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Modelling spatial distribution of the Croatian marine benthic habitats

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Abstract

Within the framework of the 3-year project "Mapping the habitats of the Republic of Croatia" the marine benthic habitats of the entire Croatian maritory were mapped. The supralittoral and the mediolittoral were mapped as a function of the coastal lithology and the presumed levels of human impact (both in scale of 1:100,000). The infralittoral was mapped on the basis of spatial modelling (using neural networks as a modelling tool, data about habitats collected by fieldwork as the independent variable for training and testing the model, and the digital bathymetrical model, the distance from coast, the second spectral channel of Landsat ETM+ satellite image and the sea bottom sea temperature, salinity and current magnitude, as dependent variables). The circalittoral and the bathyal were mapped by overlapping and reinterpretation of the existing spatial databases (bathymetry and lithology) within the framework of the raster-GIS.

Keywords: Landsat ETM+; Neural networks; *Posidonia*; Raster-GIS; Sea bottom current magnitude; Sea bottom salinity; Sea bottom temperature

1. Introduction

The preservation, protection and improvement of the environment quality, including the conservation of natural habitats and of wild fauna and flora, are an essential objective of general interest pursued by the European Community (see Council Directive 92/43/EEC). Natural habitats in Europe continue to deteriorate and an increasing number of wild species are seriously threatened. Because the threats are often of trans-boundary nature, protection and conservation measures should be taken not only at the European Community level but also in the neighbouring countries like Croatia (Bakran-Petricioli, 2004). It is important to define a certain habitat and/or species as having pri-

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ority, in order to promote the early implementation of measures to conserve them.

The Ministry of Environmental Protection and Physical Planning of the Republic of Croatia financed the project “Mapping the habitats of the Republic of Croatia”, contracted by Oikon Ltd., Institute for Applied Ecology from Zagreb. The 3-year project was finished in the spring 2004, resulting in the multi-layer spatial database of Croatian habitats, necessary for the application of the new Croatian Law on Nature Protection and for use in related areas (nature conservation, natural resources management, environmental impact assessment, landscape planning, etc.).

In the land part of the Croatian territory, the data sources for mapping were both the classified and interpreted Landsat ETM+ satellite images, with minimum mapping area (MMU) of 9 ha, and the results of intense fieldwork. Two sets of images were simultaneously used: the spring and the autumn set. In the first step, each Landsat ETM+ scene was classified using supervised classification (e.g. Lillesand and Kiefer, 1994) on the basic landcover units. In the second step, each landcover unit (on each scene) was classified on the subunits using unsupervised classification, supported by the optimising of number of clusters (e.g. Lillesand and Kiefer, 1994; Tou and Gonzalez, 1974). The final results of unsupervised classification were interpreted on the basis of the field sample, additional spatial data sources (old vegetation maps, forest management maps, and lithological maps) and literature. The current database represents the main result of the project, which was also cartographically prepared for printing on the scale of 1:100,000 standard sheets of the state topographical maps. The lateral results of the project were the database covering the spatial variability of polygons of the main result, the line database of elongated habitats with MMU smaller than 9 ha (watercourses, cliff and scree habitats, coastal habitats), the literature-based point database of typical non-elongated habitats (localities) with MMU smaller than 9 ha (as the basis for the future complementing by new data) and the polygon database of marine habitats (related exclusively to the benthos).

This paper deals with the mapping of the marine benthic habitats (other parts of the project will be discussed in separate papers). The existing data for the sea bottom mapping, as well as any new data which could have been collected during the project, were not sufficient to cover the large spatial variability of marine habitats in Croatia, therefore different methods were used. While remote sensing supported by field checking and previously collected spatial data were used for land habitats mapping, the mapping of marine benthic habitats was based on the application of the spatial modelling (according to the experiences collected primarily in research of similar biogeographical problems on land, e.g. Antonić et al., 2000, 2003; Brown, 1994; Brzeziecki et al., 1995; Tappeiner et al., 1998; Van de Rijt et al., 1996; Zimmermann and Kienast, 1999) and the compilation of existing databases within the framework of the raster geographic information system (GIS)—basically due to temporal and financial limitations of the project and the complexity and expensiveness of submarine fieldwork.

In the Mediterranean, special attention has been paid to the mapping of *Posidonia oceanica* (L.) Delile meadows because of the biological and ecological importance of the species, as well as its vulnerability to increased human impact. Methods used in mapping varied from the direct mapping (transects), aerial photography (with ground truth), satellite image (with ground truth), side scan sonar (with ground truth), and/or combination of this methods, mostly used in recent years (e.g. Ballesta et al., 2000; Gili and Ros, 1985; Pasqualini et al., 1998, 1999; Pergent et al., 1991; Piazzi et al., 2000). It is important to be aware that, whatever cartographic method used, no map of benthic communities is accurate everywhere and on all scales, and that the relevance of a map depends on the purpose for which it was established and the use for which it was intended (Leriche et al., 2004).

For the Croatian part of the Adriatic Sea there are no measurements (or even estimates) of the areas covered by the particular infralittoral biocenosis. This poses a problem in the management of infralittoral zone, i.e. it is impossible to assess accurately the endangerment of a certain species (like *P. oceanica*) or habitat. The data about lithology, one of the most important determinants of benthic biocenoses distribution, are scarce in the infralittoral zone (which surrounds the approximately 6000 km long Croatian coast) and insufficient to be used for mapping of the benthic biocenoses. Direct mapping (using data collected by submarine fieldwork) is not applicable when such large areas are concerned, so we tried to solve the problem by the present model.

2. Material and methods

2.1. The infralittoral

The infralittoral was mapped on the basis of spatial modelling within the framework of the raster-GIS (with spatial resolution of 30 m × 30 m), using neural networks (NN) as a modelling tool. This tool was chosen because of its flexibility in solving the complex regression and classification ecological problems with insufficiently known physical, chemical and biotic background, and using the previous experience of the project team (Antonić et al., 2000, 2001, 2003).

The basic infralittoral habitat types, determined by SCUBA diving (self-contained underwater breathing apparatus) on 1004 locations in the infralittoral zone along the Eastern Adriatic coast (Fig. 1), represented the dependent variable. In this zone, the following biocenoses/habitats defined according to the Croatian National Habitat Classification (as separate result of the same project, based among other sources upon the Mediterranean marine habitats classification, UNEP(OCA)/MED WG.149/5, 1998; UNEP(OCA)/MED WG.154/7, 1999) were sampled:

1. the biocenosis of fine sands in very shallow waters (44 locations);
2. the biocenosis of well sorted fine sands (72 locations);
3. the biocenosis of well sorted fine sands with *Cymodocea nodosa* (16 locations);
4. the biocenosis of superficial muddy sands in sheltered waters (58 locations);
5. the biocenosis of superficial muddy sands in sheltered waters with *C. nodosa* (30 locations);
6. the infralittoral gravels (32 locations);
7. the *Posidonia* meadows (136 locations);
8. the biocenosis of photophilic algae (616 locations).

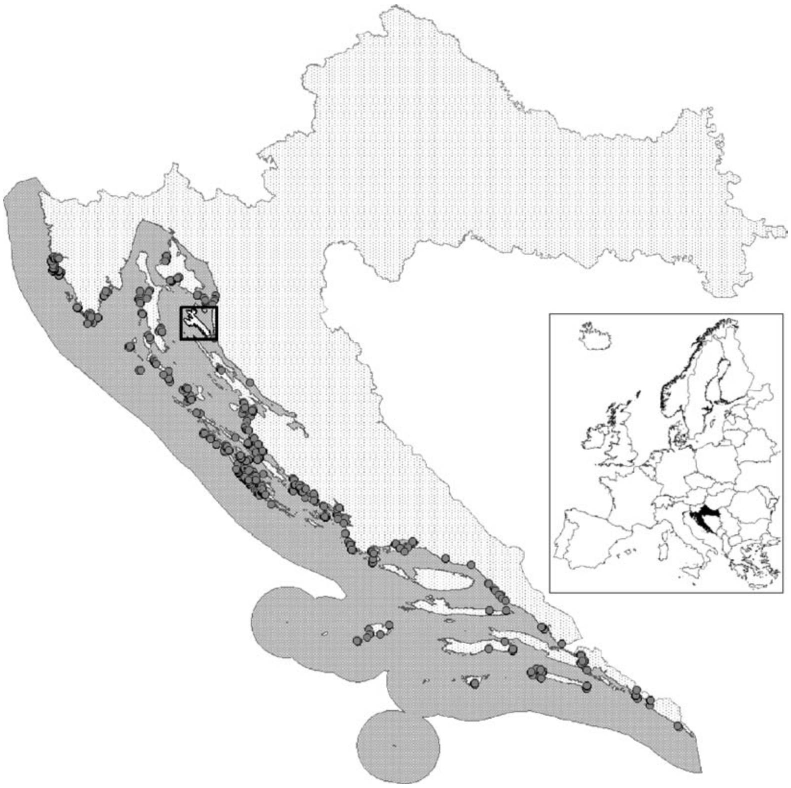

Fig. 1. Locations along the Eastern Adriatic coast with the infralittoral habitat types determined by submarine fieldwork. Several points stand for groups of locations. The area in the small frame is enlarged in Fig. 3.

For the purpose of modelling, this list of habitat types was reduced (by omitting the sixth type being only locally relevant because of the dominant impact of coastal lithology and merging seven other habitat types into logical groups) on the four main infralittoral types: (1) the *Posidonia* meadows, (2) the biocenosis of photophilic algae, (3) the fine sand habitats, and (4) the muddy sand habitats.

On the subject of the independent variables, the first step was to examine a long list of potential variables (which may be regarded as direct or indirect independent environmental estimators). Main logic groups of these variables were:

1. the digital bathymetric model (produced by digitalisation and rasterisation of nautical maps on the scale of 1:100,000), and its derivatives (the bottom slope and curvature);
2. the Euclidean distance from the coast and its spatial statistics (medians of distances in the circles of different diameters around each unit of spatial resolution, as indicators of geomorphologic sheltered state);
3. the spectral channels of Landsat ETM+ satellite image (eight channels, assuming that some of them could be usable for specified purpose in the upper photophilic zone);
4. the sea bottom current magnitude (including: residual current magnitude for each of four seasons, tidal current magnitude, current magnitude in case of strong north-eastern wind) (“bora”; one of the two dominant winds of Eastern Adriatic), and current magnitude in case of strong south-eastern wind (“scirocco”; the second dominant wind); see also Janeković et al. (2005), parallel contribution in the same volume);
5. the sea bottom temperature (for each of four seasons; see also Janeković et al. (2005), parallel contribution in the same volume);
6. the sea bottom salinity (for each of four seasons; see also Janeković et al. (2005), parallel contribution in the same volume);
7. the longitude and latitude (as potential estimators of main geographic gradient).

All mentioned variables were prepared as grids which cover the entire infralittoral part of the Croatian maritory in spatial resolution of 30 m × 30 m. Independent variables obtained by a 3D finite element model (see Janeković et al. (2005), parallel contribution in the same volume) were transformed into analogous grids, using simple linear interpolation between the points of triangular mesh.

Through the sensitivity analysis procedure, the wide list of variables was reduced (each variable from the wide list was included into the final list of independent variables, if its contribution to habitat type variability explanation was significant—using the previously built neural networks) on the following final list of independent variables, used as input into the final model:

1. the Euclidean distance from the coast (logarithmically transformed);
2. the median of Euclidean distances from the coast (logarithmically transformed) in the circle of 1 km around each unit of spatial resolution (30 m × 30 m);
3. the second channel of Landsat ETM+ satellite image;
4. the spring residual current magnitude;
5. the current magnitude in case of strong bora wind;
6. the current magnitude in case of strong scirocco wind;
7. the spring sea bottom temperature;
8. the summer sea bottom temperature;
9. the winter sea bottom salinity;
10. latitude;
11. longitude.

Additionally, due to the fact that the entire Croatian maritory was covered by three Landsat ETM+ scenes, the identification number of particular scene was included as a categorical independent variable (i.e. three “dummy” variables), in order to explain variability between scenes influenced by different atmospheric conditions in the moment of shooting.

The initial data set of 972 cases (localities with known infralittoral habitat type, with the exception of infralittoral gravels) was randomly split into two subsets: the training and the verification set (both approximately 50% of cases). The first set was used for finding of the NN parameters, and the second to check for overfitting during the NN training (e.g. Lawrence et al., 1997) and to evaluate the final model. The original data set used for model development was unbalanced, i.e. the particular habitat type was represented with a different number of localities. During the separate analysis, it was found that the use of balanced data set (made by the multiplication of cases with less represented types) significantly improved the model reliability.

The prediction model was derived using the feedforward NN with multilayer perceptrons (MLP), which is appropriate for classification problems (e.g. Bishop, 1995 or Patterson, 1996). The logistic function was used as an activation function, and the backpropagation method for the network training. During the preliminary research, various NN architectures were tested. Each of the tested architectures had an input layer with 14 independent variables (11 environmental estimators and 3 'dummy' variables—one for each Landsat ETM+ scene), an output layer with four main infralittoral habitat types and one hidden layer (but with variable number of neurons). The finally chosen NN architecture (Fig. 2) had seven neurons in the hidden layer. Further increase in NN architecture complexity did not yield significant model improvement, however it lead to the overfitting.

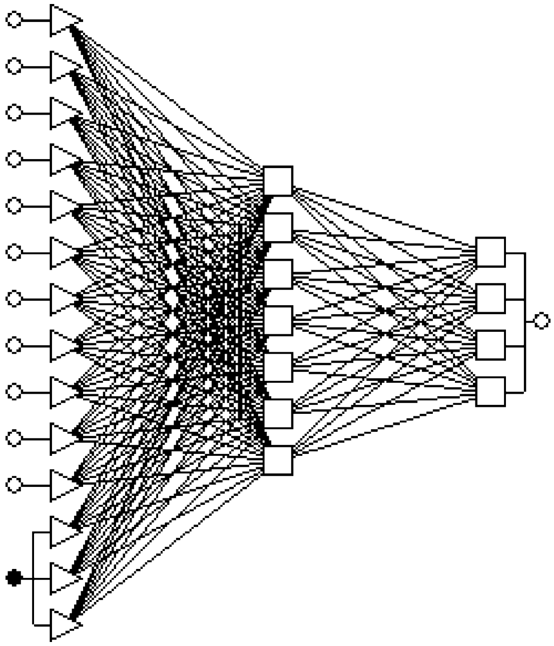

Fig. 2. Graphical visualization of neural network architecture used for the model development. The first (left) layer represents independent variables (white circles denote 11 continuous variables, i.e. environmental estimators; black circle denotes categorical variable, i.e. 1 'dummy' variable for each Landsat ETM+ scene). The second, hidden layer contains neurons which increase complexity of the model, while the third (right) layer contains the model output, namely that is the probability for each main infralittoral habitat type (the type with maximum probability is chosen as a final result).

Each neuron of the hidden and the output layer calculates its output value using the expression:

$$\beta = \mathrm{act}\left(a + \sum_{i=1}^{n} b_i \alpha_i\right) \tag{1}$$

where β is the neuron output value, α_i ith neuron input value, n the number of input connections, a and b_i are empirical parameters (a is the neuron threshold and b_i is ith input weight), and act is the activation function:

$$\mathrm{act}(x) = \frac{1}{1 + \mathrm{e}^{-x}} \tag{2}$$

For the model application on the entire infralittoral belt in the Croatian maritory, the best (in the sense of total classification correctness) of 10 NN initialisations were chosen. In order to define spatial domain for the model application using the spatial distribution of independent variables as spatial predictors, lower border of infralittoral was set up bathymetrically. The infralittoral zone is the region of optimal conditions for life of marine phanerogams and photophilic algae, and it extends from the lower margin of the mediolittoral to the lower bathymetric limit of these species distribution. In the Northern Adriatic, which is less transparent, this limit extends at the most to 20 m, while in the Central and Southern Adriatic it is somewhere between 30 and 40 m (Gamulin-Brida, 1967; our field data). Although in the open Southern Adriatic, due to high transparency, this limit can be as deep as at 50 m, on the basis of our data for locations mostly concentrated in the Central Adriatic, we decided to set the bathymetric limit for infralittoral at 30 m. For the Northern Adriatic it was set at 20 m.

2.2. *Other parts of marine benthos*

The supralittoral and the mediolittoral (together with the halophytic vascular vegetation) were mapped as habitat complexes in the function of spatial distributions of two basic classes of coastal lithology (mobile and solid substratum) and three presumed basic levels of human impact (natural coastal habitat complexes outside the settlements, seminatural coastal habitat complexes within the settlements, highly artificial coastal habitat complexes), both on the scale of

1:100,000. Using the intersection of these two spatial distributions, the entire coast (over 6000 km) was divided into six classes (the combinations of two basic classes of coastal lithology and the three basic classes of presumed human impact).

The circalittoral and the bathyal, for which the accessible data were extremely scarce, have been mapped by overlapping and reinterpretation of existing small-scaled spatial databases within the framework of the raster-GIS (using spatial resolution of 100 m × 100 m) as follows: (1) bathymetry represented by the mentioned digital model (used for the determination of border between the circalittoral and the bathyal, (2) the lithological map of the sea bottom on the scale of 1:1,000,000 (AAVV, 1985), and (3) map of circalittoral biocenoses on the scale of 1:3,000,000 (Gamulin-Brida, 1974). The last map was the result of intense sediment and bottom fauna sampling from 1965 to 1972 and the subsequent determination of benthic biocenoses in the circalittoral zone of the Adriatic (Gamulin-Brida, 1974). In our work, the limit between the circalittoral and the bathyal was set bathymetrically at 200 m (sensu Pérès and Picard, 1964). The bathyal is defined as a deep-sea zone without photosynthetic organisms (due to lack of light intensity necessary for photosynthesis). However, there are controversies about this limit in the Adriatic, because in the Jabuka pit, in the Central Adriatic, some algae were registered as deep as 250 m (Gamulin-Brida, 1974).

The intersection of the listed spatial databases, followed by the simplification of the primary intersection results on the basis of expert knowledge, resulted in the setting up of the seven habitat classes for the circalittoral (the detritic bottoms of the open Adriatic, the muddy bottoms of the open Adriatic and channels of the North Adriatic, muddy detritic bottoms, coastal detritic bottoms, sticky coastal terrigenous muds, soft coastal terrigenous muds, and coralligenous bottom) and three habitat classes for the bathyal (bathyal muds, bathyal sands, bathyal hard bottom and rocks).

3. Results and discussion

The results of mapping the coastal habitat complexes (the supralittoral and the mediolittoral together with halophytic vascular vegetation) as well as the results of mapping the circalittoral and bathyal habitat types are not presented and discussed here, as they are scientifically less interesting results yielded by relatively simple procedures (intersections of spatial databases).

Regarding the modelling of the infralittoral habitat types, the NN model mentioned above originally calculates the probability of incidence of each habitat type for the given set of input values. Thus, the model returns four probabilities for each case (locality). The habitat type with the largest probability was used for the classification of the given case. The classification correctness (estimated by the verification data set) in total and for particular habitat types is shown in Table 1.

Table 1
Correctness of classification according to the model in total and for particular infralittoral habitat type (V1, *Posidonia* meadows; V2, biocenosis of photophilic algae; V3, fine sand habitats; V4, muddy sand habitats)

	V1	V2	V3	V4	Total	Train	Verify
N (total)	406	406	406	406	3248	1624	1624
N (correct)	313	297	273	268	2415	1264	1151
% correct	77.09	73.15	67.24	66.01	74.35	77.83	70.87

	V1	V2	V3	V4	κ (total)	κ (train)	κ (verify)
V1	313	25	66	46	0.719	0.805	0.635
V2	53	297	55	11	0.671	0.715	0.629
V3	14	73	273	81	0.528	0.536	0.520
V4	26	11	12	268	0.719	0.768	0.669
All types					0.658	0.704	0.612

N (total) is the total number of cases (after the balancing of data set by the multiplication of cases for less represented types) within particular habitat type and within different data sets. *N* (correct) is number of cases (localities) correctly classified according to the model. Grey area represents classification matrix (rows, observed cases; columns, predicted cases; values, number of cases). κ indicates Kappa statistics.

The final model has total classification correctness of 77.83% for the training data set and 70.87% for the independent verification data set, and overall Kappa statistics (Monserud and Leemans, 1992) of 0.70 and 0.61, respectively. Consequently, the total agreement between the observed and modelled main infralittoral habitat types could be characterised as 'good' (Landis and Koch, 1977). Similar results of Kappa statistics were achieved for particular infralittoral habitat types.

Better results were achieved for the *Posidonia* meadows and photophilic algae (77.09 and 73.15% of correctly classified cases, respectively) compared to the results for fine sand and muddy sand habitats (67.24 and 66.01%, respectively). According to this result, and after the preliminary application of the described original model (using the spatial distributions of independent variables) in real space (where muddy sand habitats practically disappeared), it seemed reasonable to join fine sand and muddy sand habitats into one widely understood type (the infralittoral sand habitats). This was done without the building of a new NN; the results of the described finally chosen NN have been reinterpreted by joining the two mentioned types. The resulting aggregated type has classification correctness of 78.08%, which a posteriori increases total classification correctness to 76.60%.

The interpretation of the remaining unexplained variability could be aimed at: (1) errors in the mapping of localities with known habitat types, (2) errors in the mapping of independent variables, (3) the use of discrete and general habitat types, while natural boundaries between types are often blurred, (4) the impact of other potential spatial predictors, and (5) the model error.

Regarding the impact of potential spatial predictors not included in the model development, the rapid increase of explained variability could be expected after the inclusion of the lithological substratum as independent variable, taking into account the data from the existing lithological maps (e.g. such as one by Juračić et al., 1999, which covers just one small part of the examined area) or collecting new data using special devices for the remote sensing of sea bottom (e.g. high resolution side-scan sonars, e.g. Kenny et al., 2003; McRea et al., 1999; Pasqualini et al., 1998, or bottom profiling imagery, e.g. Karakassis et al., 2002).

Up to now, the optimal results for mapping the *Posidonia* meadows for conservation and management purposes have been achieved by integrating several different methods chosen on the basis of area characteristics, maximum depth to be reached and the level of precision required (Pasqualini et al., 1998; Piazzi et al., 2000). However, it has to be emphasized that any kind of direct lithological mapping of the sea bottom (as well as direct mapping of habitats), cannot be effectively used for the larger area, due to the complexity and expensiveness of submarine fieldwork. Due to technical complexity of SCUBA diving and human physical limitations, an average diver can work underwater on habitat mapping for approximately 1 h per day, only to the depths of 40 m (if diving with compressed air). Although precise, this method for habitat mapping is very time-consuming and expensive, yielding small amount of mapped areas per unit of time. This fact strongly increases the usability of the approach presented in this paper, especially in combination with remote sensing of sea bottom and direct field sampling (as the only source of necessary biological ground truth data; Freitas et al., 2003; Kenny et al., 2003).

The part (for the small framed area on Fig. 1) of final spatial distribution of the three infralittoral habitat types yielded by the quoted reinterpreted model (applied for the entire Croatian maritory within the raster geographic information system in a spatial resolution of 30 m × 30 m, aiming at construction of hypothetical spatial distribution of three main infralittoral habitat types), with superimposed circalittoral habitat types (obtained separately), is shown on Fig. 3.

The presented spatial distribution of infralittoral habitat types has been achieved by spatial generalization of the primary result of the NN application onto the entire spatial domain of interest (i.e. after computing the most probable main habitat type for each element of spatial resolution). This spatial generalization included: (1) 3 × 3 focal majority filter (choosing the habitat type which is most frequent in the 3 × 3 neighbourhood of each pixel) and (2) the omission of all homogeneous groups with MMU less than 2.25 ha (which were replaced by the closest surrounding habitat types).

According to the results of all mapping procedures used in this research (from spatial modelling to the

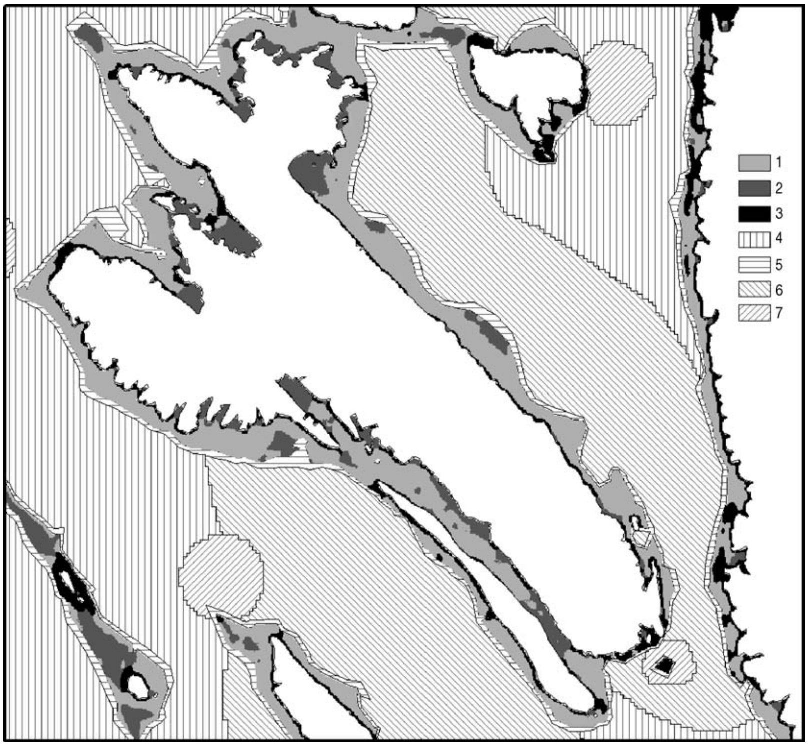

Fig. 3. Spatial distribution of infralittoral habitat types yielded by the model (grey scale: 1, *Posidonia* meadows; 2, infralittoral sand habitats; 3, biocenosis of photophilic algae) and circalittoral habitats, mapped by using a different method (patterns: 4, muddy bottoms of the open Adriatic and channels of the North Adriatic; 5, coastal detritic bottoms; 6, soft coastal terrigenous muds; 7, coralligenous bottom).

spatial generalization), areas of main infralittoral habitats as well as the total area of the infralittoral zone in the Croatian maritory could be estimated as follows: the *Posidonia* meadows—1451 km^2, infralittoral sand habitats—1054 km^2, biocenosis of photophilic algae—143 km^2, total infralittoral area—2648 km^2.

The surface area of the *P. oceanica* meadows is usually expressed as area covered by *Posidonia* per km of the coastline: it ranges from 14.46 to 67.59 ha km^{-1} for certain Mediterranean locations. Surface area for Elba Island was 25.03 ha km^{-1} and it was obtained by the side scan sonar mapping in combination with direct observations (Piazzi et al., 2000). In the Croatian part of the Adriatic, the surface area obtained with our model was 24.07 ha km^{-1}. This result, although in concordance with literature, should be taken with caution since in our work it covers a much larger area. The same applies to comparisons of infralittoral areas covered by particular biocenosis. Pasqualini et al. (1998) registered 30–58% area covered with the *Posidonia* in the zone from 0 to 50 m, while we obtained 55% in the zone from 0 to 30 m. Since this is also the result obtained for the whole Croatian part of the Adriatic Sea it should be considered as rather overestimated. Gili and Ros (1985) directly mapped benthic assemblages in the area around the Medes Islands in Spain (Western Mediterranean) and noted that in the infralittoral zone photophilic algae dominated in the areal cover compared to the *Posidonia* (58% versus 21%, respectively). Although it is possible that *Posidonia* cover more than 50% of surface area (as noted on the Corsican coast, but considered exceptional even at the Mediterranean level, Pasqualini et al., 1998), it seems that the results of our modelling (which also show that *Posidonia* dominate in comparison with the photophilic algae) does not completely reflect the usual natural situation. Therefore, more research is needed in order to explain this part of the results.

4. Conclusion

The developed model explains a significant part (more than three quarters) of the total variability of the main infralittoral habitat types recognized during the fieldwork on almost thousand localities. Due to the fact that the mentioned level of the total variability explanation was estimated on the basis of independent data which was not used for the model development, it is possible to use the present model for construction of the preliminary spatial distribution of main infralittoral habitat types for entire Croatian maritory. This preliminary distribution is the first and the only spatial database that covers the entire infralittoral area of the Croatian maritory.

Apart from the fact that the use of neural networks and raster-GIS modelling enabled the inclusion of the infralittoral habitats mapping into the mentioned national project, despite the lack of large amount of field data (which probably could inspire similar applications in the field of the sea benthos mapping), it could be generally concluded that the results of this paper also illustrate the possibility of the reconstruction of complex spatial phenomena on the basis of limited field sample (comparable to the work of Antonić and Legović, 1999).

Future improvement of this kind of models (in case of their application for mapping of infralittoral habitat types) could be expected in the following directions: (1) focusing on smaller and ecologically less heterogeneous areas, (2) increase in spatial resolution, (3) prediction of habitat types at finer scale (using more specific types), (4) prediction of spatial distribution of particular benthic species as more objective model output, and (5) inclusion of other hypothetically usable independent variables (e.g. detailed spatial distributions of light quantity at the sea bottom—following experiences from land, e.g. Antonić, 1998; Dubayah and Rich, 1995, human impact, but, above all, the sea bottom lithological types, mapped in as much detail as possible).

Regardless of the level of future improvements, it is expected that this kind of model could give significant support to the nature protection and sea management purposes, especially regarding the generalization of existing data which are usually scarce due to the complexity and expensiveness of submarine fieldwork.

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