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Spatial characterization of marine socio-ecological systems: A Portuguese case study

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ABSTRACT

There is a lack of available methods to understand the associations between land and sea in social and ecological systems. This work adapts a methodology to explore how coastal-marine areas in the Portuguese Mainland Subdivision spatially differ in socioeconomic and marine environmental characteristics. The methodology used a combined spatial analytical approach of ecological, social, economic, and land-cover variables. The outputs of this work were Marine Socio-Ecological Categories (MSEC) mapped along the coast. Results show contrasting ecological and societal conditions across the coastal municipalities. The northern region and some parts of the Algarve coast are experiencing higher socioeconomic development but are also facing higher resource demands and placing more pressure on marine and coastal ecosystems. MSEC categories are valuable to understand how different conditions may be dealt with at regional and national contexts in future management and planning policies. Mapping socio-ecological systems aid sustainable economic development, but further research is needed to improve the system analysis. This study shows that there is no land-sea divide and the interactions between both systems should be reflected in the existent policy framework.

1. Introduction

Marine or Maritime Spatial Planning (MSP) aims to contribute to a more balanced and sustainable use of ocean resources by defining priority or restricted areas to decide which outputs are to be produced from a marine area over time (Gee et al., 2017). While the ecological and economic evidence base for MSP tends to be relatively well developed, this cannot be said for the social dimension of the sea. The incorporation of social data into ocean plans or information on social-ecological linkages has not received sufficient attention (Cornu et al., 2014). The MSP Directive (2014/89/EU) at the European level identifies MSP as a process to organize human activities in marine areas and urges the Member States to have plans in place until 2021 and within an Ecosystem-Based Management (EBM) approach, social aspects shall be considered. EBM as “an approach which integrates the connections between land, air-water, and all living things including human beings and their institutions” must incorporate spatial consideration to manage human uses and requires an understanding of social processes and human preferences (Mee et al., 2015). One of the identified aims of the Directive is to deliver social cohesion, along with economic growth and sustainable development. The way or form of how to take them into the plan is left to Member States definition (Hassler et al., 2019). But authors as Flannery et al. (2016) are concerned with the lack of attention to social aspects given in MSP plans that embody the blue economy developments. A review on coastal and ocean planning processes showed that less than 50% included social data and only 10.8% of social data were spatially characterized (Cornu et al., 2014). Noble et al. (2019) suggests for MSP Plans that socially-based spatial information shall be integrated concerning environmental information in a way that supports both social and ecological resilience. In a recent review of socio-ecological MSP case studies, Noble et al. reported the need to develop innovative predictive modeling techniques to understand how social uses change over time and how marine ecosystems may respond to potential direct and indirect disturbances. This means understanding the interconnecting issues and linkages involving people in coastal communities, interested groups and decision-makers, marine and coastal

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ecosystems emphasizing adopting an adaptive management approach.

While MSP is still in its early stage of development, the operationalization of EBM in MSP is far from simple. Besides the sea dynamics, the marine space is a public good and requires the inclusion of public representation into the MSP process. Coupled Social-Ecological Systems (SES) concept emerged from the realization that human and ecological systems shall be viewed as inextricably linked. SES are complex adaptive systems in which social and biophysical components are interacting at multiple temporal and complex scales (Berkes et al., 2003; Liu et al., 2007; Ostrom, 2009). However, the dynamic nature of SES, resulting from the interdependencies of socio-cultural, economic, and biophysical variables makes it difficult to understand the complex feedbacks between variables. The way as human actions are affected and have effects on the ecosystems is difficult to assess and is varied at different scales (Martín-López et al., 2017). There is nowadays a consensus over the need to understand the complex dynamics of SES in an effort towards sustainability, to reverse the fragmentation of knowledge, and promote a holistic approach to management and planning (Crowder et al., 2006; Douvere, 2008; Katsanevakis et al., 2011; Mee et al., 2015). This holistic approach is tackled using methodologies such as dynamic system models that capture the most important variables in a given system and evaluate how they interact with one another. (Banos-González et al., 2015; Hanspach et al., 2014). These works focus on the social-ecological associations but assessing the spatial configuration of the SES remains a challenge (Martín-López et al., 2017). Few studies have developed tools spatially assessing SES and their potential for informing management and planning. Alessa et al. (2008) identified geographical areas (SES hotspots) where human-perceived landscape values and biophysical values converged to identify areas of high concern and to the components of the system that lend resilience or vulnerability. Castellarini et al. (2014) developed a framework to build socio-ecoregions using ecoregions and human development index. The information on the location and extent of different eco-regions would support federal or state level policy design. Hanspach et al. (2016) identified social-ecological units that represent different types of villages with distinct species diversity patterns to inform biodiversity conservation. However, all these exercises were on land (Lazzari et al., 2019). updated a framework developed by Martín-López et al. (2017) to identify and characterize socio-ecological associations at the Land-Sea Interface (LSI) in the Mediterranean Coast of Andaluzia. Although information at the national or regional level is relevant for planning, especially in the land-sea divide as it represents the space where interests and problems for different stakeholders connect with decision-makers, the characterization of SES at the local level, mostly at the municipal scale matters because it has direct impacts on the wellbeing of the populations and may be addressed at local and regional policy level (Balvanera et al., 2017; Martín-López et al., 2017).

In Portugal was recently approved the first line instrument in MSP, PSOEM (*Plano de Situação do Ordenamento do Espaço Marítimo,* (DGRM, 2019). One of the major needs of the planning at the LSI, embedded in PSOEM, is the improved understanding of how the land-sea systems, which are rather complex, interface and connect between the SES. There is a lack of studies incorporating spatial information on the social and ecological dynamics at the mainland coastal-marine scale. Moreover, the application of the MSP plan, which is in its early stages has considerable options of incorporating new information, improving its coherence, and properly addressing the issues at the LSI (Creamer et al., 2020).

This study applied and adapts a methodology previously developed for the coast of Andaluzia (Lazzari et al., 2019) to the mainland coast of Portugal to spatially explore how coastal-marine areas differ in environmental and socioeconomic characteristics. Although this categorization is developed at the municipal level, it has a national scope as it covers all the mainland coast of the country. This categorization aims to support management and planning policies to improve sustainability at the LSI.

2. Materials and methods

2.1. Study area

We selected the coastal-marine area of Mainland Portugal, where increasing pressures on marine coastal resources with socioeconomic and environmental changes and challenges have been intensified and documented in recent years (Fernandes et al., 2020). At the same time, two new policy frameworks were designed in separate for the terrestrial and the marine system (Becker-Weinberg, 2015), posing new challenges, but also new avenues to address the complex dynamics at the LSI.

Mainland Portugal is divided into 4 NUTS (Nomenclature of territorial units for statistical purposes), a hierarchical system that divides the territory into regions (DGT, 2018a), they are called Norte, Centro, Alentejo, Algarve, and Área Metropolitana de Lisboa (AML). There are 51 municipalities (see Fig. 1) that share a boundary with coastal waters (EU, 2000). This territory has a wide variety of uses, including protected areas, urban and industrial centers, intensive farming, and fishing areas. Most of the population lives in coastal municipalities (around 75%) and larger cities are in river mouths hosting ports, which are an important part of the highways of the sea. The latest available data from National Statistics Institute (INE - Instituto Nacional de Estatística) indicated that the maritime economy accounted for 3.1% of the Gross Value Added (GVA) and 3.8% of national employment and trend (INE, 2016), showing a growth dynamic above the national average (Mateus et al., 2019). Relevant activities regarding the sea economy are tourism, shipbuilding, fisheries, and transport (Mateus et al., 2019). The average unemployment rate in coastal municipalities, in 2018, was 4.7% with a monthly average base salary of 816 euros, with the highest income around 1400 euros in Oeiras.

The highest population densities are occurring in Lisbon and Porto metropolitan areas (941,9 and 843,1), quite above the national average of 111.5 inhabitants per km^2 (PORDATA, 2019).

The Portuguese continental coast presents a mixture of sandy shores and rocky cliffs, with a regular soft relief with prominent canyon features, Nazaré and Setúbal-Lisbon promoting the occurrences of coastal upwelling which produces a high productivity environment (Lastras et al., 2009; Relvas et al., 2007). The highest anthropogenic pressures, mapped on previous research, appear in the transitional and coastal areas in the north (Norte), center (Centro), and western Algarve (Fernandes et al., 2017).

The Spatial Planning and Urban Development Law of 1998 (Law 48/1998) set the beginning of the spatial planning organization in Portugal. The law was amended in 2014 (Law 31/2014) to integrate soil, spatial planning, and urban principles under the same legal regime. Together with the Decree-Law 80/2015 that sets the Legal Framework of Territorial Management Tools, these documents establish the basis of the territorial planning instruments, their articulation, and tools.

The territorial system in force is divided into 4 areas: national, regional, inter-municipal, and municipal. At the regional, intermunicipal and municipal level instruments can be programs or plans (see Fig. 2), such as regional program (PROT – Planos Regionais de Ordenamento do Territorio), intermunicipal urbanization programs or municipal master plans). At the national level instruments can be sector programs (Tourism, Energy, Nature, etc …), special programs (Coastal Zone Management Plans - CZMP, protected areas management, estuaries, and public water reservoir programs), and strategic, embodied in the National Spatial Program (officially named as Program for Spatial Planning Policy, PNPOT – Programa Nacional da Politica de Ordenamento do Território, DGT, 2018b), a figure that was already created in 1998's Law but which was only produced in 2007. The program faced a revision in 2016 (Resolution of the Council of Ministers n. 44/2016 of August 23) and was finally published in 2019 through Law 99/2019.

Regarding the water resources legislation, two documents are relevant to analyze within this scope. Marine Strategy Framework Directive (MSFD - transposition into Portuguese Law by Decree-Law 108/2010)

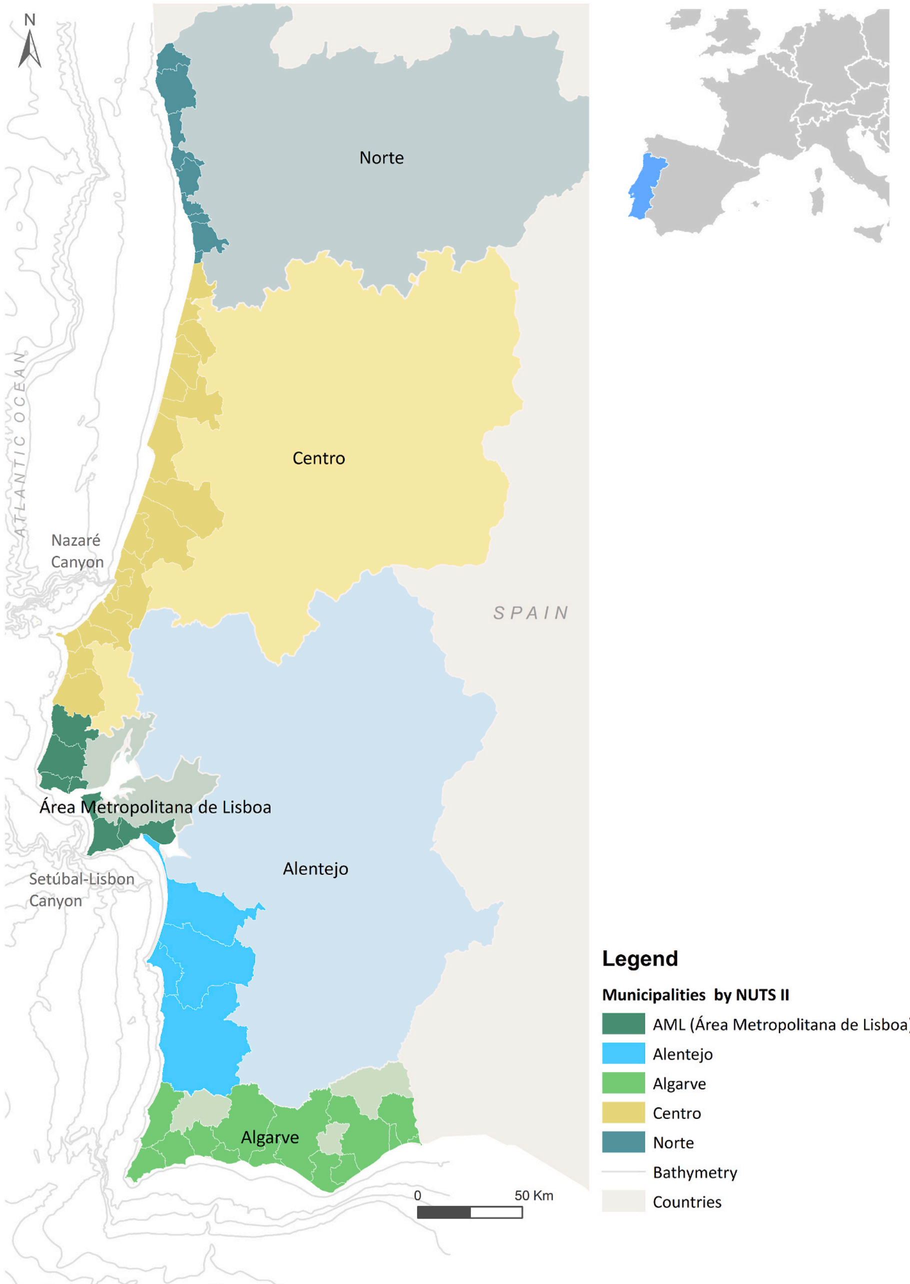

Fig. 1. Map of the study area, illustrating the geographical location of the municipalities on the coastline of Mainland Portugal. Municipalities are divided by NUTS II Area Metropolitana de Lisboa (7 municipalities), Alentejo (4 municipalities), Algarve (13 municipalities), Centro (18 municipalities), and Norte (9 municipalities).

urges the attainment or maintenance of the Good Environmental Status of marine waters and the Water Framework Directive (WFD - transposed by Law 58/2005) implemented by the River Basin Management Plans (RBMP) for each of the 8 river basins in Portugal aims to achieve a Good Ecological Status.

The National framework for MSP was also enacted in 2014, through Law 17/2014 which establishes the basis of the policy for MSP and Management (MSP Law) of the national maritime space (Becker-Weinberg, 2015). Decree-Law no. 38/2015, published in March 2015, further develops key aspects of the law and transposed the EU MSP Directive. It defines the main MSP instrument, the PSOEM, which identifies the spatial and temporal distribution of existing and potential uses and activities to be developed under a private use permit. PSOEM was approved so far for the Mainland, Madeira, and Extended continental shelf subdivisions in December 2019 (DGRM, 2019). With the new terrestrial and marine laws of 2014, there is a distinct separation between both regimes, while it is ensured effective articulation and compatibility. Fig. 2 shows the spatial extent of the different policy tools relevant within the study scope.

2.2. Data collection

We collected marine environmental and terrestrial (socioeconomic and land-cover) data and used it to identify Portuguese Marine Socio-Ecological Categories (MSEC). For the marine environmental data, we used the approach of Lazzari et al. (2019) and the data from the satellite database, BIO-ORACLE (Assis et al., 2018). We used the same variables of Lazzari et al. (2019) and we averaged the pixel values for each municipality for each variable to obtain an environmental value per municipality. A buffer to each municipality was performed, considering a

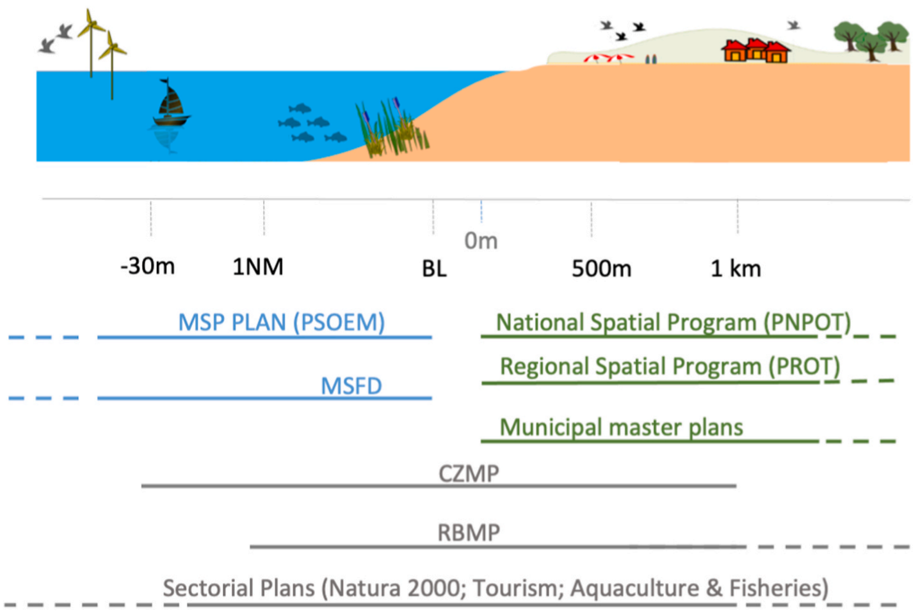

Fig. 2. Policy tools of relevance in the study area context (blue color are for marine, green for terrestrial, and grey for tools that apply in both spaces; dashed lines mean spatial limits fall outside of the scheme).

marine offshore limit. Initially, this offshore limit was to the 30 m bathymetry, as this is the limit of the CZMP in Portugal. However, this limit would deprive some municipalities of having data, as it was too near the coast in some locations. As so, a metric distance of 6 km from the coast was settled. This was a compromise to guarantee there was satellite data for all municipalities and a conservative approach to the 30 m bathymetry all over the Portuguese coast. We added two more variables to characterize the benthic habitats, reefs, and sand, using information from EMODNET (Galparsoro et al., 2012) and followed the same procedure of obtaining an average value for each municipality.

For the terrestrial variables, we used information from Portuguese public access databases. It was not possible to harmonize the collection dates of the information; when possible, we used the most recent information (2018), but in some cases, the information available was from the census of 2011. The socioeconomic variables were extracted from the National Statistics Institute – INE (2018) and PORDATA (2019),[1] and land-cover information was gathered from Directorate General for Territory – DGT (2018a). All the variables collected and their details are listed in Supplementary Table S1. We selected the municipality level, as it is the most disaggregated with statistical information available for all the variables. Demographic information included population density, age classes (people below 25 and above 65), education level (people with a university degree and illiterate). Economic variables included average monthly income, employment in primary, secondary, and tertiary economic sectors, unemployment, touristic accommodations, and GVA by tourism. Fisheries information included the percentage of fishers in the overall population and GVA by fisheries and aquaculture. Land use information included information on urban and industrial areas, agriculture, forests, and wetlands/water bodies. We also considered the level of the environmentally protected surface.

2.3. Data analysis

We used a combined analytical approach following the Lazzari et al. (2019) method to characterize the Portuguese MSEC (see Fig. 3). We adapted the method to support Portuguese ecological, social, economic,

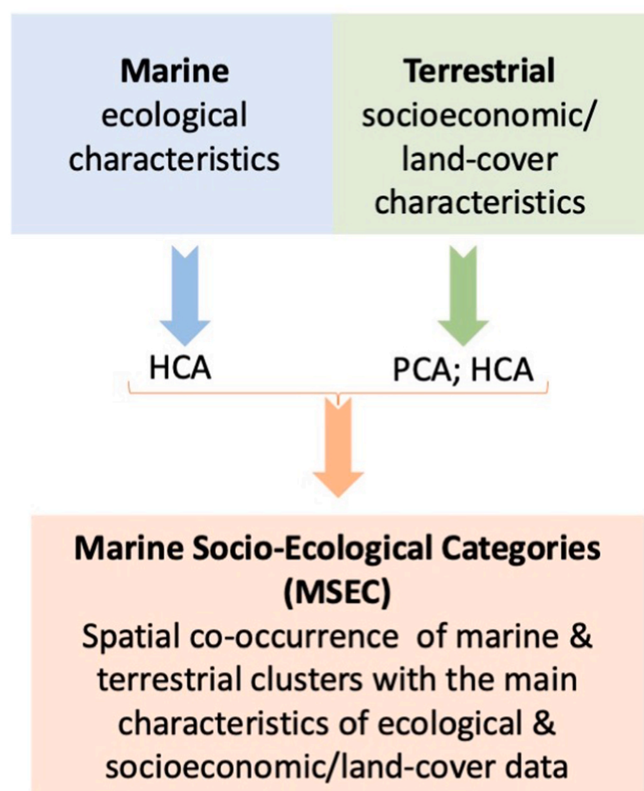

Fig. 3. Schematic methodological approach used to identify the Marine Socio-Ecological Categories (MSEC) in Portugal.

and land-cover variables. The MSEC was then analyzed to extract insights to improve the marine and terrestrial policy tool implemented in the study area. All the analyses were conducted using R software (R Development Core Team, 2011). For the terrestrial data, we performed a principal component analysis (PCA) with varimax rotation on the socioeconomic/land-cover data, using the Kaiser criterion (Kaiser,

[1] PORDATA is a Contemporary Portuguese Database equipped with official and certified statistics about Portugal and Europe.

1960) in combination with the scree test to select the number of the principal components to use (Cattell, 1966).

After, we conducted the hierarchical cluster analysis (HCA) to identify the homogeneous classes. The PCA and HCA were performed using the packages ‘FactoExtra’ and ‘FactoMiner’ (Lê et al., 2008). On the marine variables, we performed the HCA after standardizing data and used the Euclidean distance and Ward’s linkage method. To identify the suitable number of clusters, we used the package NBclust for determining the best number of clusters and propose the best clustering scheme (Charrad et al., 2014). We conducted ANOVA and Kruskal-Wallis tests for the differences in the variables among the clusters. We used the Shapiro-Wilk test to check normality for all the variables used. When ANOVA or Kruskal Wallis was significant (p-value <0.05), we evaluated the differences between the clusters using post hoc pairwise comparisons *t*-test and Dunn’s multiple comparisons tests.

Finally, we used the spatial co-occurrence between socioeconomic/land-cover and marine classes to understand their level of relationship creating MSEC. To graphically visualize the difference between categories we conducted a non-metric multidimensional scaling (nMDS) following the Lazzari et al. (2019) approach. We used radar charts to represent the influence of each variable in each MSEC.

3. Results

3.1. Terrestrial classifications

The PCA aims to reduce the number of variables to be used afterward in the analysis. The first 6 principal components (PC) are selected due to the combination of the eigenvalue (higher or approximate to 1) and explained 80% of the variance in the terrestrial data (see Supplementary Table S2). Using these 6 PCA components we identify 3 clusters (SCL1, SL2, and SL3) (Fig. 4a and Supplementary Fig. S1).

The most relevant variables for the separation among the three clusters are population density, urban and industrial land-cover (see Table 1), due to the lack of association between clusters in the pairwise comparisons test. The municipalities within the SCL3 group have the highest population density (3000 inhabitants per km^2), an outstanding value considering the average in Portugal of 111.5 inhabitants per km^2 (PORDATA, 2019). SCL3 has the highest income values and high urban and industrial cover, highest percentages of tertiary workers, university degree holders, touristic development, but also the highest unemployment rates. It includes the most developed municipalities, part of the metropolitan areas of Lisbon and Porto, and hence, the economic cores of development in the country. On the contrary, SCL1 shows the least developed profile with the highest levels of illiterate, primary workers, and older people.

SCL2 has a transition profile, with the social and economic variables showing younger and more educated municipalities than SCL1. The clusters SCL2 and SL3 shared the variables associated with high GVA from tourism, however, they are distinct on monthly incomes and university graduates, which are highest in SCL3, and on the percentage of employment in the primary sector and fishers, which shows higher averages for SCL2.

3.2. Marine environmental classifications

Through the HCA we identify 3 marine clusters (MCL1, MCL2, and MCL3) that are spatially separated as Fig. 4b (and the dendrogram in Supplementary Fig. S2) shows. All the northern municipalities are associated in MCL3, which is significantly different from the other clusters (in 9 out of 11 variables). MCL3, appearing in the northern part of the territory, shows the highest average values for Mean Calcite, Mean and Minimum Chlorophyll a, Mean Nitrate, and Phosphate (see Table 2). MCL1 and MCL2 have only significant differences on the variables associated with Sea Surface Temperature (maximum SST, mean SST, and SST range). MCL2 has lower SST variables and salinity, higher chlorophyll (mean and min), higher nitrate and covers all the Continental Atlantic Coast (from Vagos to Silves). MCL1 appears in west Algarve, from Albufeira to Vila Real de Santo António. The bottom substrate analysis, of sand and reefs, did not provide significant differences among clusters.

3.3. Characterization of Marine Socio-Ecological Categories (MSEC)

The MCL and the SCL clusters are associated by their spatial co-occurrence and form the MSEC (see Fig. 5). Category C, composed of SCL3 and MCL1 is not observed.

Fig. 6 shows the two-dimensional dispersion of the nMDS results of the MSEC. The nMDS analysis performed with a multivariate dispersion p-value of 0.02 (<0.05 and analysis of variance table $0.7436 > 0.05$ meaning there are no problems with the assumption) shows that the MSEC groups are different from each other. Categories that share the same MCL and are either SCL 1 or 2 are closer, as the MSEC A and B, D, and E show. MSEC G and H are grouped as well. Only F and I are distant from all other categories.

Fig. 7a and b shows the spatial representation of the Marine (MCL),

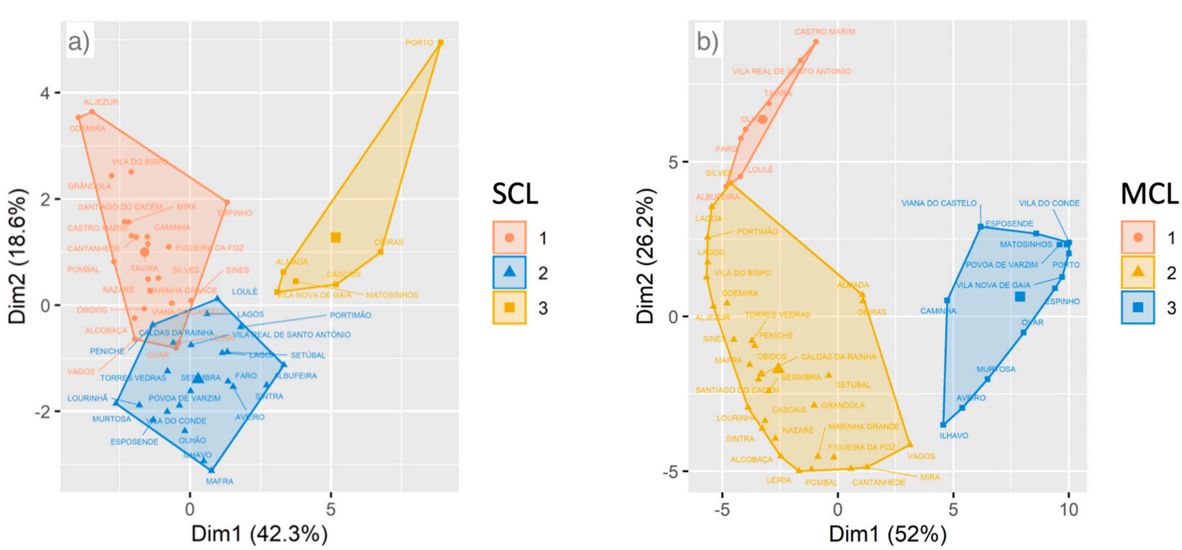

Fig. 4. Visualization of partitioning results a) Terrestrial clusters after the PCA and the HCA; b) Marine results after HCA. Final positions in the figure are influenced by all three dimensions of principal components but visually represented here from a two-dimensional perspective (hence perceived overlap).

Table 1
Resumed statistics of the terrestrial variables (Mean values for each SCL cluster; F-value, and X2 statistic for the significant differences among classes. The SCLs sharing superscript letters do not differ. The bold values indicate the cluster with the highest mean value for each variable. $^{*}p < 0.05$). For more information on the variables, see Table S1.

Variables	SCl1	SCl2	SCl3	F	X2	Pairwise comparisons 1–2	1–3	2–3
Population density (hab/km^2)	165.88a	360.12b	3030.07c		29.35*	0.0003*	0*	0.0188*
Illiterate people (%)	7.37a	4.46b	2.87b		26.87*	0.0004*	0*	0.0364
People with university degree (%)	10.39a	12.56a	21.87b		18.42*	0.0417	0*	0.0089*
People younger than 25 (%)	22.42a	26.04a	24.50a	24.07*		7.42E-11	6.73E-03	0.064615
People older than 65 (%)	24.56a	19.70a	22.55a	12.37*		1.32E-07	0.261548	0.051711
People employed in primary sector (%)	5.79a	4.67a	0.45b		15.69*	0.4341	0.0001*	0.0017*
People employed in secondary sector (%)	27.93a	23.20a	16.93a	10.14*		0.019841	0.013496	0.29093
People employed in tertiary sector (%)	66.28a	72.14a	82.62a	18.02*		0.074971	0.000348	0.030224
Unemployed (%)	4.41a	4.45a,b	6.80b		7.31*	0.9558	0.0112*	0.0277
Touristic accommodations	23.09	40.00	65.50		2.37			
Monthly income per inhabitant (Euro/hab)	783.15a	792.05a	1030.15b		12.67*	0.6746	0.0006*	0.0036*
Urban and industrial areas(%)	8.77a	14.31b	64.97c		23.29*	0.0072*	0*	0.0086*
Agricultural (%)	33.19	49.99	20.63	0.07				
Forests and semi-natural areas (%)	55.51a	27.04a	12.84a	69.09*		1.55E-08	2.90E-08	0.078856
Wetlands and water bodies (%)	2.53	8.65	1.56		1.84			
Fishers (%)	0.95a	0.95a	0.10b		11.13*	0.7863	0.0056*	0.0014*
Gross value added of Fisheries (Euro)	1 292 214	4 673 252	1 624 753		3.68	–	–	–
Gross value added of Tourism (Euro)	16 772 896a	52 192 166 b	156 039 064b		20.44*	0.0052*	0*	0.0332
Protected Areas	7.62	10.19	8.18		2.45			

Table 2
Resumed statistics of the marine variables (Mean values for each MCL cluster; X2 statistic for the significant differences among classes. The MCls sharing superscript letters do not differ. The bold values indicate the cluster with the highest mean value for each variable. $^{*}p < 0.05$). For more information on the variables, see Table S1.

Variables	MCl1	MCl2	MCl3	X2	Pairwise comparisons 1–2	1–3	2–3
Mean calcite (mol/m^3)	0.0022a	0.0026a	0.0037b	9.5448	0.9178	0.0209*	0.0067*
Mean chlorophyll a (mg/m^3)	0.1988a	0.3403a	0.9877b	30.727*	0.1755	0.0000*	0.0000*
Min chlorophyll a (mg/m^3)	0.0681 a	0.0839 a	0.2092 b	29.144*	0.6336	0.0000*	0.0000*
Mean nitrate (mol/m^3)	0.0961 a	0.1115 a	0.6535 b	28.572*	1.0000	0.0002*	0.0000*
Mean phosphate (mol/m^3)	0.0606 a	0.0654 a	0.0820 b	26.034*	0.2787	0.0000*	0.0000*
Surface salinity (PSS)	35.7700 a	35.3822 a	34.2055 b	34.158*	0.0261	0.0000*	0.0000*
Maximum SST (°C)	23.4713a	20.7390b	19.7859 c	37.828*	0.0034*	0.0000*	0.0000*
Mean SST (°C)	18.5277a	16.9041b	15.7924c	37.828*	0.0034*	0.0000*	0.0000*
Range SST (°C)	8.8140a	7.0890b	7.5272c	23.585*	0.0000*	0.0208*	0.0238*
Sand (%)	0.3737	0.4633	0.6221	4.6504			
Reefs (%)	0.0736	0.1818	0.1240	3.0356			

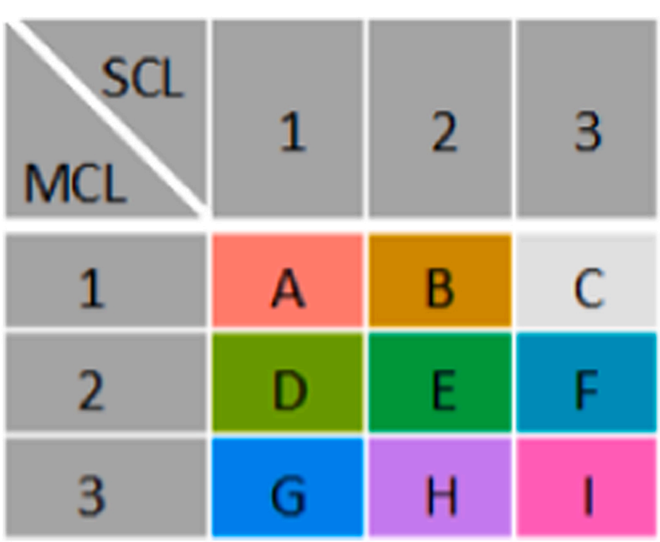

Fig. 5. Matrix of the resulting Marine Socio-ecological Categories (MSEC). The MSEC result from the spatial co-occurrence of terrestrial (SCL) and marine (MCL) clusters.

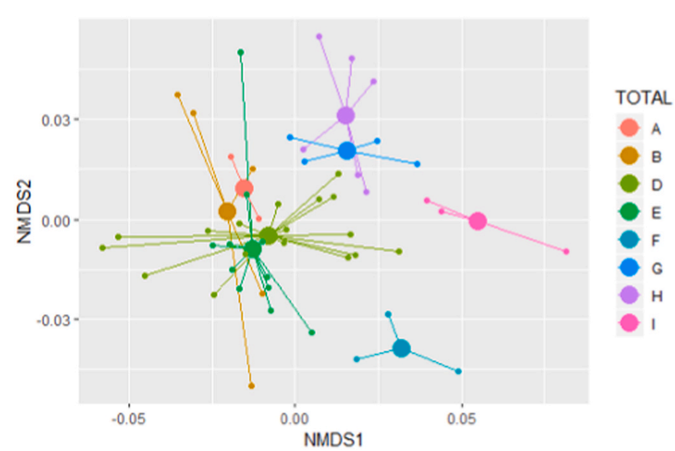

Fig. 6. Two-dimensional nMDS of the Marine Socio-ecological Categories (MSEC).

Terrestrial (SCL) clusters, and the composition of the resulting MSEC.

Fig. 8 shows radar charts representing the scaled average values from the municipalities composing each category. Each chart shows the different 4 groups of variables: social, economic, land-cover, and ecological.

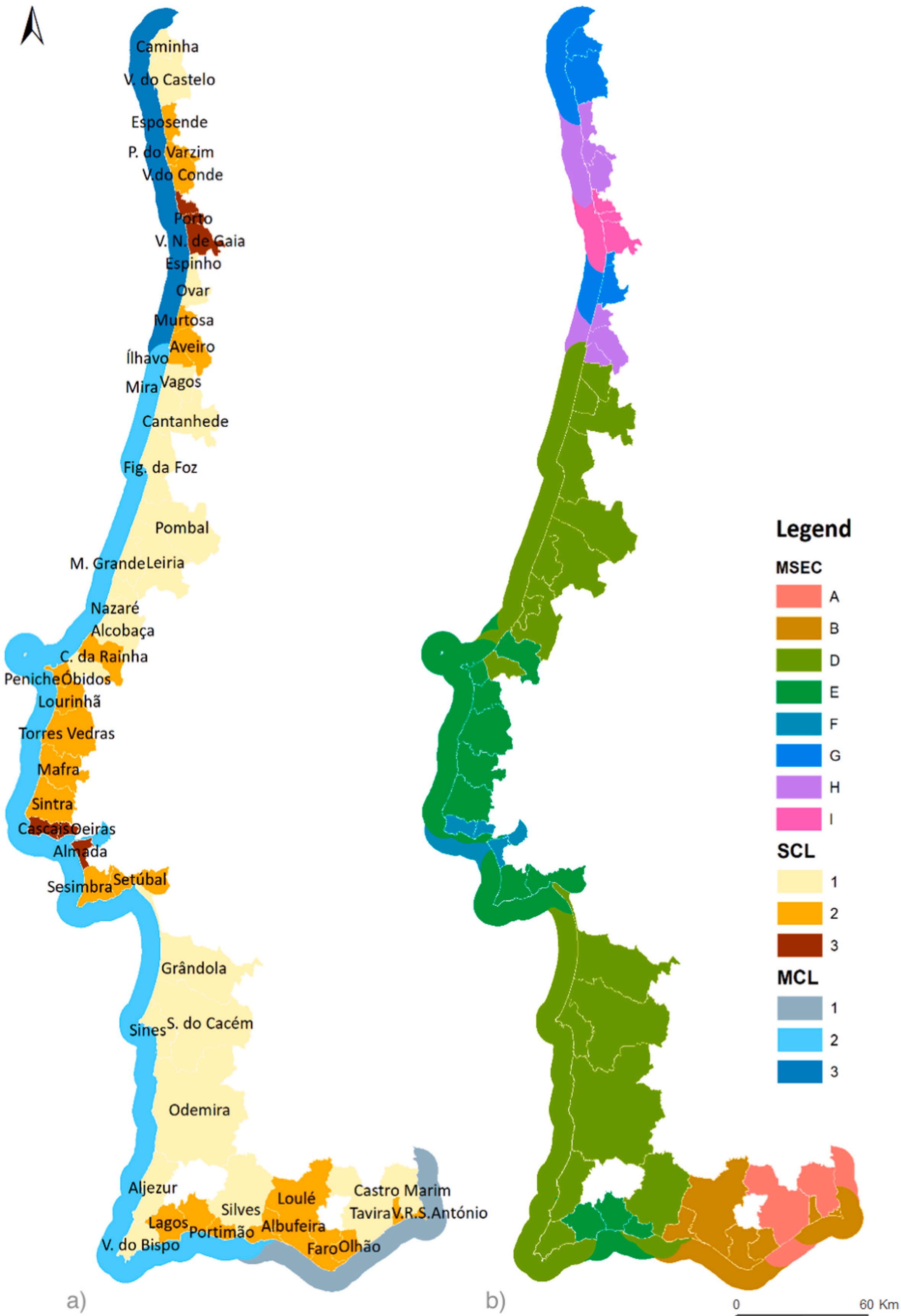

Fig. 7. a) Marine (MCL) and Terrestrial (SCL) clusters; b) Combined 8 categories of Marine Socio-ecological Categories (MSEC).

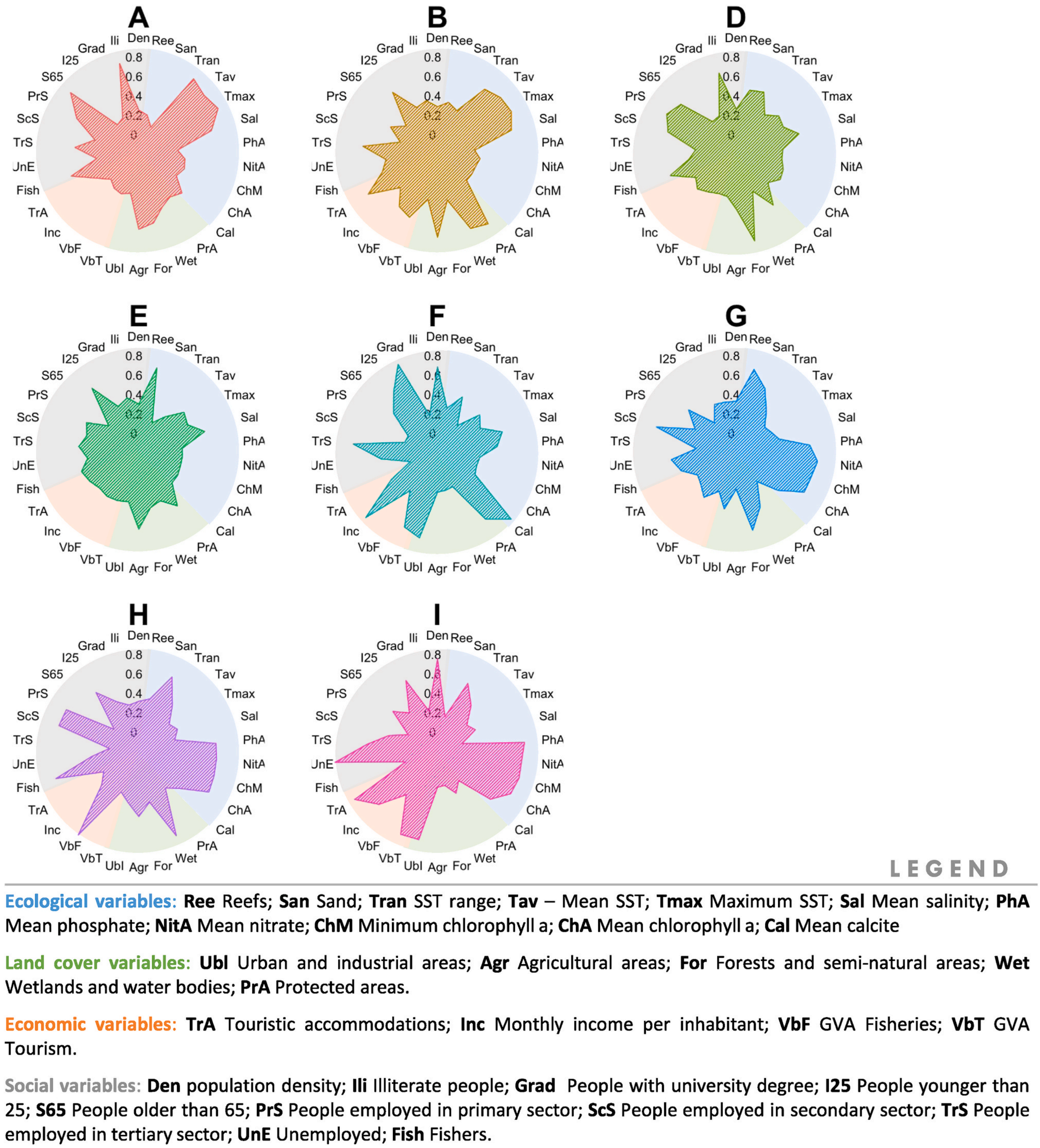

Fig. 8. Variables used in each category of Marine Socio-ecological Categories (MSEC).

The resulting MSEC represent different territories, with different specificities:

East Algarve: MSEC A and B sharing the MCL 1 are found in Algarve coast between Albufeira and Vila Real de Santo António (see Fig. 7b). Both MSEC A and B have higher temperature waters and high agricultural areas are common in both categories. More specifically:

- MSEC A shows a rural profile (SCL1), with low average economic variables and higher rates of older and illiterate people.
- MSEC B shows a higher average on economic sectors and higher rates of young people.

South and Center Atlantic: MSEC D, E, and F share the same marine cluster, MCL2. Although it's the same cluster, its ecological variables have differences within each category. In more detail.

- MSEC F is showing lowest values of productivity (Chlorophyll related variables) and Nitrates, with the highest values of Inorganic carbon. It has an urban profile, appearing in municipalities from the AML region and closer to Lisbon (Oeiras, Cascais, and Almada) with the highest indicators on urban and industrial area, population density, highest average graduated people, tertiary workers, and highest national average income. It also shows the 2nd highest revenues from tourism.

- MSEC D shows higher levels of nutrients; older, illiterate, and primary sector workers. It has the municipalities with the highest superficial area, and it shows the highest forest occupation in the coastal municipalities and low levels of urban and industrial areas.
- MSEC E is characterized by rocky coastline municipalities, most of them located north of Lisbon, the highest level of young people, higher levels of population density and higher incomes from tourism and fisheries, and low level of urban and industrial areas.

North Atlantic: MSEC G, H, and I share the same MCL3, all located in the Northern part of the country. They share the highest levels of productivity and nutrients in the water, with the lowest salinity and temperatures. On socioeconomic/land-cover levels, these categories all have higher population densities with high percentages of urban and industrial land-cover. Detailed relevant features of these MSEC are described below:

- MSEC I occurs in 3 municipalities Porto, Vila Nova de Gaia and Matosinhos. It has the highest national averages of population density, unemployment levels, touristic accommodations, and tourism GAV. Besides, it shows the highest urban and industrial land-cover. It is the second-best ranking category on monthly incomes and an average of graduates in the population, only behind category F (covering the municipalities around Lisbon, as Oeiras, Cascais, and Almada).
- MSEC H appears in the boundary areas of MSEC I, with the highest average values on fishery-related categories, incomes, and fishers, and the highest national average of workers in the primary and secondary sectors. In opposition, it shows the lower levels of unemployment, older people (above 65 years), and a lower number of touristic accommodations.
- MSEC G is characterized by the lower levels of income, percentage of graduates among the population, the low added value from tourism or fishing activities, and higher illiterate and older people (above 65 years) when compared with H and I. It also shows a higher area covered by forests and semi-natural areas within its municipalities. Alike MSEC H, also G has low levels of unemployment and high levels of workers in the secondary sector.

4. Discussion

4.1. Implications for management and planning policies

We followed a methodology developed in terrestrial systems and later adapted to marine systems (Lazzari et al., 2019; Martín-López et al., 2017). Through the application of the method, we identified several MSEC showing different marine socio-ecological patterns along the Portuguese coast. This study allowed identifying specific factors either socioeconomic or ecological behind the similarities and differences within MSEC, essential to better understand the specificities of each region and improve design policy-making decisions and management measures, which is especially relevant since a new policy framework is implemented.

From the analysis of the MSEC, it is noticeable the need to address socio-ecological issues at LSI that are closely interconnected. This analysis allows to extract valuable inputs to improve the terrestrial and marine policy frameworks. An example is the maritime pollution levels, the population density patterns, and their effects on coastal and marine ecosystems. The northern territories related with MSEC G, H, and I exhibit a profile with the highest maritime pollution (level of nutrients, mainly nitrogen), higher inorganic carbon, and lower marine temperatures, in a territory with a high industrial profile (APA, 2017; DGT, 2018c), mainly evident in MSEC H and I. This aspect was identified in the analysis of the chemical water quality report of the WFD (Lopes et al., 2017), where the streams faced high nitrate concentration. Being a territory with strong socioeconomic dependency on fisheries, such as MSEC H (see the employment and GVA from fisheries) the ecological quality of water is of the utmost importance. Moreover, these territories that are already facing high marine pollution also have higher rates of young people, meaning they will be dealing with higher human pressures and higher resources demands. In this sense, it will be relevant to develop policies, mainly at the regional level, such as the CZPM and the RBMP that promote the control of chemicals used in agriculture and to develop supporting structures to cope with the urbanization of the territories.

MSEC D and E in the Atlantic coast show a divided territory where different challenges arise to the marine and coastal ecosystems conservation and the sustainable development of communities. MSEC D appears in the center region, the coastal stretch between Vagos and Óbidos (except for Caldas da Rainha), and at the south of Lisbon, the Alentejo coast (between Grândola and Vila do Bispo, see Fig. 6b), showing the least developed profile of the Atlantic coast. The demographic challenge in this territory is obvious, with high rates of older people and lower rates of youngsters, being vulnerable to depopulation. Different challenges arise on the contiguous MSEC E, which has a semi-urban profile (population densities above 100 and below 500 hab/km^2, see INE, 2014), with a younger population and better economic conditions. It combines fishery and touristic aspects, it includes Peniche a well-renowned hub for fisheries and tourism, Portimão and Sesimbra, traditional artisanal fishery ports (Mateus et al., 2019). Interestingly, MSEC D and E spread pass-thru regional boundaries indicating that national policies will be more relevant to tackle the issues, than regional ones. Moreover, MSEC D and E differ on socioeconomic characteristics and their management measures and policies should target their challenges accordingly. For example, in MSEC E with higher population densities and rates of younger people, more economic activity as coastal tourism, policies shall target specific human pressures (due to increased resources consumption, urbanization, and urban sprawl). On the contrary, MSEC D with higher rates of older people and an economic profile focused on agricultural and forestry systems shall target policies to develop sustainable growth, capture more young people and improve their education, although considering as well foster development and preserving the ecosystems at the same time. For the maritime landscape, the MSP has also a part to play in the outcome of the regional development. Several projects are expected to come to reality in the next years in the Atlantic Coast, such as Aquaculture and Renewable Energies (Fernandes et al., 2020) urging the need for a good EBM management not only of the connections between the maritime projects and the land but also considering the communities that may benefit from the developments, especially in MSEC D.

The Algarve coast is divided into 4 categories (MSCE A, B, D, and E), showing the dissimilarities and the fragmentation of the territory. Locations as Faro, Portimão, Lagos and Albufeira (MSEC E and B) are more developed, with strong touristic activity and more dynamic than Castro Marim and Tavira, MSEC A (DGT, 2018c; Freire et al., 2009). This unbalanced growth between neighboring municipalities in Algarve is a challenge for management and planning, where some municipalities show the relevance of the primary sector and the incidence of agricultural tradition, with aging and depopulation as the main challenge alongside territories more economically developed but focused mainly in tourism services activities (Freire et al., 2009; Freitas and Dias, 2019). Mainly for MSEC E and B, the two clusters more economically developed but with average lower primary production indicators in Algarve, management and policies measures should focus on environmental education oriented on promoting sustainable fisheries and diversified touristic activities, to reduce the pressures on ecosystems.

One of the major vulnerabilities exposed by the patterns is the aging territories together with the low development of the economy, mainly in some parts of the coast of Algarve and in the Alentejo and Centro Region. These territories may experience the development of agricultural or maritime activities, but the difficulty of attracting young people may hinder this process. On the other side, territories that have younger profiles may experience increasing pressures on the ecosystems, such as in the North and on the Algarve coast. At the same time, it is clear that less developed territories have natural values, such as wetlands and forests that need to be appropriately protected to support sustainable growth.

The policy tools shown in Fig. 2 can acknowledge the MSEC to design more efficient management actions and policies at different spatial scales. At the national level with National Spatial Program (PNPOT), and at a regional level with Regional Spatial Programs (PROTs) and Water Management Plans (RBMP) that have a strategic regional vision may benefit from this cluster analysis to reduce disparities between levels of development among clusters and improve cohesion over the different territories. Accessibilities, Tourism, Fisheries, and Coastal Zone programs can also incorporate items from the analysis. MSP may incorporate information from the analysis by exploring the most resilient municipalities to changes in fisheries and tourism activities, relevant within the maritime sector, but also to explore the differences in demographic and socioeconomic conditions on coastal municipalities. For example, MSEC H and B, F, and I are benefitting the most from coastal and maritime activities and careful consideration should be paid to maintaining good health ecosystems and good social conditions to maintain the human capital, vital to the economic development that the patterns show.

Studies that focus on the SES framework provide guidance on how to assess the different dimensions and how they can contribute to the sustainable development and efficient resource use and management (Leslie et al., 2015; Liu et al., 2007). The MSEC show the imbalances found when considering the social, ecological, and economic dimensions throughout all the categories. This study point directions to the design of more efficient management actions and policies at different spatial scales towards more social-ecological sustainability, where the needs both of people and nature are met, now and in the future (Ostrom, 2009).

4.2. Limitations and further research

In this study, we identified several limiting factors. On the socioeconomic characterization, there was mainly a lack of information on data inputs by years. This may be improved in future studies with more information, such as the information made available by the new census from in 2021. The terrestrial analysis may also in the future encompass neighboring municipalities that although do not have waterfront are near to be exposed to maritime influence.

The three marine clusters were identified based on the SST variables, mean, range, and maximum. The clusters on the Iberian coast MCL 2 and 3 showed lower SST temperatures, higher chlorophyll levels, and low salinity levels. The Iberian coast, in Nazaré, but also around Lisbon, Setubal, and Cabo São Vicente is known to be prone to upwelling events, which transport cold and nutrient-rich upwelled water, typically occurring between Spring to Autumn (Moita, 1993; Relvas et al., 2007). Understanding these events and specifies is beyond the scope of this work, however, this does show that some trends may appear related to known trends of the Western Iberian coast and therefore, the indicators used for the accessing ecological system can be improved. We used the database of Bio-Oracle with derived metrics that were not accounting for inter-annual and seasonal differences, which characterize ecological systems. In the future, species richness, abundance, or functional biodiversity (Foley et al., 2010). Hanspach et al. (2016) included in their study species richness models to develop a typology of terrestrial socio-ecological units. Also, the study of Gomes et al. (2018) identified several areas of marine biological value which are a good proxy for ecological characterization which can be useful to support the categorization in a future implementation.

The MSEC categories provide a good starting point for further studies of socio-ecological dynamics and trends, such as the work of (Hanspach et al., 2014) shows, where a spatially explicit approach is coupled with SES dynamics and development trends. This would provide more information on the feedback and interconnections between the different variables and therefore between natural and human systems, improving the overall understanding of the opportunities and tradeoffs for managing the sustainability of coupled SES systems.

5. Conclusion

The characterization of marine SES can support policy design by displaying comparative research on the contrasting ecological and societal conditions across the Portuguese coastal municipalities. Socio-ecological regional mapping characterization exercises are still in an early phase and were mainly focused on inland. We adapted a methodology to assess how the coastal-marine Mainland Portugal spatially differs in socioeconomic and ecological terms. The results show that Algarve and Centro regions have high territorial disparities that need to carefully be considered when designing regional policies. In some of these municipalities, marine and inland economic development are vulnerable to the aging population. Northern territories, and the west Algarve on the other side, have a young profile but must address the health of the ecosystems to support the demographic growth that is expected.

This exercise showed that the spatial information extracted from the categories was valuable to understand how different conditions along the territory may be dealt with at regional and national context in future management and planning policies. Such studies make clear that there is no land-sea divide as these complex systems are closely interlinked. Therefore, the connections between both systems as well as their socioeconomic impacts should be reflected in the existent policy framework.

Author contributions

MLF and FA conceived the research; MLF structured and developed the research activity and wrote the first draft; All the authors contributed to the assessment and revised the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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