obtained by remote techniques. Heterogeneous databases from different sources can be employed. Main environmental drivers for habitat distribution can be identified.	Strongly dependence on data reliability, accuracy and resolution. Sea-truthing remains indispensable for prediction and to verify accuracy.
Opportunities	Threats
Setting territorial management strategies is facilitated. Produced maps allow sharing knowledge among managers, thus helping consensus building. Exposure of vulnerable habitats to human disturbances can be visualised. Various management scenarios for marine spatial planning can be envisaged. Different temporal or spatial situations can be compared to evaluate trends of the habitat considered.	Wrong interpretation of outputs and results can lead to management errors. Basing on unreliable data may lead to unsuitable management strategies.

Facies with *Axinella polypoides* has no EUNIS equivalent to date, even if has been already observed in other Mediterranean regions.

Starting from a basic set of explanatory variables (distance from coast, depth, lithotype, distance from nearest neighbour, relative fetch index), the model correctly classified the near totality of the coralligenous habitats in the area (Mori et al., 1995; Bianchi et al., 2007). The main obstacle to the widespread use of predictive models resides in the availability of a full coverage dataset, something that modern acoustic technologies made quite easily obtainable. The high cost, in term of both time and money, of sea-truthing processes (Pergent et al., 2017) has been minimised in this study by the adoption of a comparatively low amount of filed scuba diving surveys and the collection of presence-absence data only. Given that scuba diving still provides the most accurate method for the study of coralligenous habitats but is affected by time limitations when working at depth (Parravicini et al., 2010), the synergy between this kind of data acquisition and the application of spatial models can represent an optimal solution.

The final SWOT analysis evidenced that weaknesses and threats may depend on data quality but highlighted the strength of the method in providing high-quality results with a comparatively simple procedure, thus confirming its potentialities for marine environment management.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2018.04.016>.

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