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Using catenas for GIS-based mapping of NW Mediterranean littoral habitats

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A B S T R A C T

Studies aimed at describing habitats and mapping their distributions are pivotal to implementing management plans and to effectively guide conservation measures. We developed a novel approach of data collection and entry (CAT-LIT) to establish a detailed cartography of the littoral habitats found along the Catalan coast (Spain). Field data were recorded using coded, two-digit hierarchical lists (e.g. Aa, Ab, etc.) of horizons found at each point along the coast, called catenas. The horizons were either dominated by species (on the rocky bottoms) or sediment types (on the beaches) and corresponded to LPRE, EUNIS and CORINE habitats. Catenas were transferred into a database and calculations about the extent of bottom types, habitats, and catenas themselves along the coast were carried out with GIS tools. In addition, habitat link richness was calculated and represented using network analysis programs. The application of CAT-LIT to the Catalan coast showed that the habitats dominated by the lichen *Verrucaria amphibia* and the flattened barnacle *Euraphia depressa* and those dominated by the barnacle *Chthamalus* spp. were almost ubiquitous. Those dominated by the red alga *Corallina elongata*, the mussel *Mytilus galloprovincialis* and the red alga *Rissoella verruculosa* were also common. Because of the frequency of their connections, those habitats formed a huge hub of links in the networks. By using catenas, the habitats can be viewed using GIS based programs keeping the catena as the main informational and ecological unit. The catenas allow maximum compactness when vertically distributed habitats are to be shown on a 2D map. The complete cartography and dataset on the spatial distribution of the littoral habitats from Catalonia is valuable for coastal management and conservation to study changes in the habitat distribution and relate such changes to anthropogenic pressures. Furthermore, the CAT-LIT can be easily adapted to shores of other seas and oceans to obtain accurate cartographies of the spatially-reduced and highly vulnerable littoral habitats.

1. Introduction

The habitat is perhaps the most commonly used landscape unit in ecology, despite the fact that it lacks a universal definition and many doubt that it represents a general ecosystem division (see discussion in Mitchell, 2005). The persistence of the habitat as an ecological concept arises perhaps from the need to describe and categorize natural systems into subunits that can be clearly delineated in time and space. For instance, in the European Union Habitats Directive (92/43/EEC), a habitat is defined as a terrestrial or aquatic area distinguished by geographic, abiotic and biotic features, whether entirely natural or semi-natural. While this definition may reflect a mere pragmatic convenience, studies aimed at describing habitats and mapping their distributions are pivotal to implement management plans for the rational use of both land and sea, as well as to effectively guide conservation measures that are often focused on the habitat as the unit of action (Fraschetti et al., 2008, 2011).

Littoral zones are at the interface between land and water and show strong gradients of environmental conditions. It has long been recognized (see Whittaker et al., 1973) that, while variable in their intensity and persistence, such environmental gradients continuously force all species, particularly plants and sessile fauna, to keep within their limits of tolerance. At the same time, some species are able to adapt to those limiting conditions, significantly

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broadening their distributions. This dynamic adaptiveness, along with interactions among individuals, populations and species, leads to the existence of distinctive bell-shaped frequency distributions along the environmental gradients (e.g. Ballesteros and Romero, 1988). The midpoints of these ranges, which correspond to the species optimum conditions are clearly recognizable. Although species may have different optima along one environmental gradient because of the interaction of more-than-one environmental factor (Pakeman et al., 2008), these limits are, very often, visibly definable especially for large organisms. This pattern helps recognize habitats dominated by species distributed perpendicular to the main environmental gradient as belts or horizons, which, although they may overlap to some extent, are essentially identifiable as separate units. These horizons, which are mainly dominated by periwinkles, barnacles and limpets in upper levels and by seaweeds in lower levels of rocky shores, have long been recognised for both tide-dominated (see Stephenson and Stephenson, 1949), and tideless seas such as the Mediterranean (Feldmann, 1937).

Littoral soft bottoms essentially differ from rocky shores because of the general instability of the substrate. For this reason, sand, gravel, and cobble shores are preferentially inhabited by animals rather than by benthic weeds. Furthermore, they have, in general, few or no sessile organisms. This makes the recognition of clear zonation patterns from features visible to the naked eye problematic (see Dahl, 1952). Moreover, universal zonation schemes both in time and space have been long debated (mainly for intertidal soft bottoms; see Haynes and Quinn, 1995). In the Mediterranean Sea the morphological characteristics of sediments, particularly the sediment size, the beach profile, and the hydronynamics mainly determine the availability of water and thus the distribution of organisms along the vertical axis (Pérès, 1967).

In Europe, the Council Directive 92/43/EC (Habitats Directive), although partial and very incomplete with respect to the marine realm, represented a significant step forward in instructing and creating awareness about habitats and their conservation. For the marine environment, the EU Marine Strategy Framework Directive 2008/56/EC (MSFD) aims to attain healthy ecological conditions and perseveration in their protection and conservation. To this end, according to Annex II of this Directive, EU member states have to define and map the habitats and their biological components within the limits of their territorial waters.

Following the progress in field technology and computer-based tools, digital mapping of aquatic habitats has become widespread (e.g. Belsher et al., 2005; Rovere et al., 2010; Barberá et al., 2012) and some methodologies have been developed even for the intertidal and shallow subtidal zones (Chust et al., 2008, 2010; Thorner et al., 2013). Geographic Information Systems (GIS), apart from being very precise when habitats need to be located, allow the design of management and conservation plans at different spatial scales. Moreover, such tools make it possible to precisely register and evaluate changes that may affect natural systems over time (Rodríguez et al., 2009). Despite this, it is often difficult to link the details in habitat description in the field with GIS databases, especially when wide areas and coastlines are to be mapped. For instance, habitat digital mapping becomes a particularly complex challenge to carry out on steep slopes shores of tideless seas. Partial cartographic data of several habitats have been obtained for Mediterranean Sea rocky shores (Ballesteros et al., 2007; Nikolic et al., 2013). Nevertheless, a methodology specifically focused on mapping all the littoral habitats does not exist.

The main purpose of this research was to build a detailed cartography of the littoral habitats found along the Catalan coast (north western Mediterranean; Fig. 1). To this end, we describe a novel approach (CAT-LIT) of field data collection and entry into GIS databases that could significantly ease the complex mapping and bidimensional representation of vertically stratified near-shore habitats. We provide information on both substrate and habitat distributions, as well as some insights into the relationships among the habitats found on rocky shores.

2. Materials and methods

The tideless littoral zone studied here consists of a fringe of variable width that comprises the more or less regularly-splashed, never-submerged supralittoral zone, the intermittently-submerged mediolittoral zone, and the permanently submerged upper infralittoral zone (see Pérès and Picard, 1964). This fringe stretches along the entire coast of Catalonia and between two specific points (3°10′28.072″E, 42°26′17.619″N and 0°30′57.001″E, 40°31′26.302″N; Fig. 1). The total length of the coast measured at 1:1500 scale (see below) is 909.7 Km without considering the harbour docks and marinas (205 Km), and encompasses most of the Mediterranean littoral habitat diversity. Although the same conceptual frame was applied for both rocky and soft-bottom shores, we used different field sampling methods, which are detailed hereinafter.

2.1. Rocky habitats

Mapping of the rocky littoral habitats in the field was done using a modified CARLIT methodology (Ballesteros et al., 2007). We steered a small inflatable boat (4.1 m length, 18.4 KW engine power) along the coast, visually identifying the different belts or horizons encountered and recording this information on an A4 paper format map. The scale was set at 1:1500 and the sectors of coast mapped measured 10 m minimum, with the exception of some horizon from specific environments (e.g. caves, rock pools) for which the sampling unit was scaled to the area they occupied and the exact positioning recorded by a GPS. The identification of infralittoral horizons was done directly from the boat, although we occasionally needed to snorkel or use a glass bottom bucket to do it. The entire field exercise required 1200 man hours to survey approximately 1000 Km of the Catalan coast over a two-year period.

The number of horizons at each sector varied from one to ten, making their complete annotation on the maps difficult to record at a reasonable speed in the field. To ease this task we first ordered the most common horizons into a limited number of topographical sequences and then built up new sequences as new horizons were found whilst sampling. Across the 910 Km of the Catalan coast we identified up to 213 sequences of vertically stratified horizons. These sequences will be referred hereafter to as catenas in line with the nomenclature used for terrestrial environments by other authors (e.g. Rivas-Martínez, 2005).

Catenas are defined here as a series of horizons linked by their topographic occurrence, namely their position along the vertical axis, which extends from the upper level of the supralittoral zone (from about 50 cm on protected shores to more than 10 m on more exposed shores) to 1 m depth. We occasionally collected samples by hand to validate doubtful species identification. Samples were later accurately identified in the laboratory.

We gave each catena a two-letter alphabetic code in a sequence roughly similar to Aa, Ab, Ac …, Az (see Annex A) where each capital letter often referred to a group of similar catenas sharing characteristic horizons. For example the catenas Aa and An belonged to the same group because the horizons of the red alga *Rissoella verruculosa* and the brown alga *Cystoseira mediterranea* were present in both, but they differed because of the presence of the horizon of *Lithophyllum byssoides* in Aa. However, any simple code (either alphabetic, numeric or any of the types allowed by GIS-

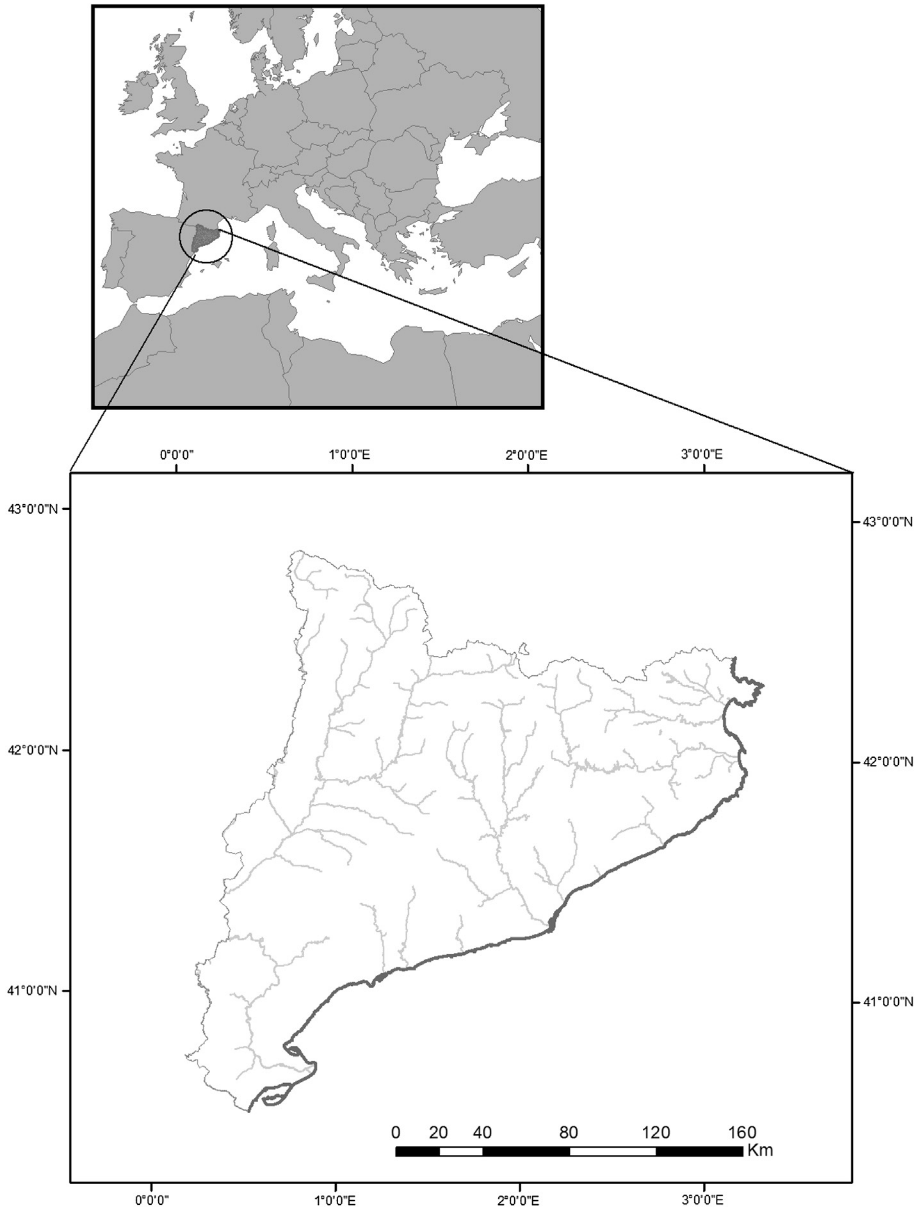

Fig. 1. Map of the coastline studied.

based programs) could be appropriate. When two or more horizons were found at the same height at one particular point the dominant one was qualitatively estimated and the location was assigned to the related catena.

Most of the littoral horizons detected during the survey corresponded to habitat units as defined in the Spanish "Lista Patrón de los Hábitats Marinos Presentes en España" (hereafter LPRE; Templado et al., 2012). The LPRE habitat list can be easily converted to the nomenclature used by the European Nature Information System (EUNIS) of the European Environment Agency and by the Coordination of the Information of the Environment (CORINE) Biotopes (see Annex B). The habitats assigned to CORINE biotopes were based on the "Manual dels Hàbitats de Catalunya", which is an adapted version of the CORINE Biotopes Manual to the Catalan habitats (Curcó et al., 2008). As an example, the horizon of the red alga *Rissoella verruculosa* corresponds to the habitat 02010215 (LPRE), A1.133 (EUNIS), and 11.1313 (CORINE Biotopes, Catalan Manual; Annex B). Sampling was conducted from the end of March to late July (in 2010 and 2011), when most of the littoral assemblages reach their optimal development and thus are easy to identify (Feldmann, 1937; Ballesteros et al., 2007).

2.2. Soft-bottom habitats

To be consistent with the sampling of the rocky shores and with the three habitat classification systems used, the soft-bottom habitats of the supralittoral, mediolittoral, and upper infralittoral (down to 1 m depth) levels were distinguished.

Beach mapping was conducted from October 2010 to September 2012. All the 566 beaches found in Catalonia were visited. These ranged from tiny coves to long sandy shores stretching out for tens of km. To avoid people, most of the beaches were visited during fall and winter months. Some beaches, especially those inaccessible by land, were mapped whilst sampling the rocky shores by boat in spring and summer.

The sampling consisted of an overall categorization of the three littoral levels studied at each site according to the habitat lists mentioned above. At the same time, a classification of the sediment types into several main categories (see below) was conducted. At 47 sites, three (one per each level) or more sediment samples, were collected depending on the beach granulometric heterogeneity, stored in 250 mL plastic pots and taken to the laboratory for analysis of sediment size. Photographic images were taken on each beach to compare the sediment size evaluated in the field with the results of the grain analyses from the laboratory. In the laboratory samples were analysed either by sieving the dry sediment through a 2000, 1000, 750, 500, 375, 250, 125, and 63 μm column of mesh sizes, or by an automatic Mastersizer 2000 (Malvern instruments Ltd., UK), particularly when fine grains were found.

Most sedimentary habitats from the CORINE and EUNIS lists are essentially defined by their physical (mainly sedimentological) properties, whereas the LPRE classification includes habitats defined by species and genera, particularly for the mediolittoral and infralittoral levels (see Annex B). Nonetheless, LPRE has a hierarchical structure with the upper levels defined only by sediments (e.g. Mediolittoral Sands and muddy Sands, habitat no. 020202; Annex B).

Therefore, three different horizons were mapped at each beach site. For consistency with the system used for the rocky shores, a special nomenclature of horizons was created to fit into soft bottom catenas. Each horizon represented the combination of the most frequent sediments found along the coastline (e.g. Supralittoral Cobbles, Gravels and Sands; habitat no. 01020101; see Annex B) that best fit the habitat classification lists used and each catena had a two-digit alphabetic code as for the rocky shores (see Annex A). Some of the catenas included habitats of sheltered coastal bays dominated by seagrasses and other plants such as *Phragmites australis* and *Ruppia cirrhosa*. Other catenas included both soft and hard bottoms (see Annex A for details).

2.3. Digital cartography and data entry

The digital cartography was developed using Geographic Information System (GIS) techniques with the program ArcGis 10 (ESRI). The Projected Coordinate System was the European Datum 1950 UTM Zone 31N. The digital cartography was done at a scale of 1:1500. Data were entered in a line vector digitized by the Institut Cartogràfic de Catalunya (ICC) with scale 1:1000, which represents the coastline of Catalonia. The digital coastline was corrected to match the most recent shoreline. We did this using the command “reshape feature” in ArcEdit, connecting the digital map with overlays from aerials images (file name: Ortofoto de Catalunya 25c, 2012) available in the Web Map Service of the ICC. The digital coastline was imported as feature class in a Personal Geodatabase where all datasets were stored in a Microsoft Access data file (the .mdb file).

By clicking on each line segment the relative data collected in the field were entered into the attribute table of the line. The first attribute to be entered was the bottom type. We created ten bottom types as they were identified in the field: beach, rock, rock without supralittoral, natural rocky boulders, harbour docks, breakwaters, rocky pools, caves, concrete walls, and underwater rocks (max. 1 m depth). Each site was additionally given an attribute based on its catena, as they were recorded in the field.

Since the segments of the original digital coastline often differed in size from those used for the field mapping, they were resized according to the length of substrate types and catenas. Hence, with the exception of the automatic fields generated by ArcGis (e.g. object id), each attribute table had three fields: the length, the substrate type, and the catena.

As described above, each catena comprised several horizons and each horizon could correspond to one or more habitats, most of them described by the three classifications used: LPRE, EUNIS, and CORINE. Thus the link between each catena and its corresponding horizons was stored in a second table (here, Order Catena). Furthermore, the correspondences between the horizons and the habitats were stored in a third table (here, Habitats). Finally, to have each habitat on a specific line segment, the tables “Order Catena” and “ Habitats” were first joined through the common field “Horizon” (with the ArcMap's table tools) and then related to the attribute table of the line through a simple relationship class with a cardinality of one-to-many using the common field “Catena” with the ArcCatalog tools.

In summary, in ArcMap, after clicking with the Information button on a line segment, the corresponding catena, the substrate, and the length of the segment were shown. Additionally, by clicking on the plus-minus icons underneath the relationship Order Catena_Habitats, the relative horizons and their correspondences to the habitats (LPRE, EUNIS and CORINE) were shown (Fig. 2).

2.4. Data analysis

Once the digital cartography was completed, a series of simple analyses could be carried out directly from the project in ArcGis 10 or in Microsoft Access. For example, general information about the extent of specific bottom types, horizons, catenas and habitats could be easily obtained through queries such as the statistics (Σ) in the panel relative to the Shape Length in ArcGis 10. The percent cover of each habitat was calculated with respect to the approximately 900 Km of the coastline excluding the mediolittoral and upper infralittoral levels of the marinas and harbour docks (see Results and Discussion for details). In contrast, the percent cover of each bottom type and catena was calculated relative to the whole coast length.

Two symmetric matrices were built up in order to test hypotheses about the frequency of links among the identified rocky habitats ($N = 43$) and to show the degree of habitat connectedness. The first matrix had the shared distances in Km for all paired habitats and the second had the number of times paired habitats coincided in the catenas. With the exception of those included into wider habitats (see Annex B), the habitats of supralittoral and mediolittoral rock pools were not included in the analysis. Both measures (coast length occupied and frequency in the catenas) relative to the horizon characterised by the red alga *Hypnea musciformis* were included in the data of the habitat of *Corallina elongata* mediolittoral because of the wide ecological overlap between both. In the specific instances where the habitat as conventionally defined could potentially mask more interesting species-specific patterns, we subdivided them to reflect compositional differences. For instance, we allocated the horizons dominated by the corals *Oculina patagonica* and *Corynactis viridis* or by some species of the genus *Cystoseira* into habitats of their own to elucidate their distributional patterns (see Annex B and Discussion). Significance in the hierarchical differences among habitats in the matrices was tested through a standardized Mantel (9999 permutations) test assuming, as a null hypothesis, that the distances between the objects in the two matrices (Km and frequencies) were not linearly correlated (see Legendre and Legendre, 1998). The underlying idea is that the number of times one particular habitat was connected to others in the catenas should be comparable to the kilometres it shared when both measures were tested with those from a randomly generated matrix. The Mantel test was performed with R version 3.0.1. A network relative to the interaction links among rocky habitats was visualised using the program Gephi 0.8.2 beta. Each of the 43 habitats found were placed as neighbouring nodes

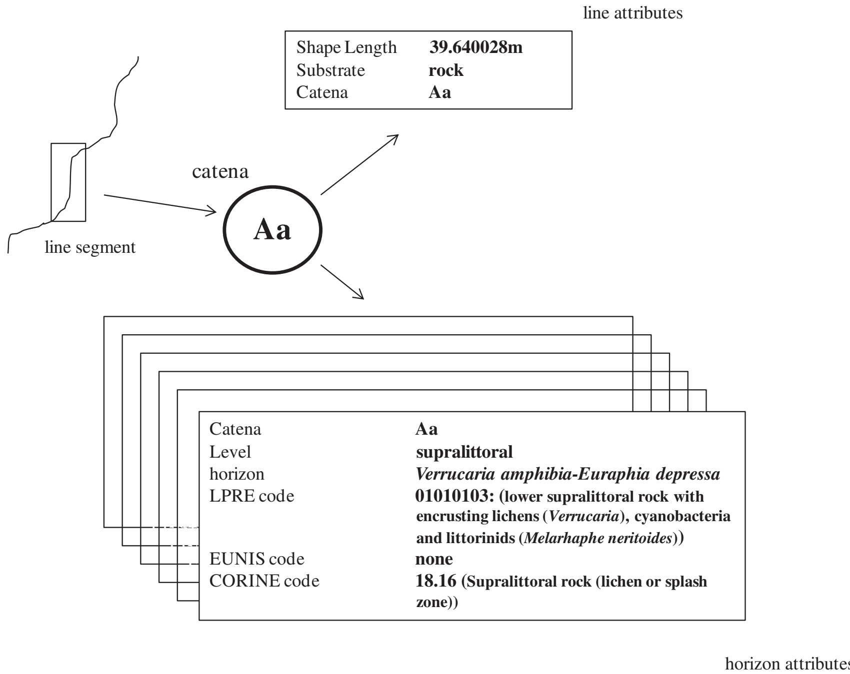

Fig. 2. Overall representation of the information shown in ArcMap after clicking with the Information tool on a specific line segment. Each horizon is displayed separately in different windows.

through the Fruchterman-Reingold algorithm (Fruchterman and Reingold, 1991) before improving the visualization using Gephi tools.

As mentioned above, and particularly from a monitoring point of view, littoral rocky habitats differ essentially from the soft bottom habitats because, in the first, organisms are the main structuring agents configuring the habitats whereas grain size largely determines habitat in the second. Furthermore, here the horizons corresponded to the littoral levels (supralittoral, mediolittoral and infralittoral) in sites with soft bottoms, so that only three horizons can be recognized at a determinate point of the coastline. Yet, with two exceptions, strong variation in faunal assemblages did not exist and species had a wide range of adaptations to grain sizes along the vertical axis thus determining the lack of any clear association between a particular grain size and a species, at least for the mediolittoral and the infralittoral levels (Mariani et al. unpublished results). For all these reasons we did not construct matrices for soft bottom habitats similar to those made for the rocky habitats, nor were networks created.

3. Results

While a different array of layer properties can be used, a possible outcome of the final digital mapping is shown in Fig. 3. It shows a portion of 420 m of the coastline with different line colours and labels for each catena. The catena present at a concrete point over the digital line is shown in ArcGis by clicking with the "Identify" button. The different habitats comprised in each catena can be seen either as explained in the Methods Section, as shown in Fig. 3 or by checking the Annex A and B sequentially.

The most frequent substrate type was the rocky shore, extending over 400 Km, 36% of the total coastline (see Fig. 4). Beaches constituted 339 Km (30.6% of the total) followed by harbour docks (209 Km, 18.8%) and breakwaters (94 Km, 8.5%). Concrete walls were present over 32 Km (2.9% of the coastline), whilst large natural rocky boulders represented over 30 Km (2.7%) of the coast. The other bottom types accounted for less than 1% of the coastline: rocky shores whose emerged portion did not reach the supralittoral level (2.9 km), the infralittoral, not emerging rocks (0.6 Km), caves (2 Km), and the 222 rocky pools mapped, which covered 2257 m^2 altogether.

Among the 77 horizons identified, 48 were found on rocky shores and 28 on beaches. On the rocky shore, the horizons corresponded to 45 LPRE habitats (Annex B). The supralittoral habitat dominated by the lichen *Verrucaria amphibia* together with the flattened barnacle *Euraphia depressa* and the periwinkle *Melaraphe neritoides* and the upper mediolittoral habitat dominated by the stellate barnacles *Chthamalus stellatus* and *Chthamalus montagui* were the most frequent habitats (see Fig. 5). Both occupied almost 60.6% of the littoral (547 Km). The third and the fourth most frequent rocky shore habitats were those dominated by the coralline alga *Corallina elongata* which forms extensive carpets at the lower mediolittoral level (473 Km, 52.5% of the coastline) and at the infralittoral level (353 Km, 39%). The fifth most frequent habitat was dominated by the mussel *Mytilus galloprovincialis* in the mediolittoral rocky shores (290 km, 32%). The mediolittoral habitat formed by the red alga *Rissoella verruculosa* was found over 265 km (29.4% of the coastline). The habitat dominated by the massive coralline alga *Lithophyllum byssoides* grew over 191 Km (21%) whereas the infralittoral habitat dominated by the brown alga *Cystoseira mediterranea* was found along 176 Km (19.6%). Among the habitats of special ecological and conservation interest (see Discussion), the distinctive mediolittoral rims of *L. byssoides*, so called "trottoir" (pavement in French), covered over 26 Km (2.9%) of the coast.

As for the beaches, the horizons corresponded to 27 LPRE habitats (Annex B). Specifically, the habitats characterised by medium and fine sands extended over 206 km (22.9% of the coastline; see Fig. 6). Medium and fine sands dominated the supralittoral (191 Km, 21.2%), the mediolittoral (188 Km, 21%), and the upper infralittoral (142 Km, 15.7%; see Fig. 6) levels. The beaches characterised by coarse sands and gravels were found over 110 Km (12.2%), extending respectively over 107 Km (12%) in

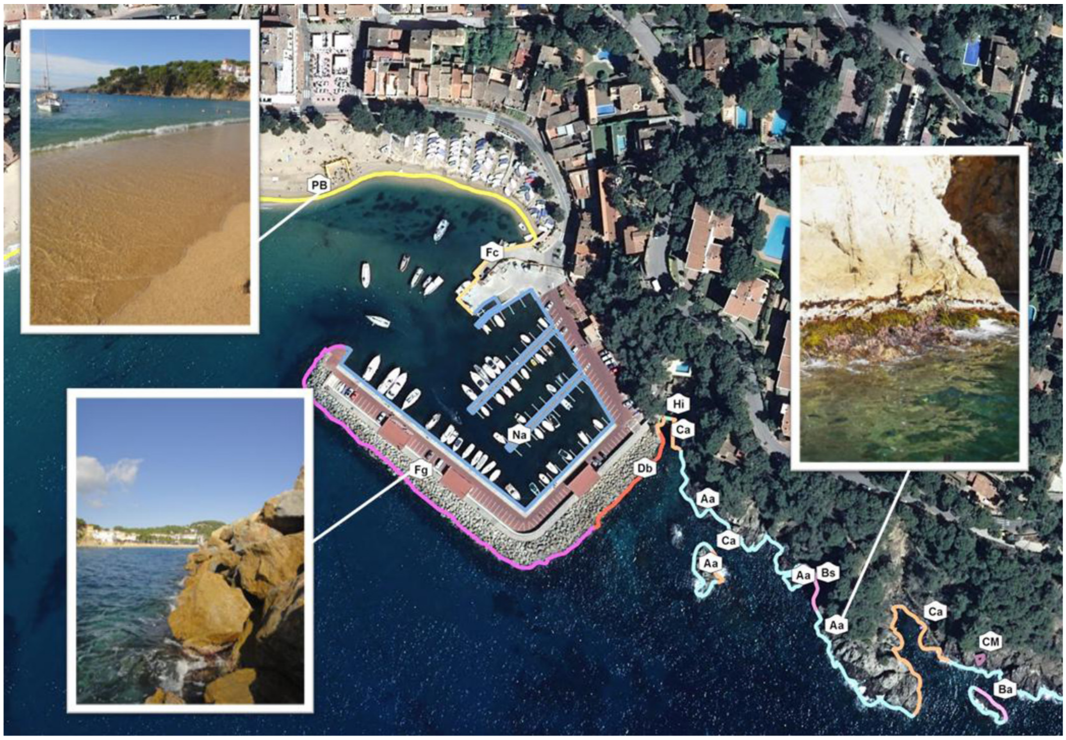

Fig. 3. Representation from ArcMap of the line showing different colours and labels for each catena. The images are relative to the catenas PB, Fg, and Aa as they were seen whilst sampling (some horizons are recognisable as separated belts).

the upper infralittoral level, 79 Km (8.8%) in the mediolittoral level, and 78 Km (8.6%) in the supralittoral level (see Fig. 6). The infralittoral estuarine muddy sands habitat and the mediolittoral muddy sands habitat were the dominant habitats along 53 Km (5.9%; Fig. 6) of coastline. The habitats of the supralittoral fine sands and the infralittoral sands of sheltered environments occupied 33 (3.7%) and 30 Km (3.4%) respectively (Fig. 6). Finally cobble dominated beaches were found over 22 Km (2.4%; Fig. 6), along 20 Km (2.3%) in the supralittoral level, 17 Km (1.9%) in the mediolittoral level, and 12 Km (1.3%) in the upper infralittoral level, respectively.

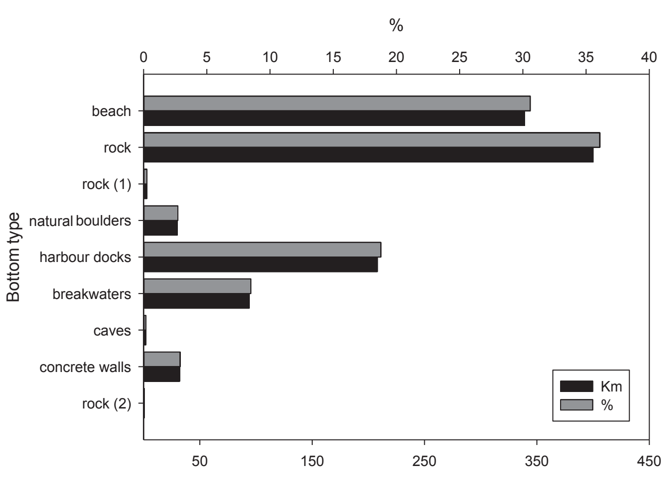

Fig. 4. Frequency and extent of the different bottom types mapped. Rock (1) represents the rocky shores without the supralittoral stage, and rock (2) the submerged rocky substrates.

A particular horizon was created for all the habitats found in the mediolittoral and the upper infralittoral levels of the harbour docks. The resulting habitat was characterized by having different species of algae and animals particularly dependent largely on its distance from the open sea.

We created 190 catenas of rocky-shore horizons (including the harbour docks) plus 23 catenas of soft-bottom horizons (Annex A).

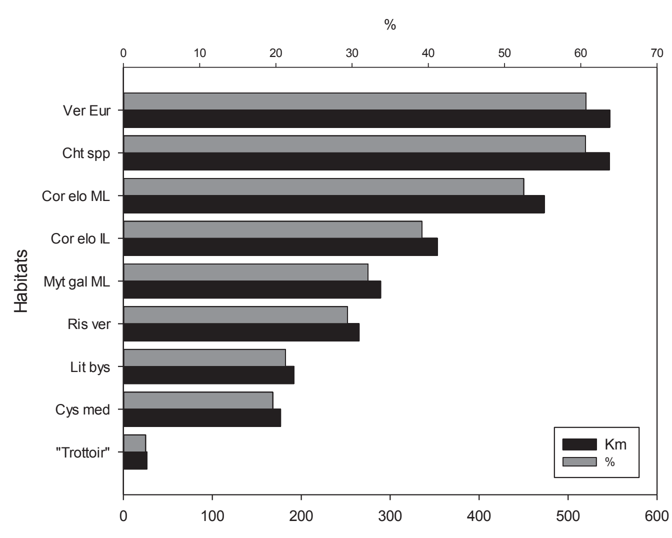

Fig. 5. Frequency and extent of the commonest habitats on the rocky shores plus the "Trottoir". Abbreviations: Ver Eur (*Verrucaria amphibia* and *Euraphia depressa*), Cht spp (*Chthamalus* spp.), Cor elo ML (Mediolittoral *Corallina elongata*), Cor elo IL (Infralittoral *C. elongata*), Myt gal (Mediolittoral *Mytilus galloprovincialis*), Ris ver (*Rissoella verruculosa*), Lit bys (*Lithophyllum byssoides*), Cys med (*Cystoseira mediterranea*).

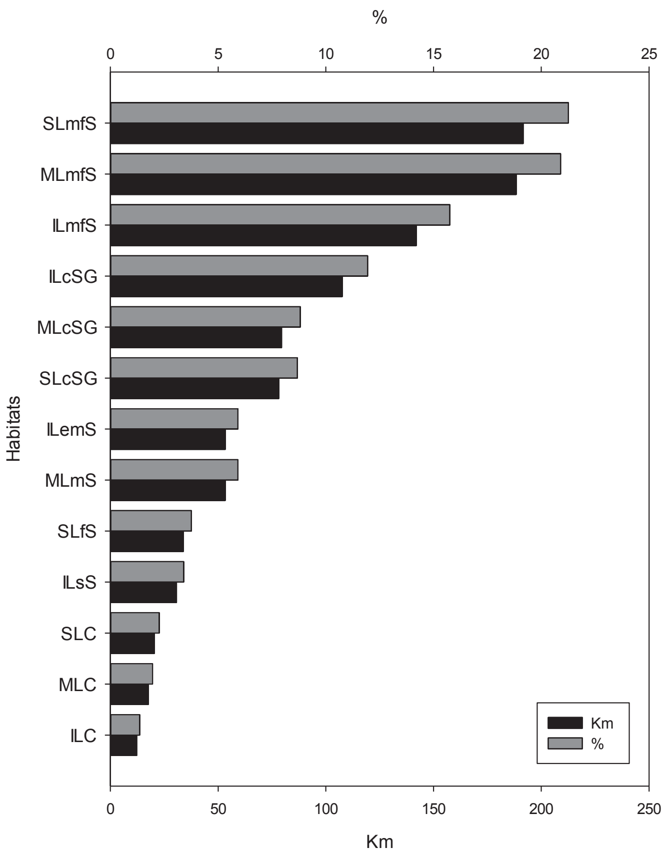

Fig. 6. Frequency and extent of commonest habitats from the beaches. Abbreviations: SLmfS (Supralittoral medium and fine Sands), MLmfS (Mediolittoral medium and fine Sands), ILmfS (Infralittoral medium and fine Sands), ILcSG (Infralittoral coarse Sands and Gravels), MLcSG (Mediolittoral coarse Sands and Gravels), SLcSG (Supralittoral coarse Sands and Gravels), ILemS (Infralittoral estuarine muddy Sands), MLmS (Mediolittoral muddy Sands), SLfS (Supralittoral fine Sands), ILsS (Infralittoral sheltered Sands), SLC (Supralittoral Cobbles), MLC (Mediolittoral Cobbles), ILC (Infralittoral Cobbles).

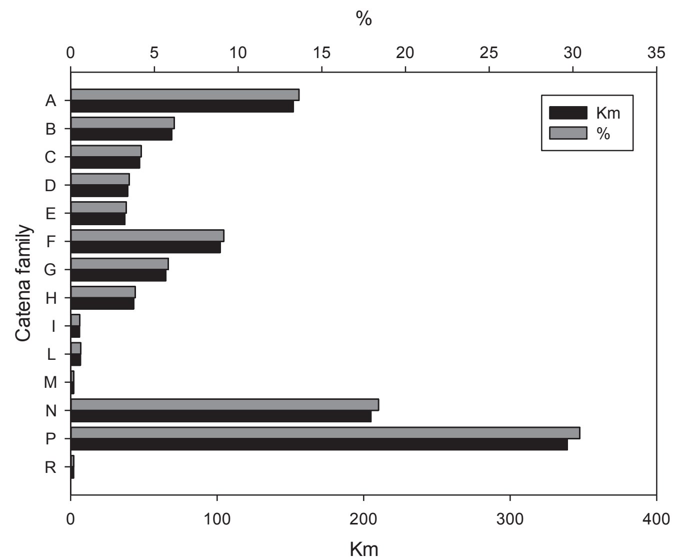

Fig. 7. Frequency and extent of the catena families.

The most abundant family of catenas was P (named from the Catalan "platja", for beach), found over 339 Km (see Fig. 7). The dominant catenas were PL (129 Km, 38% of the total beach substrata) and PB (76 Km, 22.4%: Fig. 8). PL had medium and fine sands (between 125 and 500 μm) whereas PB had coarse sands and gravels (between 500 and 1000 μm). Hence, sands and gravels dominated the supralittoral, mediolittoral, and infralittoral of Catalan beaches.

The second most abundant family of catenas (based on the Km occupied) was N (205 Km, 18.4% of the coastline). This group contained three catenas with Na accounting for 99.9% of the total coverage. This catena was roughly organised as having two horizons, the upper one corresponding to the supralittoral habitat dominated by *Verrucaria amphibia* and *Euraphia depressa* and the lower one corresponding to the mediolittoral and infralittoral habitat from harbours. The catenas Nb and Nc contained the coral species *Oculina patagonica* and *Corynactis viridis* respectively in the infralittoral level (see Discussion for details).

The A family accounted for 13.6% of the total coastline (152 Km). The common characteristic of the A catenas was the presence of the horizons of the red alga *Rissoella verruculosa* and the brown alga *Cystoseira mediterranea* in the mediolittoral and infralittoral levels, respectively (Fig. 8). The most common A catena (72%) was the Aa formed by the *Verrucaria amphibia* and *Euraphia depressa* horizon in the supralittoral zone, the *Chthamalus* spp. horizon in the upper mediolittoral zone, the *R. verruculosa* horizon (see Annex A) underneath the *Chthamalus* spp. horizon, the *Lithophyllum byssoides* horizon in the lower mediolittoral level, and the infralittoral habitat of *Corallina elongata*.

The other families of catenas showed decreasing abundances along the coastline (Figs. 7 and 8) and all of them are reported in Annex A. Some of the described catenas are worth noting because of their singularity or presence of rare species (see Discussion): the Es (6.3 Km), characterized by the mediolittoral rims of *Lithophyllum byssoides*, and the group M (2 Km) with horizons dominated by endangered species of the genus *Cystoseira* (Fig. 8).

The frequency of catenas and Km shared by habitat pairs was highly correlated and, in general, the more a habitat stretched along the coast the more frequently it was represented in the catenas ($r = 0.913$, $P < 0.001$). Table 1 and Fig. 9 show the degree of connectedness of the 43 rocky habitats (nodes) and the frequency of the relationship between pairs. The habitats *Verrucaria amphibia–Euraphia depressa* and *Chthamalus* spp. were almost ubiquitous. However, they were neither connected to habitats of freshwater sources (yellow node) nor to sciaphilic caves where the red algae *Hildenbrandia rubra* and *Phymatolithon lenormandii* dominated in the mediolittoral level (pink node). In the same Figure the most common habitats (in darker brown) are in a central component with larger node diameters and edge widths (i.e. their weight). Green nodes, located at the upper part of the figure, correspond to the four rare brown algae species of the genus *Cystoseira* (i.e. *Cystoseira elegans*, *Cystoseira spinosa* var. *tenuior*, *Cystoseira sauvageauana* and *Cystoseira crinita*), present only in sheltered environments. The species dominating sciaphilic habitats like the red algae *H. rubra* and *P. lenormandii*, the sciaphilic *Corallina elongata* and the generic habitat of sciaphilic algae are at the lower left periphery of the network. Finally, the habitats of the coral species *Corynactis viridis* and *Oculina patagonica* (red nodes) are situated at opposite positions in the figure.

4. Discussion

We developed a detailed mapping of the littoral habitats of a long coastline (more than 1000 Km). This product was achieved through a new methodology named CAT-LIT (from "CATenas" and "LIToral"). This is based upon the use of catenas, i.e. ordinated

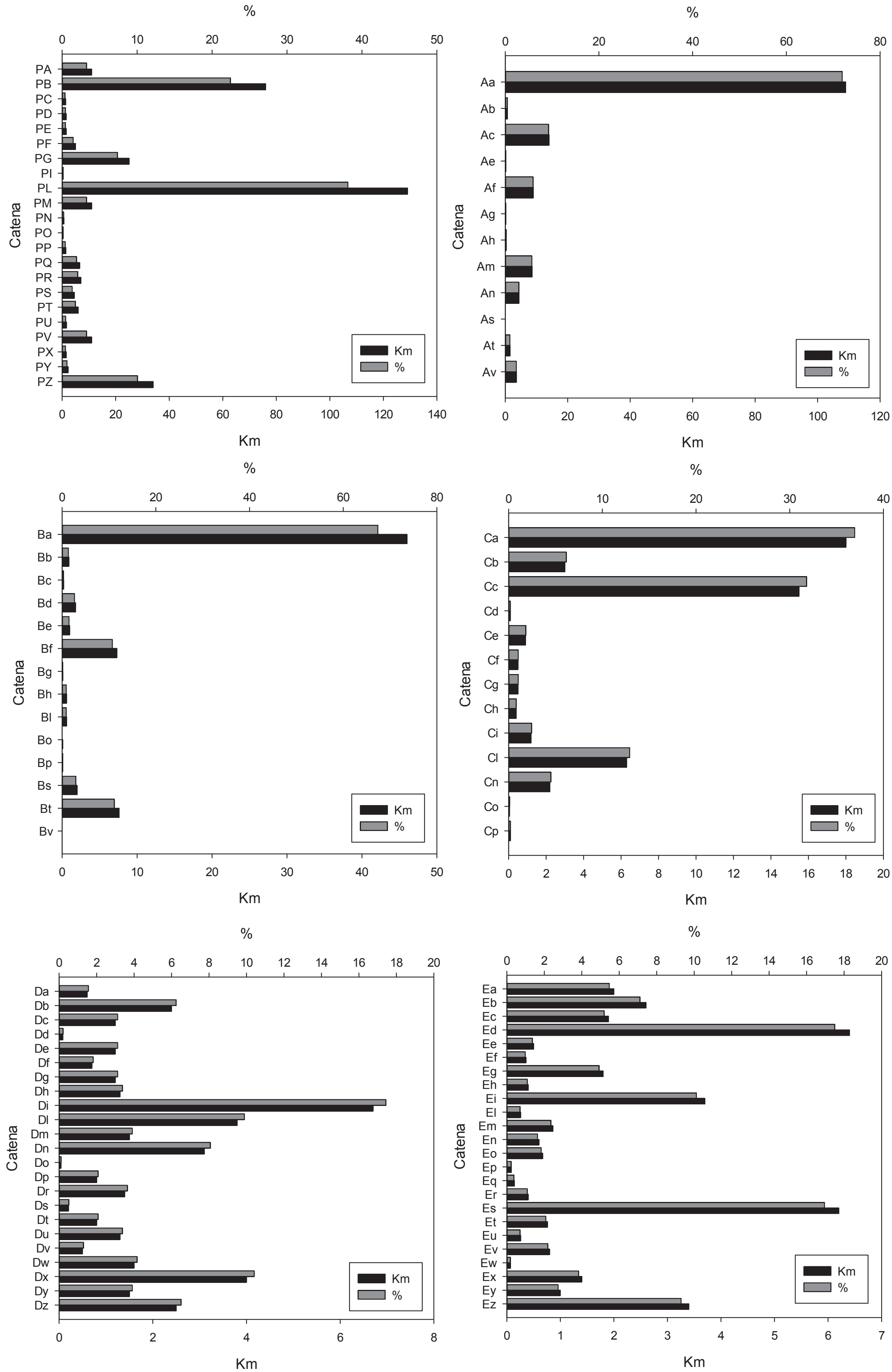

Fig. 8. Frequency and extent of the catenas by family.

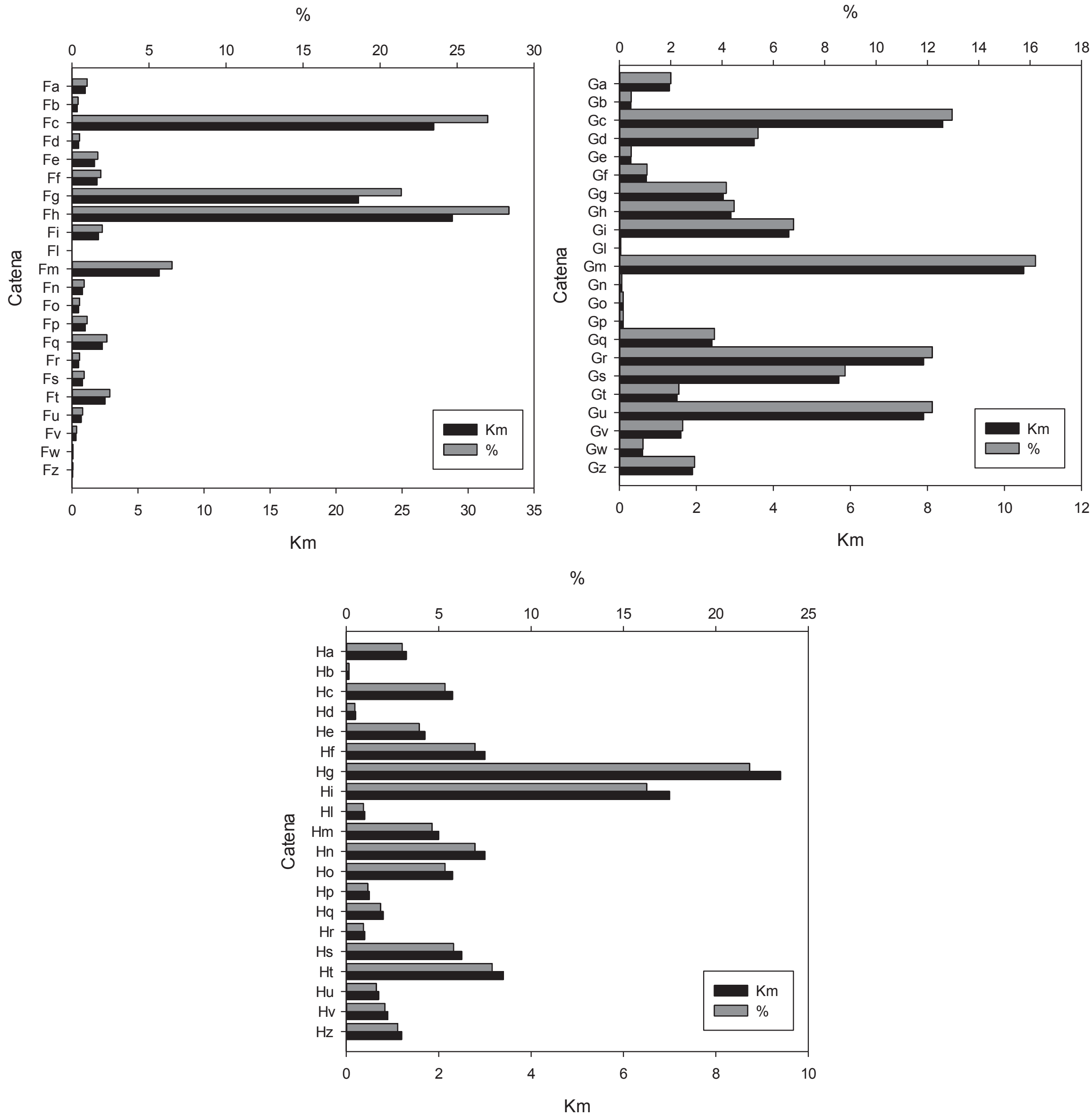

Fig. 8. (*continued*).

sequences of habitats vertically distributed from the upper to the lower littoral levels. The catenas are visually mapped in the field whilst steering a boat along the coast at a reasonable speed or, especially on beaches, whilst just walking. This method relies strongly on a hierarchical ordination of species and assemblages along the vertical axis perpendicular to the coastline. Such distributions have long been recognised among plants and animals (e.g. Zaneveld, 1937; Ballesteros and Romero, 1988; Somero, 2002; Chappuis et al., 2014). More specifically, a study conducted by our research group on 143 vertical transects positioned along the same stretch of coast shows that littoral habitats are arranged as belts or horizons parallel to the water surface. This zonation arrangement is the main distribution pattern of littoral habitats at a regional scale (Chappuis et al., 2014). It validates the use of catenas for littoral habitat cartographic purposes.

By using the catenas, the habitats cannot only be mapped quickly in the field, but can also be transferred into databases and finally viewed using GIS based programs keeping the catena as the main informational and ecological unit. The catenas also allow maximum compactness when vertically distributed habitats need to be displayed on a 2D map.

The catenas used in our study were defined during the field work. Codes were assigned whilst sampling and then reorganised to groups sharing similar horizons once all data were entered. While the coding employed here to set the horizons into the catenas is certainly subjective, any catena, regardless of the code used, provides very relevant information about the ecological characteristics of a specific area along the coast, indubitably at a more comprehensive level than that offered by a simple analysis of a single habitat. This is essentially because the catena integrates the organism adaptations to a wide range of environmental gradients (temperature, humidification, substrate type, etc.) present at each point of the littoral zone.

For example, the commonest catena type on the rocky shore was the A, and the commonest catena Aa (see Figs. 7 and 8) was found along 109 Km. Since the habitats of *Verrucaria amphibia* and *Euraphia depressa*, *Chthamalus* spp. and *Corallina elongata* (both mediolittoral and infralittoral) are nearly ubiquitous, the unique

Table 1
Habitat codes ranked by the number of connections between them (see Fig. 9).

Habitat	Code	Connection degree	Habitat	Code	Connection degree
Verrucaria amphibia and *Euraphia depressa*	Ver Eur	40	*Pterocladiella capillacea*	Pte cap	11
Chthamalus spp.	Cht spp	40	Mediolittoral *Lithophyllum incrustans*	Lit inc ML	11
Mediolittoral *Corallina elongata*	Cor elo ML	37	Infralittoral *Lithophyllum incrustans*	Lit inc IL	10
Photophilic algae	PA	29	*Pyropia elongata*	Pyr elo	10
Infralittoral *Corallina elongata*	Cor elo IL	28	*Bangia fuscopurpurea*	Ban fus	9
Mediolittoral *Mytilus galloprovincialis*	Myt gal ML	26	Sciaphilic algae	SA	9
Rissoella verruculosa	Ris ver	24	*Sabellaria alveolata*	Sab alv	9
Gelidium pusillum/Gelidium crinale	Gel pus/Gel cri	23	*Cystoseira caespitosa*	Cys cae	8
Cystoseira mediterranea	Cys med	21	*Dendropoma petraeum*	Den pet	8
Ralfsia verrucosa	Ral ver	20	*Cystoseira crinita*	Cys cri	6
Ulvales	Ulv	19	*Cystoseira spinosa* v. *tenuior*	Cys ten	6
Polysiphonia sertularioides	Pol ser	19	*Cystoseira elegans*	Cys ele	6
Infralittoral *Mytilus galloprovincialis*	Myt gal IL	17	*Sphaereocuccus coronopifolius*	Sph cor	5
Ceramium spp./*Osmundea* spp.	Cer Osm	16	*Lithophyllum papillosum*	Lit pap	5
Lithophyllum byssoides	Lit bys	15	*Polyandrocarpa zorritensis*	Pol zor	4
Infralittoral sciaphilic *Corallina elongata*	Cor elo SIL	15	*Oculina patagonica*	Ocu pat	4
Lithophyllum cf. *vickersiae*	Lit vic	14	*Cystoseira sauvageauana*	Cys sau	4
Nemoderma tingitanum	Nem tin	14	*Corynactis viridis*	Cor vir	4
Neogoniolithon brassica-florida	Neo bra	13	*Hildenbrandia rubra* and *Phymatolithon lenormandii*	Hil Phy	3
Cystoseira compressa	Cys com	12	*Lithophyllum pustulatum*	Lit pus	3
Ceramium ciliatum	Cer cil	12	Freshwater sources	FS	2
"Trottoir"	Trottoir	11			

habitats' continuum formed by *Rissoella verruculosa*, *Lithophyllum byssoides* and *Cystoseira mediterranea* appears to be the most frequent system subset (Fig. 9). The extraordinary diffusion of the catena Aa provides, at the same time, ecological information of the extent of rocky shore influenced by moderate to strong waves, high light intensity and good water quality (Ballesteros, 1992). Similarly but in the opposite direction, the extent of the Na catena allows a quick evaluation of the distribution of harbour walls colonised by organisms either adapted to highly fluctuating environmental conditions (see Serrano et al., 2013) or very abundant because of a

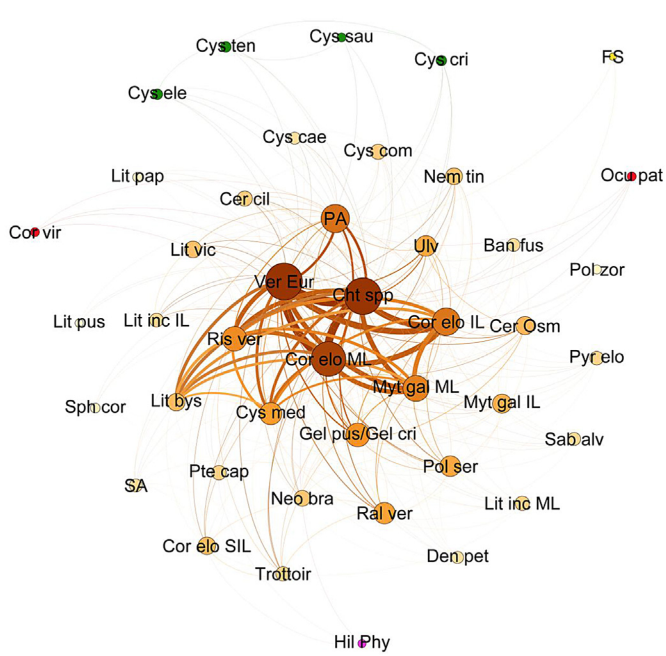

Fig. 9. Network of the 43 rocky habitats used for the analysis. Codes for the habitats are in the Table 1 as well as the number of connections between them. The diameter of nodes and the colour darkness is relative to the degree of connections. The yellow, pink, red, and green colours are used to separate and highlight particular habitats (see the text for details).

lack of effective competitors on poorly colonised substrates. Such simple information coupled with information provided by the frequency of connections between habitats in the networks helps depict an ecologically relevant image of the interactions among habitats and species along the rocky coast.

The use of catenas for soft bottoms is useful to map and provide information on the distribution of beach grain sizes. Nevertheless, their value for describing the distribution of the organisms relative to each habitat appears limited compared with rocky habitats.

Despite the practical usefulness of catenas and their relevance as ecosystem units, the ultimate category to be mapped for cartography and conservation purposes is the habitat.

Both ontological and epistemological considerations arise when apparently dogmatic physical and conceptual boundaries influence ecological concepts (see Jax, 2006). Nevertheless, the habitat remains one of the most practical ecological components when communities need to be defined and quantified (Ferraro, 2013). Here, we refer to habitats as rather conventional units whose physical boundaries can be visually defined by any medium-trained observer. Definition and implementation of such a practical unit, however, needs the approval of ecologists and managers concerned with environmental conservation (see Costello 2009). Species living in the littoral zone often show localized optima on the vertical axis, although some habitat-defining species show wide vertical distributions (e.g. *Chthamalus* spp.), may move (e.g. *Melaraphe neritoides*), or are too ephemeral to be detected throughout the year (e.g. *Ulva* spp.) (Chappuis et al., 2014; Ballesteros and Romero, 1988; Ballesteros, 1992; Chappuis et al., 2014). Hence, precise knowledge (e.g. Ballesteros, 1991) of both the distribution patterns of the main species and the time of the year when they are most developed (i.e. spring) is required to obtain precise and reliable habitat mappings using CAT-LIT.

Besides the practical use of the CAT-LIT methodology, some relevant outcomes of the present study for conservation purposes were the localization of endangered or exotic species across the surveyed coastline. For instance, we detected small populations of four species of the genus *Cystoseira* (mainly the M catenas) that were thought to be extinct in Catalonia (*Cystoseira crinita*, *Cystoseira elegans*, *Cystoseira spinosa* v. *tenuior*, *Cystoseira sauvageauana*). Additionally, we found wide extensions (44% of the rocky shore) of the habitat dominated by *Cystoseira mediterranea*, a species very sensitive to water pollution (Arévalo et al., 2007; Pinedo et al., 2007, 2013). These results indicate that an equivalent portion of the rocky coasts of Catalonia show pollution levels low enough to maintain important populations of this species. Another example is the "Trottoir" (i.e. *Lithophyllum byssoides* rims), which is protected by the Barcelona Convention (UNEP, Mediterranean Action Plan). The habitat is facing a general recession across the NW Mediterranean rocky coast (Boudouresque, 2004), mainly due to mechanical impacts (e.g. trampling). In contrast, two zooxanthellate coral species *Oculina patagonica* and *Corynactis viridis* were detected and mapped in the shallow waters of two close harbours. The first species, which is probably non-indigenous, is experiencing a northward spread along the coast of Catalonia (Serrano et al., 2013). In the Mediterranean Sea, populations of the jewel anemone *Corynactis viridis* can be found in shallow sheltered environments (Cebrián and Ballesteros, 2004), though they are much more widespread in the Atlantic Ocean. A huge community dominated by this species homogeneously occupied more than 150 m between 0.5 and 1 m depth inside a harbour. An accurate cartography of these species may be used in the future to assess either their regression or progression and, thus, facilitate better management of their populations.

Catenas and the associated database enabled an assessment of the number of interaction links that different habitats establish along the studied shore. While some habitats had few links, such as those present at cave entrances (dominated by the species *Hildenbrandia rubra* and *Phymatolithon lenormandii*), a few abundant habitats created a hub of links with many other habitats, such as those dominated by the coralline alga *Corallina elongata* both at the mediolittoral and the infralittoral levels. Links were present both at the simple informational level (the numbers of connections each habitat shows with the others through the catenas) and at the spatial level (the length of the coast a habitat shares with the others). However, habitats are linked into a catena without the need to physically interact, as it is the case with the infralittoral and the upper mediolittoral habitats, which might interact only by propagule flux.

The non-random frequency of a habitat in the catenas may provide a direct measure of its "sociability", namely its propensity to occupy different environments with different biotic and abiotic characteristics. Future work on our data is needed to explore habitat sociability and other characteristics of the network such as the degree of redundancy in the habitat interactions or the relationship between generalist and specialist habitats. Furthermore, other interesting characteristics such as the relationships between the distribution of both habitats and catenas and environmental variables such as lithology, wave and wind exposure, coast slope or orientation deserve further attention (research in progress by our research group). Exploring the distribution patterns of habitats and catenas in relation to anthropogenic pressures can also shed some light on possible new bioindicators to be used to implement European Directives.

Past attempts at mapping long coastlines have typically relied on interpreting aerial photograph and video, supplemented by groundtruthing of some areas (see Banks and Skilleter, 2002). More recently these techniques have extended to include side scanning coupled with sample collection and visual observations (see Barberá et al., 2012) or airborne laser scanning LIDAR (see Chust et al., 2008; Thorner et al., 2013). These methods may reduce the time required for mapping, especially for underwater habitats, although they do not provide the same accuracy as field-based habitat visual mapping. In addition, they are of much less use in mapping littoral, often-vertically-distributed and closely interspersed habitats (e.g. in intertidal areas). These techniques are generally too coarse to provide ecologically-meaningful habitat classifications that could translate into on-ground management efforts. The alternative approach of detailed habitat mapping is much too time-consuming to be conducted at relevant scales for management purposes. In that instance, CAT-LIT represents a valuable compromise, reducing the time needed for data collection in the field and successive data entry. The present study represents approximately 1200 man-hours of field work conducted over two years to accurately sample 1000 km of the Catalan coast.

In conclusion, the application of the CAT-LIT to the Catalan shores generated a unique and accurate cartography and a complete dataset on the spatial distribution of the littoral habitats. Our cartography can be now used for coastal management and conservation, and to implement the Water Framework Directive or the MSFD. Moreover, the cartography can be used in the future to study changes in the habitat distribution and relate such changes to anthropogenic pressures. In our opinion the CAT-LIT is an effective technique for mapping littoral habitats from long coastlines. It can also be easily adapted to shores of other seas and oceans in order to obtain accurate cartographies of the spatially-reduced and highly vulnerable littoral habitats.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2014.05.030.

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