Cap de Creus MPA - VULNERABILITY ASSESSMENT

MPA ENGAGE

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Final Report VA MPA Cap de Creus		4	Description of the Vulnerability Assessment process for Cap de Creus; results, main findings and conclusions.

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1 Summary

A standardized and replicable Socio-Ecological Vulnerability Assessment has been implemented in Cap de Creus MPA. The tool combines indicators that represent the basis of the index and by aggregating them, we obtain the components, which combined then make up the dimensions of exposure, sensitivity and adaptive capacity, that together form the Social-ecological Vulnerability Index. While sensitivity and exposure increase the vulnerability of the MPA, adaptive capacity reduces its vulnerability. This methodology is replicable and can be updated over time to track the evolution of the MPA risks and facilitate adaptation planning.

This process, carried out during 2020, although some delays, has been effective and fluent thanks to UVIGO guidance and also to the professionalism of a multidisciplinary team formed by the public administration of the Generalitat de Catalunya –Subdirecció General de Biodiversitat i Medi Natural, Oficina Catalana del Canvi Climàtic and managers of the PN Cap de Creus MPA - and the private sector (Fundació ENT).

It has been relatively easy to get all the information needed, especially these related to the data from the MPA management board, but also the information from other public entities such as the University of Barcelona, experts in the fields of cartography and GIS, the Institute of Statistics (IDESCAT) or the Catalan Water Agency. In contrast, the information related to socioeconomic aspects has been quite difficult to obtain, and it has been collected from the private sector and through user's groups questionnaires and interviews. As a result, the quality of the data is high for the indices monitored during several years, but not so consistent for those obtained punctually. To conduct better vulnerability assessments in the future, it is necessary to broaden the monitoring system in order to get more data and cover an increased number of indicators.

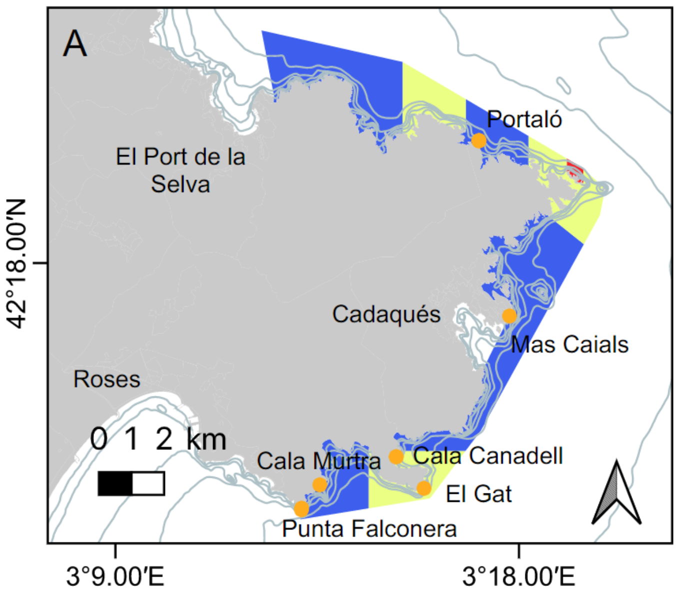
The results of the socio-ecological vulnerability assessment show a high and very high vulnerability in Cap de Creus MPA. During this process, the ecological aspects of the protected area as well as the socioeconomic ones have been studied separately. The results show that ecosystems are highly vulnerable, so there is an urgent need to improve habitat and species protection and restoration plans as a priority for the MPA as well as to strengthen control over tourism, fishing and recreational activities. The Vulnerability of Cap de Creus users varies greatly between sectors, but generally increases in scenarios with RCP 4.5 and 8.5 at 2100, being divers the least vulnerable group of all those analysed. At the other extreme, we find nautical activities that will become extremely vulnerable, indicating an urgent need for better management of these activities. Regarding the key vulnerability factors, it is necessary to enforce public engagement in the decision-making processes as a key factor in order to assure a participative governance model of the MPA. In this sense, the Master Plan for the Use and Management of the marine environment of the Cap de Creus Natural Park (PRUG) is currently being drafted and all these issues will be taken into account.

Looking forward to the near future, the Vulnerability Assessment of Cap de Creus MPA has laid the foundations to establish a baseline of the MPA vulnerability and facilitate the process of elaboration of the next management plans. Furthermore, it has highlighted the needs of both, ecologic and socioeconomic aspects to improve the conditions for a proper management system with the implication of all the agents involved in the protected area.

2 Introduction of *Cap de Creus MPA*

The natural park of *Cap de Creus* is in the Northwest Mediterranean, and it is included in the *Costa Brava*, a coastal region of Catalonia (Spain). The park has 13.823 ha, comprising a terrestrial and marine area of

10.767 ha and 3.056 ha, respectively.[1] A total of eight municipalities from the administrative county of *Alt Empordà* and the corresponding province of *Girona* are part of *Cap de Creus*, namely *Cadaquès*, *Llançà*, *Palau-saverdera*, *Pau*, *el Port de la Selva*, *Roses*, *la Selva de Mar* and *Vilajuïga*. Altogether, the municipalities had 31.559 inhabitants in 2020.[2]



Catalonia has the Catalan network of natural protected areas (National Parks, Natural Parks, etc.) and the "*Pla d'Espais d'Interès Natural*" – PEIN (in English "Plan for Areas of Natural Interest") as the main protective policy figures for natural conservation. The PEIN was approved by the regional government of Catalonia in 1992 (Decree Law 328/1992[3]), following the provisions of the Law 12/1985 of natural protected areas[4]. *Cap de Creus* was the first marine-terrestrial natural park created in Catalonia in 1998, through the Law 4/1998[5], under the PEIN legislation (Sardà et al., 2012). There are three modalities of protection for the natural areas of *Cap de Creus*: 1) natural park areas; 2) natural sites of national interest (*Paratges naturals d'interès nacional* - PNIN); and nature reserves (partial or strict). The terrestrial part of the park includes natural park areas, three PNIN (*Cap Gros*-*Cap de Creus*, in the north; *Punta Falconera*-*Cap Norfeu*, in the south; and *Serra de Rodes*, in the west), and two strict nature reserves (*Cap de Creus* and *Cap Norfeu*). As for the marine part, there are natural park areas, three partial nature reserves (*Punta dels Farallons*, *Cap de Creus*, and *Cap Norfeu*), and the strict nature reserve with the islands of *S'Encalladora* and *La Maça d'Or*. Moreover, all the islets are considered as PNIN, apart from those islands and islets contiguous to the terrestrial part of the strict nature reserve.[6] Most of these protected areas are also included into the Natura 2000 Network at European level.

Cap de Creus' continental shelf presents morphological differences between the northern and southern flanks, with the former being mainly depositional and the latter erosional. Main marine and coastal habitats of *Cap de Creus* include coastal terrigenous muds; coastal and muddy detrital bottoms; coralligenous reefs, rocky bottoms and photophilous algae; coarse sands and gravel; and *Posidonia Oceanica* beds. Flagship

[1] http://parcsnaturals.gencat.cat/web/.content/home/cap_de_creus/coneix-nos/centre_de_documentacio/fons_documental/biblioteca_digital/memories/memoria_resultats_2010.pdf.
[2] http://www.ddgi.cat/xifra/demografia/dpt.asp?IdMenu=03020101 (11/10/2021).
[3] https://portaljuridic.gencat.cat/ca/pjur_ocults/pjur_resultats_fitxa/?action=fitxa&mode=single&documentId=80837&language=ca_ES.
[4] https://portaljuridic.gencat.cat/ca/pjur_ocults/pjur_resultats_fitxa/?action=fitxa&documentId=239736.
[5] https://www.boe.es/buscar/doc.php?id=BOE-A-1998-12319.
[6] http://parcsnaturals.gencat.cat/web/.content/home/cap_de_creus/coneix-nos/centre_de_documentacio/fons_documental/biblioteca_digital/memories/memoria_resultats_2010.pdf.

species include, *inter alia*, coralline calcareous algae (e.g., *Lithophyllum byssoides*); gorgonians such as the *Paramuricea clavata* (red gorgonian), *Eunicella cavolini* (yellow gorgonian) and *Corallium rubrum* (red coral); *Posidonia* oceanica; *Palinurus elephas* (European spiny lobster); and *Epinephelus marginatus* (dusky grouper).

Some of the previous habitats and species are vulnerable to various environmental and non-environmental pressures (e.g., sea warming, ocean acidification, marine pollution, invasive species, poaching, non-responsible boat anchoring techniques and scuba diving behaviour). The marine biodiversity monitoring implemented in *Cap de Creus*[7] noticed a worrying state of conservation of red gorgonians with an increase in mortality linked to sea warming in 2019. Red coral populations observed a reduction in their average size between 2017 and 2019, but some recovery might occur as an outcome of a harvesting ban implemented for the period 2018-2028. This species has observed a significant depletion in the Mediterranean in the past decades because of overexploitation for commercial purposes (Garrabou et al., 2017). Moreover, red coral is also vulnerable to environmental pressures such as summer heatwaves (Garrabou et al., 2001) and ocean acidification (Bramanti et al., 2013). The marine biodiversity monitoring also showed an increase in the bleaching of coralline algae between 2015 and 2019.

Regarding the socio-economic profile of the eight municipalities composing the natural park, the average share of workers by economic sector in September 2020 was 74,4% in the services sector, followed by construction (13,7%), industry (10%), and agriculture (1,9%).[8] Data from the same year shows that the local dependence on tourism, measured through the number of jobs in food and accommodation services, diving activities, recreational boat activities, and recreational fishing over the total number of jobs, reaches approximately 16%.[9] Another tourism indicator relates to the number of beds in accommodation establishments per 1.000 inhabitants. Data from 2020 shows a higher capacity in the municipality of *el Port de la Selva* (5.409 beds/1.000 inhabitants), followed by *Cadaquès* (2.565), *Llançà* (1.863), *Roses* (1.700), *la Selva de Mar* (1.123), *Pau* (418), *Palau-saverdera* (359) and *Vilajuïga* (120), 1.695 tourist beds/1.000 inhabitants on average, much higher than the average of all the municipalities in the county (Alt Empordà: 641 tourists places/1.000 inhabitants)[10], suggesting a more tourism-oriented economy of the municipalities of *Cap de Creus*.

Regarding professional fishing, there are currently no limitations on the number of fishermen allowed to fish in the park, and they can fish with any gear, except trawling and encircling, both within the nature park and in the partial nature reserve. However, in the framework of the co-management committee, that was set up at the end of 2020, it is intended to establish a limitation on the number of authorized fishermen.

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7 This monitoring programme is promoted by the Government of Catalonia, and is coordinated by the University of Barcelona with the involvement of other research centres. Available at: http://www.seguimentmari.cat/index.php.

8 This analysis combines the number of workers affiliated to Social Security with those that are self-employed. Available at: https://observatoritreball.gencat.cat/ca/ambits_tematics/mercat_de_treball/afiliacio_ss/mineria_carbo_i_regim_especial_autonoms/ (01/12/2020).

9 Estimated with data obtained from Camerdata (food and accommodation services), MPA staff and diving centers (diving activities), Catalan Association of Maritime Activities (nautical activities), fishing gear shops (recreational fishing), and IDESCAT (total number of jobs).

10 http://www.ddgi.cat/xifra/indicadors/ActivEcon/TurX1000h.asp?IdMenu=040403 (11/10/2021).

Except for management and scientific activities, all the other activities are forbidden in the small integral nature reserve (north of Encalladora Island, just above Punta de Cap de Creus).

The natural park of *Cap de Creus* presents a high-level of attractiveness for the development of various coastal and marine recreational activities such as scuba diving, snorkelling, recreational fishing, boat cruises and kayak tours. There are currently about 15 dive centres in *Cap de Creus*, and more than 75.000 dives are made per year (Gencat, 2002). Estimates for the period 2006-2010 show a total of 1.080 recreational fishers per year in *Cap de Creus* (Lloret et al., 2013). Moreover, in 2016 the Natural park administration accounted for 37.171 people attending the information points, and estimated approximately 440.000 visitors/year, and a daily boat transit of 90 to 100 boats during the peak season.[11]

3 Scope of the Vulnerability assessment

The present vulnerability assessment evaluates the habitats, species, uses and management of the MPA in the face of climate change future impacts. The analysis focuses on the MPA social-ecological vulnerability, which considers the ecological sustainability under climate change as well as the vulnerability of the MPA uses. The units of analysis are the MPAs, and we also include information about species groups and habitats, as well as user groups. However, the analysis is based on indicators and groups of species, habitats and users, and is not spatially explicit (although it could be transformed to be, for example based on species distribution or habitats and human uses).

3.1 DEFINING THE UNITS OF ANALYSIS

A co-development process was initiated within the project and guided by UVIGO to identify the units of analysis. From each MPA, we provided information about the habitats, species and user groups at the local scale, as well as on their interactions this process started with several questionnaires done by managers, and interactions during the training events of MPA-Engage and many following exercises. The process started in January 2020, within the context of the MPA-Engage project that helped provide guidance and expert support from the rest of the consortium. A series of regular meetings and training events facilitated the development of the approach and the data collection process. The MPAs provided all the inputs for the

[11] http://parcsnaturals.gencat.cat/web/.content/home/cap_de_creus/coneix-nos/centre_de_documentacio/fons_documental/biblioteca_digital/memories/memoria_2016.pdf.

quantification of the indicators that were then processed by UVIGO partners, who developed the tool where we can calculate our results and interpret them and improve them.

The **objective** of the vulnerability assessment is to have a useful tool to evaluate the MPA risks and performance confronting climate change impacts and help in the design of adaptation plans. The specific objectives are: 1) to understand ecological and socio-ecological vulnerability in the MPA under different future scenarios; 2) to identify the species at risk and the most vulnerable habitats; 3) to identify the user groups that are most vulnerable in the MPA; 4) to identify key vulnerability factors that can be improved to decrease vulnerability in the future. At the same time, the results of the vulnerability assessment can be used for dissemination purposes and awareness raising.

The assessment focuses on the four groups of species that we have identified during the development of the vulnerability approach: endangered species, fished species, flag species and invasive species. The hazards we focus on are the increase in maximum Sea Surface Temperature (SST99) over the periods of 2050 and 2100 and the increase in Marine Heat Waves (MHW) intensity over the same period, based on model projections over three scenarios of low (RCP2.6), medium (RCP4.5) and high emissions (RCP8.5) scenarios. Therefore, this vulnerability assessment is respect to future expected impacts in the MPA, in years 2050 and 2100, and under three climate change scenarios (2.6, 4.5 and 8.5).

As a result, the assessment has a visualization and index calculation tool where we are able to introduce a template with all the data for the MPA. The outputs we obtain are the figures shown in this report, basically the main overall indices of vulnerability (0 low vulnerability, 1 high vulnerability) for ecological and social-ecological vulnerability. Another input is the results by species, users and habitats. Finally, we also have results in terms of the indicators contributing most to vulnerability, and information on the gaps in data and quality of the analysis.

3.2 CLIMATE CHANGE IMPACTS IN THE MPA

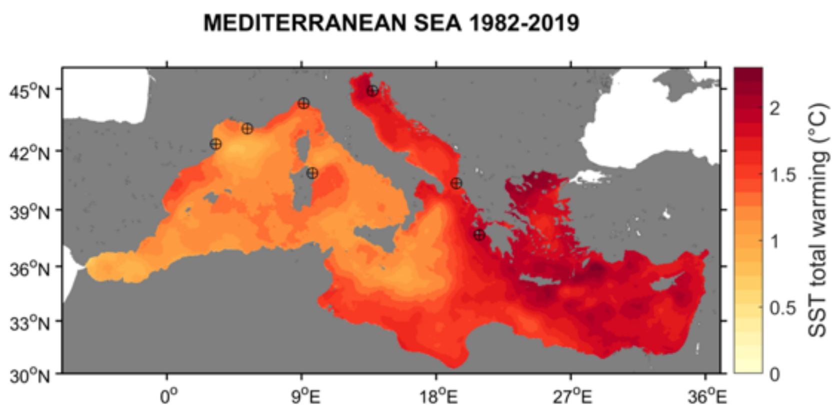
Climate change impacts are in the form of Sea Surface Temperature increase (SST99) and Marine heatwaves (MHW) increase in the periods of 2041-2050 and 2091-2100, as defined here:

- SST99: 99th percentile of SST yearly anomaly (ºC) with respect to reference period (1950-1980)
- MHW: Cumulative intensity of MHW events (ºC * days) with respect to the reference period (1950-1980)

This climate data is retrieved using multi-model and multi-scenarios from MedCordex, also known as Fully coupled Regional Climate System Models, from CNRM, representative of global warming scenarios with respect to the 1950-1980 average. Robust min and max (1st and 99th percentiles) were calculated over the entire Mediterranean and for each MPA. The same method was applied at Mediterranean scale (over each pixel of CNRM simulations) for the RCP8.5 scenarios to define mean, as well as robust min and max anomaly

(1st and 99th percentile) for normalization of warming data at two time horizons: 2041-2050 and 2091-2100.

Figure 1. Current warming observed in Mediterranean MPAs, period 1982-2019 respect to 1950-1980



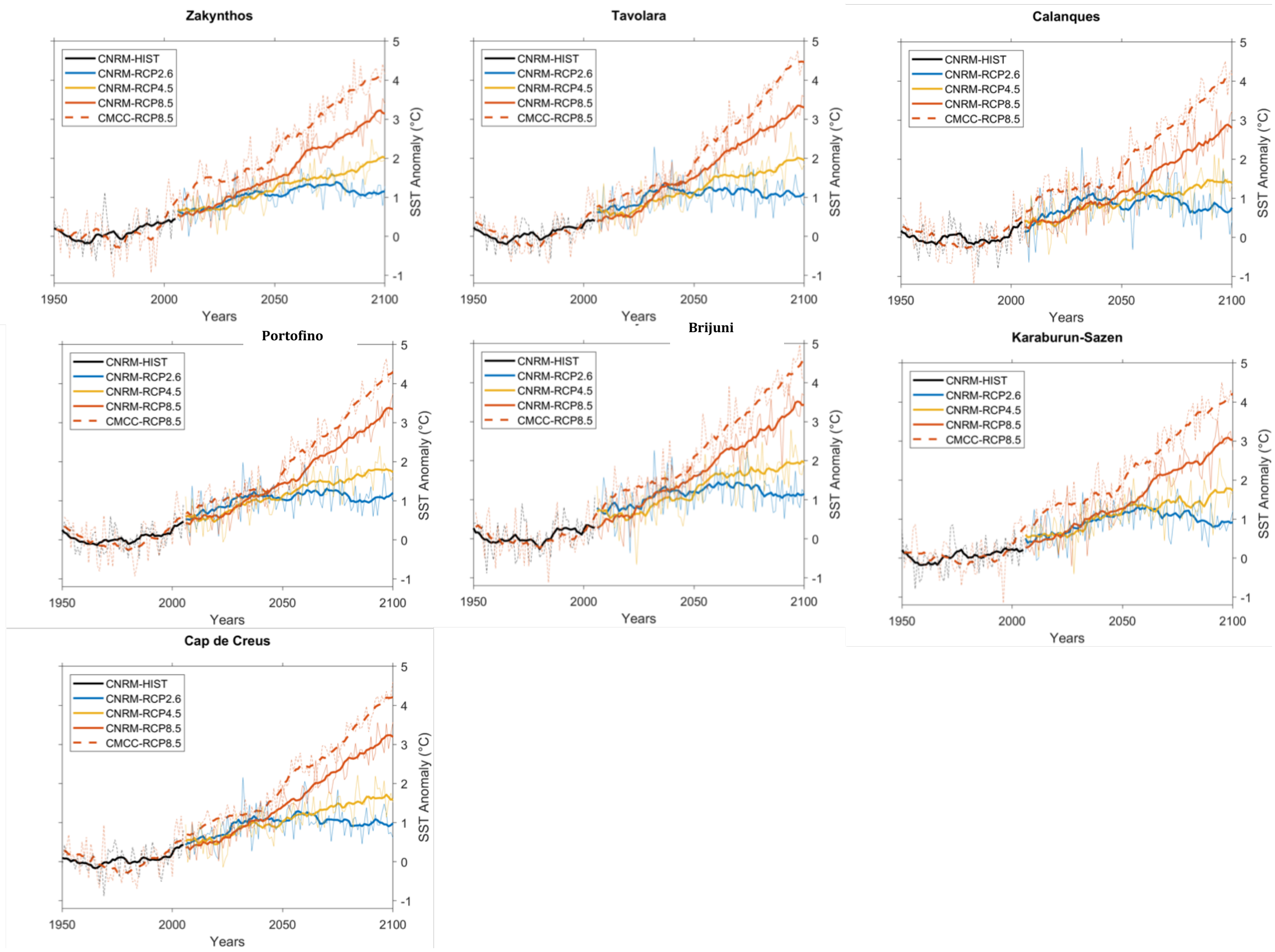


Figure 2. SST99 anomaly projected for the MPA with climate change scenarios.

Marine Heatwave analysis following the definition of Hobday et al. (2016), as fully described in Bensoussan et al. (2019). We consider the warm period from June to November (JJASON), and quantify MHW-days and MHW maximum intensity (°C). These two metrics are aggregated into the cumulative MHW value (ºC*days) that we use, applied to MedCordex simulations, considering historical run of 1950-2005, and scenarios 2006-2100, 30 years' climatology over the 1950-1980 period.

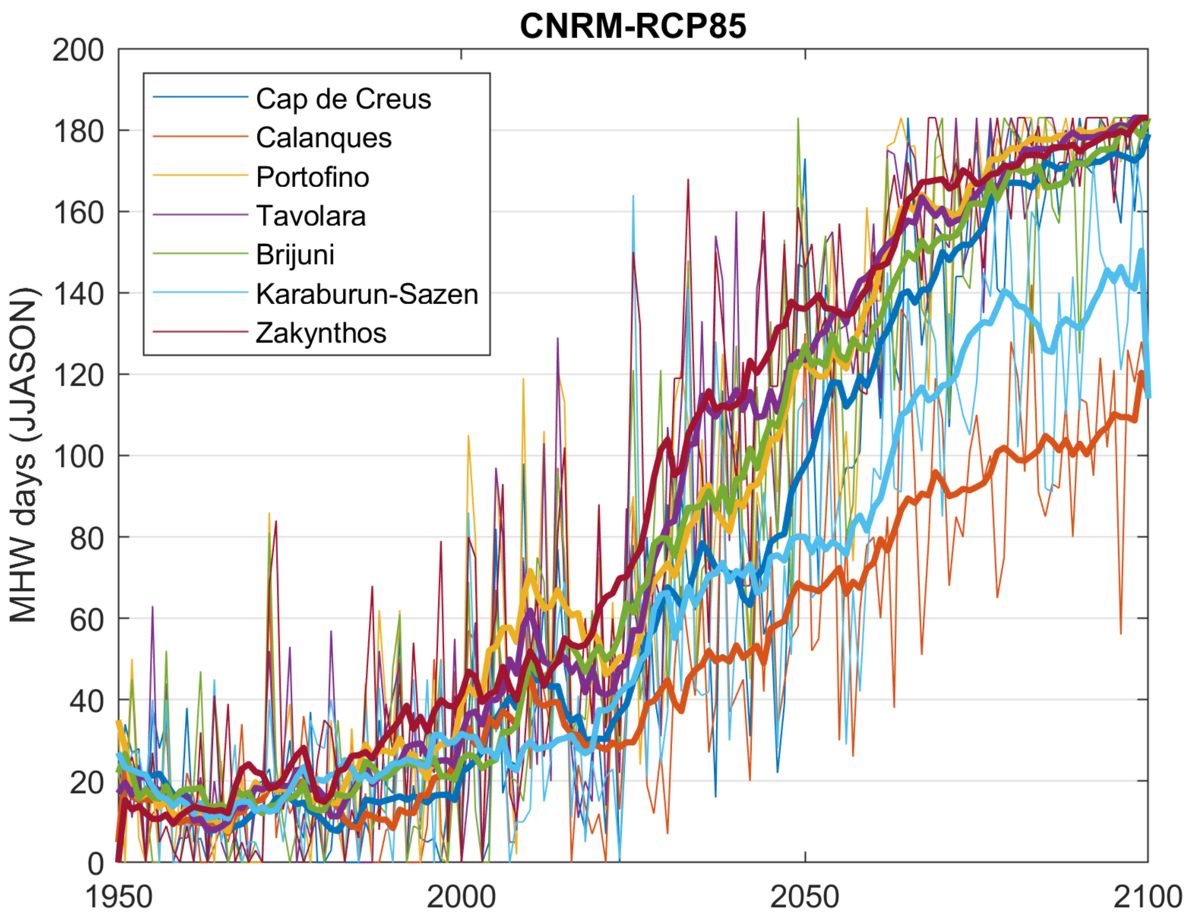


Figure 3. Projected MHW-days over the warm period (JJASON) of each year under climate change scenario 8.5.

4 Methodology

4.1 SOCIO-ECOLOGICAL VULNERABILITY ASSESSMENT

A standardized and replicable Socio-Ecological Vulnerability Assessment has been implemented within the MPA-Engage project. Vulnerability refers to a degree to which a system is susceptible to the impacts of climate change, defining how severe the effects of climate change can be. The elements that build up the Vulnerability of the system are three: exposure, sensitivity and adaptive capacity (Figure 4). Exposure refers to the direct impacts of the changing climate on the system, sensitivity refers to the degree to which the system could be damaged, and adaptive capacity refers to its capacity to reduce the disturbances by taking actions to enhance resilience. This framework aggregates a set of qualitative and quantitative indicators along the dimensions of vulnerability, to provide a composite index on vulnerability.

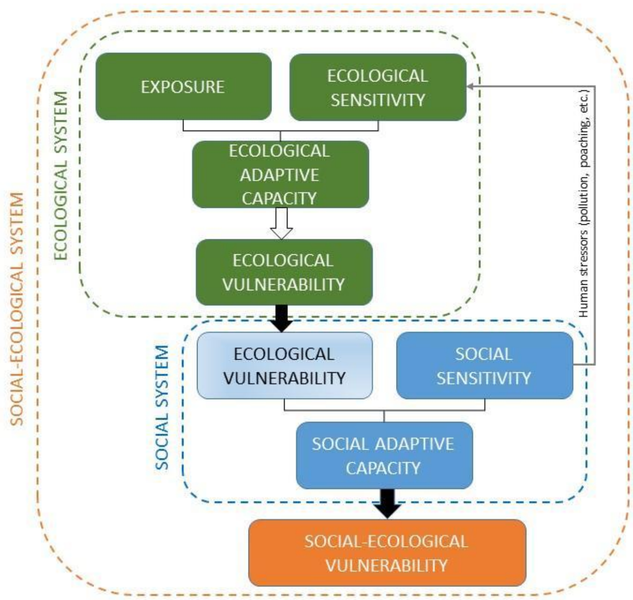


Figure 4. Social-ecological climate Vulnerability framework.

The application of the Socio-Ecological Vulnerability Assessment to the Marine Protected Areas contexts represents a useful tool to analyse and interpret the vulnerability of the MPA and its species, habitats and user groups in relation to the projected impacts of climate change. Information on both the ecological system in the MPA and the social system (users of the MPA) can be combined under this framework. As a result, this methodology is replicable and can be updated over time to track the evolution of the MPA risks and facilitate adaptation planning.

4.2 VULNERABILITY ASSESSMENT TOOL

The vulnerability assessment tool follows the framework in Figure 4 above and combines indicators of exposure, sensitivity and adaptive capacity. The indicators represent the basis of the index and by aggregating them, we obtain the components, which combined make up the dimensions of exposure, sensitivity and adaptive capacity, that together form the Vulnerability Index (Figure 5). While sensitivity and exposure increase the vulnerability of the MPA, adaptive capacity reduces its vulnerability and therefore we correct for the relationships between indicators, components and dimensions to aggregate the final index. The indicators have been selected considering the ecological and socio-economic context of Mediterranean Marine Protected Areas and are presented in Annex 9.1 tables.

Figure 5. Levels in the composition of the vulnerability index.

For the calculation of the Vulnerability Index, the combination of indicators, their normalization and weighting is operationalized in an online tool. The tool performs a standardized calculation of the Social-Ecological Vulnerability in a MPA based on a scaling system at the Mediterranean level. This allows for cross-MPA comparison. The tool works through an input file (.xls) that includes the indicators with their values assigned, the scale of the indicator (MPA, species, habitat, user and hazard), the number of years that the values refers to, and if it is a qualitative or quantitative way of measurement.

Once the input file has been uploaded to the programme (R studio, ref), the code normalizes the values of each indicator between 0 and 1, following the normalization ranges established in the methods (see document VA-tool indicator processing for normalization values). Normalization ranges are numerical values for quantitative indicators, based on the Mediterranean when possible, this is establishing the maximum and minimum ranges outside of the MPA data. Normalization for qualitative indicators is done in the same way, but converting qualitative scales into numerical scales first (i.e. very low to 1; low to 2, intermediate to 3; high to 4 and very high to 5). Both normalization processes follow equation (1), where X can be an indicator, a component a factor or a dimension:

$$X = \frac{(X_i - X_{min})}{(X_{max} - X_{min})} \qquad (1)$$

Indicators are tested for correlations and in the case of a Pearson correlation value between indicators or above 0.8 one of the indicators is randomly dropped. This process is to avoid double information and using indicators that are very closely related to each other.

The normalized indicators (I) are then aggregated at the component level (C), following the index structure in Tables 9.2A and 9.2B (Annex9.2) considering the weights (w), following equation (2):

$$C = \frac{(I * w_1 + I_2 * w_2 + I_3 * w_3 + \cdots + I_n * w_n}{\sum_1^n w} \quad (2)$$

The same process of aggregation is repeated for each component, dimension and the final index, also using equation (2). At each step, values of the components, dimensions and indicators are always normalized following equation (1), such that the Vulnerability Index score for the MPA is going to be a value that ranges between 0 and 1.

Finally, the weights we use are based on an expert consultation process where only the components were assessed. For the ecological components and the social components, four experts each evaluated the level of contribution to these components to vulnerability. The experts used a scale from 0 to 10 (W) for the contribution to vulnerability, and a confidence level n their response that ranged from 1-3 (ϑ). To calculate the final component weight, we use equation (3):

$$w_i = W_i{}^* \, \vartheta_i \quad (3)$$

These expert elicited weights are used in equation (2) for the aggregation of the components (see table 1 weights). For the aggregation of indicators and dimensions, although we also use equation (2), in this case all the weights are all 1 (no weights). All the indicator processing and final index values for the templates are in the documents “VA-tool indicator processing”, “Template” and “Raw data”.

Table 1. Social and ecological components weight. Colour legend: Exposure components (blue), Ecological sensitivity components (light green), Ecological adaptive capacity components (green), Social sensitivity component (orange), Social adaptive capacity components (pink)

Dimension	Component	Weight	Dimension	Component	Weight
Exposure	SST threat	4.69	Social Sensitivity	Professional fishing dependency	3.54
	MHW threat	5.31		Professional fishing effort	1.91

Ecological sensitivity	water conditions	1.88		Professional fishing local dependency	4.55
	human pressure	2.97		Recreational activities employment	3.40
	habitat integrity threats	2.68		Recreational activities ecosystem	3.30
	species integrity threats	2.45		Recreational activities facilities	3.30
Ecological adaptive capacity	hab. redundancy	1.46	Social Adaptive capacity	Flexibility	2.34
	hab. Recovery potential	1.92		Social Organization	2.47
	sp. Recovery potential	1.88		Learning	2.14
	effectiveness	1.46		Assets	1.55
	conservation efforts	1.70		Agency and socio-cultural aspects	1.50
	adaptive management	1.60			

4.2.1 THE VULNERABILITY MATRIX

Once all indicators have been normalized, weighted and tested for correlation, they are combined within them based on their components they belong to. The same process of aggregation is repeated for each component, and dimension and final Index. At each step, values of the components and dimensions are always normalized following equation (1), such that the Vulnerability Index score for the MPA is going to be a value that ranges between 0 and 1.

Traditionally in Vulnerability Assessments, numerical values are transformed into qualitative categories for a better communication and visualization. Using a combination of a qualitative and a quantitative approach we created a Vulnerability Matrix for the dissemination of the Vulnerability Indices to MPA managers and users. In fact, transforming values into qualitative categories related to the levels of local MPAs Vulnerability allows users to better compare the vulnerability between different scenarios and MPAs. Specifically, in the present assessment, five categories are used: Low, intermediate, high, very high and extreme vulnerability.

RANGES				
Low	Intermediate	High	Very high	Extreme

Figure 6. Vulnerability matrix ranges.

A data-driven methodology has been applied to create and define the different categories for the Vulnerability Indices produced in this assessment: (1) Socio-ecological Vulnerability Index, (2) Ecological Vulnerability Index, (3) Species Vulnerability Index, (4) Habitat Vulnerability Index, (5) Users Vulnerability Index (Fishers and Recreational users). Associating dimension indexes to one of the five categories requires identifying mutually exclusive ranges of values, such that any value that falls under a range can be categorized into only one category. A common set of ranges has been defined as follows, 0-0.2, 0.2-0.4,0.4-0.6, 0.6-0.8, 0.8-1 for low, intermediate, high, very high, and extreme. However, this approach assumes that calculated indexes can be as close to the two extreme values of 0 and 1. In our case, this assumption does not hold and instead we obtain values in a narrower range. Thus, we define the thresholds of the ranges based on the value of the index we obtain so that the ranges reflect the index we observed rather than a theoretical range of values.

We define the ranges by performing the following steps. First, we obtain the mean and the standard deviation of calculated indexes at each dimension. Second, we perform a random draw of 1000 values from a normal distribution with a mean and standard deviation equal to the obtained values. Third, we calculate the 20, 40, 60, and 80 percentiles and define the qualitative ranges so that any value that falls within 0 and the 20 percentile is assigned to the low category, 20 percentiles to 40 percentiles as intermediate, and so on (Figure 7). Finally, we compare the calculated indexes and categorize them into one of the qualitative categories based on the ranges as defined by the percentiles.

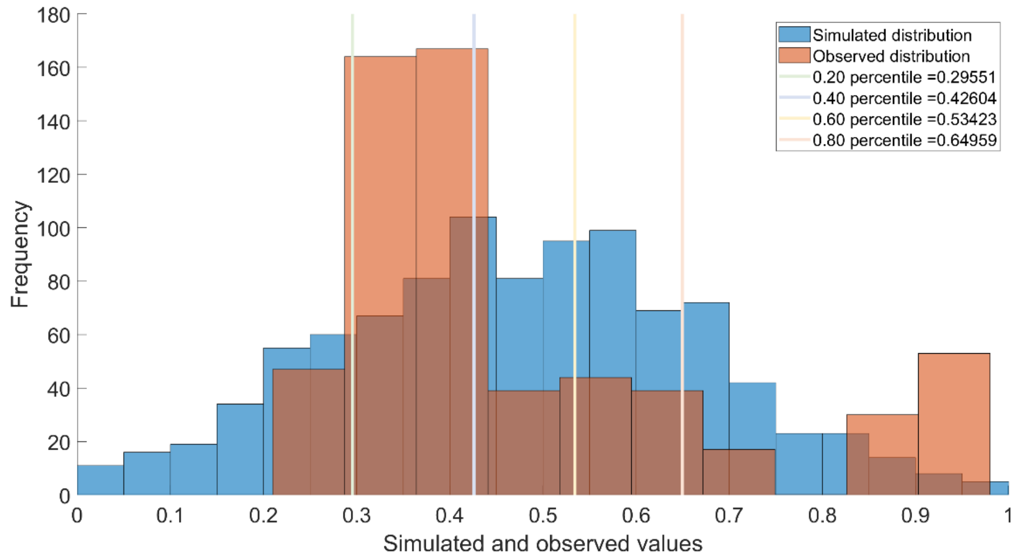


Figure 7: Plot showing the observed and simulated data used to calculate the percentiles to create the qualitative ranges for the exposure dimensions related to the Species Vulnerability Index. The colored bars in the figure reflect the upper limit of the corresponding category.

4.2.1.1 The Vulnerability Matrix

The Vulnerability Matrix created for the calculation of the different Indices is formed by the 3 dimensions that constitute the Vulnerability itself: exposure, sensitivity and adaptive capacity (Figure 8). This same order is the order used when combining the dimensions to obtain the results of the final Index. Each dimension comprises the 5 intervals calculated using the percentiles as explained in previous section. The inner part of the matrix is filled with the five categories to describe the relationship between lines and columns corresponding to the 3 dimensions. Specifically, the first 2 dimensions *Exposure* and *Sensitivity* are on the left side of the matrix, corresponding to the lines of the matrix when the dimensions are combined, while the third dimension *Adaptive capacity* is above the matrix, corresponding to the columns. Note that the dimension of Adaptive Capacity diminishes the Vulnerability of the MPA while Exposure and the Sensitivity increase it.

		Adaptive Capacity				
		Low	Intermediate	High	Very high	Extreme
	Sensitivity					
Low	Low	Intermediate	Intermediate	Intermediate	Low	Low
	Intermediate	High	Intermediate	Intermediate	Intermediate	Low
	High	High	High	Intermediate	Intermediate	Intermediate
	Very high	High	High	High	Intermediate	Intermediate

Figure 8. Vulnerability Matrix for the Index calculation. Matrix used for the calculation of the 5 indices provided in the current framework. In the application of the Matrix for each Index calculation, the dimensions can be called differently, such that exposure is substituted by ecological vulnerability, social sensitivity and social adaptive capacity when calculating the socio-ecological vulnerability index. While we use exposure, ecological sensitivity and ecological adaptive capacity in the calculation of the ecological vulnerability.

Like the ranges of the dimensions, also the intervals forming the matrix had to be calculated. To do so, we calculated the estimation of the overall vulnerability ranges based on the combination of the categories of the 3 dimensions (exposure, sensitivity and adaptive capacity). We first assigned the categorical values of the dimensions as: low=0.1; intermediate=0.3; high=0.5; very high=0.7; extreme=0.9. Then, we calculated the arithmetic average of the values of the three dimensions subtracting the value of adaptive capacity to 1 (1 - AC). The numeric value obtained in this way for the overall vulnerability was finally assigned to a categorical value considering the above ranges to populate the Vulnerability Matrix.

Even though the numerical ranges of the 3 dimensions differ between the Indices the methodology applied for the Calculation of the final Index is the same.

4.3 QUALITY OF THE VULNERABILITY RESULTS

There are two measures for the quality of the assessment that are available from the tool. The first measure is the data coverage in terms of how many indicators of the list are covered by the MPA. A percentage number is given for each dimension, indicating the proportion of indicators for which this MPA has data in the assessment. The more indicators covered, the more comprehensive is the assessment. The second indication of quality is the level of confidence that describes how certain is the measurement of the data. The level of confidence is given for the overall vulnerability and for each of the dimensions. It is measured on a scale from 1 to 5 as it is described in the table 2 below, where 1 is very low confidence on the data and 5 is very high confidence on the data. The resulting confidence value is an average number of the level of confidence of each indicator measured in the assessment, hence, the higher the number the higher the quality of the assessment.

Table 2. Level of confidence

Level of confidence	Definition
5: Very High	Score supported by at least one of these: ● Published quantitative research (models and/or statistical evidence) from the study area; ● Large (+5 years) and complete time series observations in situ provided by monitoring activities; ● Representative sample of individual surveys and interviews of 60 % of users; ● Large sample[1] of local expert[(b)] judgement whose answer is supported by quantitative data. There is a high level of agreement [(b.1)] on the answers provided (questionnaire, interviews); ● High scientific agreement.
4: High	Score supported by at least one of these: ● Published quantitative research (models and/or statistical evidence) from similar areas, similar habitats and similar species, used as proxies; ● Data from local documentation, reports, works (not peer-reviewed scientific literature), etc. from the studied area; ● In situ observations from the area with short time series (< 5 years), observations from similar areas with high quality information; ● Interviews to several key stakeholder[(a)] per user group whose answer has a high level of agreement (questionnaire, interviews); ● Large sample[1] of local expert[(b)] judgement on unit less indicators and whose answer has a high [(b.1)] level of agreement (questionnaire, interviews);

	● Representative sample of individual surveys and interviews of 50% of users with high level of agreement; ● Medium or high scientific agreement.
3: Medium	Score supported by at least one of these: ● Data from documentation, reports, works (not peer-review scientific literature), etc. from similar areas; ● Qualitative data based on several key stakeholders' knowledge and perception whose answer has a low level of agreement (questionnaire, interviews); ● Published qualitative research (models and/or statistical evidence) from similar areas, similar habitats and similar species, used as proxies; ● Large sample[1] of local expert[(b)] judgement providing unit less information and whose answer has a low [(b.2)] level of agreement (questionnaire, interviews); ● Small sample[1] of local expert[(b)] judgement (2-3) providing unit less information and whose answer has a high [(b.1)] level of agreement (questionnaire, interviews); ● Representative sample of individual surveys and interviews of 50% of users with low level of agreement; ● Qualitative information from the literature; ● Medium or high scientific agreement.
2: Low	Score supported by at least one of these: ● Qualitative data based on single key stakeholders' knowledge; ● Small sample[1] of local expert[(b)] judgement (2-3) providing unit less information and whose answer has a low [(b.2)] level of agreement (questionnaire, interviews); ● Small sample of individual surveys and interviews of users with high level of agreement; ● One source of local expert judgement; ● Medium or low scientific agreement.
1: Very low	Score supported by at least one of these: ● Very limited history or knowledge is available; ● Very limited scientific or experts' consensus exist; ● Limited number and representability of stakeholders'[(c)] knowledge and perception; ● Small sample of individual surveys and interviews of users with low level of agreement; ● Very limited information is published in the scientific or grey literature.

1- Large sample of experts refers to having +40% of the stakeholders involved (i.e. 45% diving companies).
2- (a) *Key stakeholders* refers to the representatives form a specific user group, (b) *stakeholders* refers to the users participating in the activities involved in the MPA, (c) *experts* refers to scientist and managers.
3- (b.1) *High level of agreement* means that at least half of the answers given by the experts are the same or there is only one categorical level of difference between the answers (i.e high and medium), (b.2) *Low level of agreement* means that

the answers given by the experts are the very different (less than half of the answers are the same) with more than one categorical level of difference between the answers (i.e. high and low).

There are some limitations to the current data collection and quantification of indicators, most of them intrinsic to the nature of multidisciplinary approaches such as vulnerability assessments. In the ecological domain, sensitivity to climate change temperature increase for habitats and species is based on species thermal ranges from existing global databases (fishbase and sealifebase). Both sources obtain species thermal tolerance information from models based on occurrence data. Despite many publications rely on *aquamaps* (Kashner et al., 2016) for species distribution modelling and thermal ranges (Gaines et al., 2018; Oremus et al., 2020, among others), there are two important limitations. The first one is the reliability of thermal tolerance ranges for species with very scarce occurrence data. The second limitation is the lack of information for some species that can be very important in the Mediterranean context. For few species (*Cystoseira amantacea, Caulerpa cylyndracea, Physter macrochephalus* and *Myriapora truncate*), the thermal tolerance was available qualitatively in the literature and the information was included in the assessment as a qualitative data and not quantitative. While, at this point we could not find thermal tolerance ranges for the species: *Lithophyllum spp.*, *Patella ferruginea*, *Aplysina spp.* and *Savalia savaglia*. Therefore, the current assessment has no information on sensitivity to climate change hazards for these species, and as a consequence, for these species ecological sensitivity does not depend on the hazard levels (does not vary per scenario). A second limitation is the assumption we performed for habitats, where sensitivity to SST and MHW is calculated based on the habitat key species, where we averaged across key species sensitivity. While this indicator is the best we could use to have a sense of species responses to future hazards, there are important knowledge gaps in the literature about species occurrence and thermal tolerances that could affect these results.

Another line of discussion is the stakeholder approach. While key representative stakeholders are knowledgeable about specific user groups, using them as the voices for the groups has its risks. The more questionnaires to different key representative stakeholders, the better the input data for the social components of the vulnerability assessment. This is an area for future methodological improvements where all stakeholders can be addressed and results of the questionnaires compared. At the same time, further refinements can incorporate the performance of the questionnaires directly to users, as to have first-hand information on the use and activities performed in the MPA. This method is however costlier in time and economically and should be planned in advance.

4.3.1 INDICATORS CONTRIBUTION TO VULNERABILITY

In addition to the quality of the assessment measurements, the tool implemented calculates the contribution of each indicator of exposure, sensitivity and adaptive capacity to the overall socio-ecological vulnerability. The indicator contribution is a normalized value between 0 and 1 and its calculation considers to which components and dimension the indicator belongs. For indicator c that belongs to component m and dimension d its contribution it is calculated as follow:

$$Indicator_{Contribution} = (\omega_d) * (\omega_m) * (\omega_c * x_{cmd})$$

Where $\omega_d, \omega_m, \omega_c$ denotes respectively the individual weight associated to dimension, component and indicator. x_{cmd} denotes the indicator c for component m, and dimension d.

In order to provide values with a positive contribution for each indicator considered, the values of the indicators of Adaptive Capacity (AC) have been converted in the values of Lack of Adaptive Capacity (LAC). The LAC is given by subtracting to one the normalized value of adaptive capacity following the formula:

$$LAC = 1 - AC$$

Figure 11 of section 5 “Results”, show the 10 social and ecological indicators of exposure, sensitivity and adaptive capacity contributing the most to the MPA socio-ecological vulnerability. The normalized values have been converted into % applying the formula:

$$Indicator_{\%} = Indicator_x * 100$$

4.4 HABITATS, SPECIES AND USERS SELECTION

A series of habitats, species and users were selected to assess their Vulnerability to the impacts of climate change. For each of the three categories a list was provided in order to allow the comparability of these units between different MPAs.

4.4.1 HABITATS

The habitats subject of this assessment were picked from a list which considered the habitat types used for the monitoring protocols and other activities of the project. The habitats were chosen through a survey done at the kick-off meeting in Barcelona in January 2020 and revised along the implementation of the vulnerability approach.

Table 3. Habitats selected for the assessment in the Cap de Creus MPA.

***Posidonia oceanica* meadows**	**Other seagrass meadows**	**Coralligenous**	**Infralittoral rocky bottoms dominated by macroalgae**	**Caves**
Posidonia oceanica meadows Bottom with *Posidonia oceanica*		Coralligenous, rocky bottom and photophilic seaweeds	Infralittoral bottoms with stones and pebbles Infralittoral rocky bottoms illuminated, without fucal algae,	

Mediterranean formations of *Posidonia oceanica*		Coralligenous with and without gorgonian corals	calm or with heavy waves. Infralittoral rocky bottoms, little or poorly illuminated and calm or with heavy waves	

4.4.2 SPECIES

The species subject of this assessment were picked from a multi-category list which considered endangered species, climate impacted species, target fishing species, monitored species, keystone species and flagship species. Between 3 and 5 species per criteria were chosen through an exercise during the Webinar series, performed by the MPA managers.

Table 4. Species selected for the assessment in the Cap de Creus MPA

Monitored species	Endangered species	Climate impacted species	Target fishing species	Keystone species	Flagship species
Pinna nobilis *Posidonia oceanica* *Fistularia commersonii* *Paramuricea clavata* *Caulerpa spp.*	*Pinna nobilis* *Epinephelus marginatus* *Corallium rubrum* *Caretta caretta* *Tursiops truncatus*	*Fistularia commersonii* *Paracentrotus lividus* *Paramuricea clavata* *Lithophyllum spp.*	*Octopus vulgaris* *Dentex dentex* *Epinephelus marginatus* *Palinurus elephas*	*Posidonia oceanica* *Epinephelus marginatus* *Corallium rubrum* *Paramuricea clavata* *Cystoseira sp*	*Posidonia oceanica* *Epinephelus marginatus* *Corallium rubrum* *Paramuricea clavata* *Tursiops truncatus*

4.4.3 USER GROUPS

The user groups selected for this assessment were picked from a list of the most common activities that take place in all the MPAs involved in the project. The user groups were chosen through a survey done at the kick-off meeting in Barcelona 2020 and revised along the implementation of the vulnerability approach.

Table 5. Users selected for the assessment in the Cap de Creus MPA

Professional fishers	Recreational fishers	Diving sector	Nautical activities	Tourist sector
(president of Roses fishers' guild)	(IFSUA, International Forum for Sustainable Underwater Activities)	(Sotamar Diving Center)	(president of Associació Catalana d'Activitats Marítimes)	(Roses local government)

4.5 DATA COLLECTION PROCESS

The vulnerability guidelines document (D.4.2.1. Vulnerability Assessment Guidelines) presented in spring 2020 provides the full approach for the development of the present analysis. This approach established a preliminary indicator list, and the potential data collection methods. A series of webinars with MPA managers were performed during spring and summer 2020 to advance on the data collection process and approach. There are three main sources of data for the vulnerability assessment: 1) secondary data collected from the literature; 2) data collected by the MPA for the assessment, and 3) stakeholder questionnaire data. Each MPA identified during the exercises the data availability for the indicators, and proposed a way to fill in the information at the local scale. Like this, the MPA identified the data sources and UVIGO prepared a data collection process.

- Secondary data: information on exposure, species sensitivity, or species dispersal, population, and others was collected by UVIGO based on the literature and contributions from experts (exposure).
- Data from MPA: a series of indicators were directly collected by MPA managers with specific questionnaires designed by UVIGO and existing information (data collection template). These are for example indicators like MPA shape, monitoring activities, assets in the MPA, among others.
- Stakeholder questionnaires: MPAs selected representative stakeholders to ask them a series of questionnaires to derive information for the indicators on the user group (stakeholder questionnaires). UVIGO developed the questionnaires and the MPAs translated the questionnaires and implemented them.

In the case of Cap the Creus, due to its status of Marine Protected Area and Natural Park, it has been quite easy to get all the information needed, especially the data related to the MPA (selection of species, size and length of the different areas in the MPA, etc.) which does not depend on external agents. Also the data related to ghost gears and species abundance has been easy to find and the quality of the data is acceptable as it has been collected for several years by research teams specialized in monitoring from the University of Barcelona. In addition to this, for some specific information related to water conditions or invasive species population, the data depends on public administration agencies, so it has been relatively easy to obtain it. Moreover, from the experts on Cartography and GIS of Generalitat de Catalunya, we have got the maps and the calculations needed for the different habitats. All this data was gathered during the first months of the data collection process, between June and July of 2020.

On the other side, the information related to socioeconomic aspects (job dependence, local income, fishing activities, etc.) of the MPA, has been very difficult to obtain, as there isn't much data available by public administration. So, it has been collected from the private sector (data gathering specialised companies) and also directly from the user's groups (fishers' guilds, fishing material shops, diving centres, etc.) through direct consultation and through the stakeholder questionnaires. This last task has been the most difficult of all the processes due to the restrictions imposed by the Covid-19 situation, which did not allow face-to-face meetings, and also due to the summer period conditions; it is high season for tourist, diving, nautical and fishing sectors, so they are too busy to attend the requirements from the project. This process started in July 2020 and couldn't finish until the beginning of October 2020. Regarding the users' groups, it was only possible to have one interviewed per each group of users (MPA manager, president of the main fishers' guild, technician of a recreational fishing association, president of a nautical activities company, tourism public agencies director and a diving centre).

A complete list of the data sources per indicator is available in the document "Raw data MPACap de Creus.xlsx".

4.5.1 VULNERABILITY ASSESSMENT COSTS

The work plan implemented for the execution of the Vulnerability Assessment involved different actions that are specified in table 6. The scope of this section is to have a picture on the costs and other resources that was required to complete each task of the vulnerability assessment activity.

Table 6. Costs and time invested for the implementation of the Vulnerability Assessment.

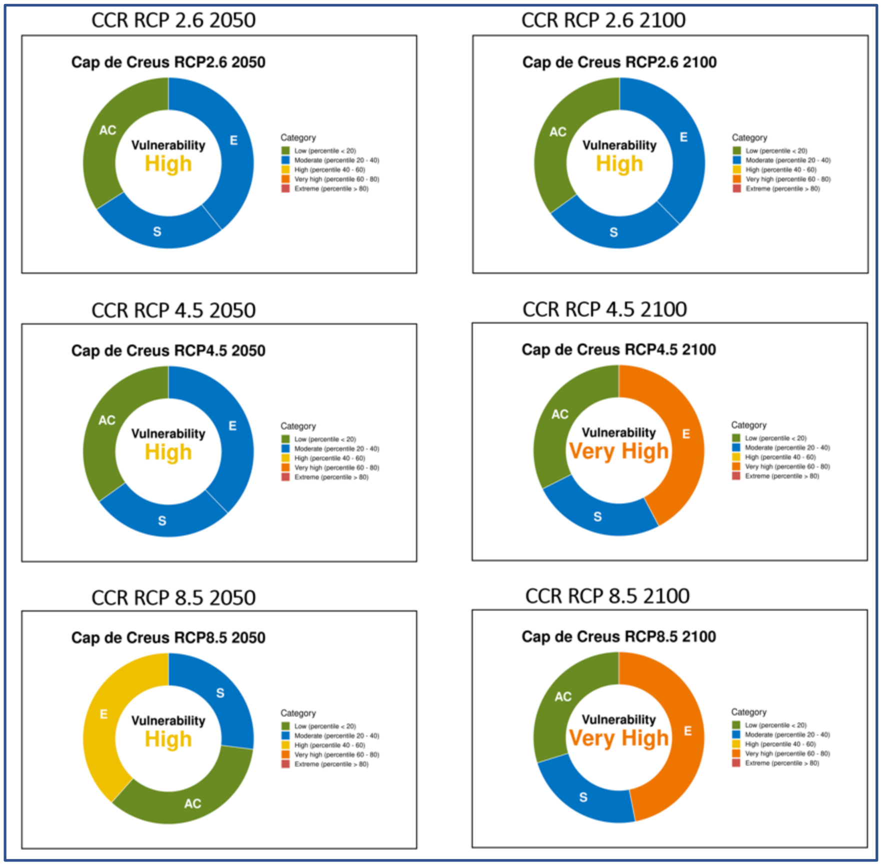
FTE = Full Time Equivalent (i.e. full days of work)										OTHER DATA RETRIEVED FROM DELIVERABLE 3.3.6		
Vulnerability Assessment												
MPA	Cost for FTE for MPA office staff (euro)	who implemented the VA (MPA/EXT)	MPA staff - preparation time in FTE (full days of work)	MPA staff - Interview time in FTE (full days of work)	MPA staff - data collection time in FTE (full days of work)	MPA staff - report writing in FTE (full days of work)	MPA staff total time in FTE (fulls days of work)	External contractor (euro)	Total costs in deliverable 3.3.6	Number of stakeholders interviewed for the assessment	Number of staff involved	Number of species, habitats and user groups assessed
Cap de Creus	203	EXT + MPA	1,5	3	9	7	20,5	6008,31	10169,55	5	4	Species: 15 Habitats: 4 Users: 5

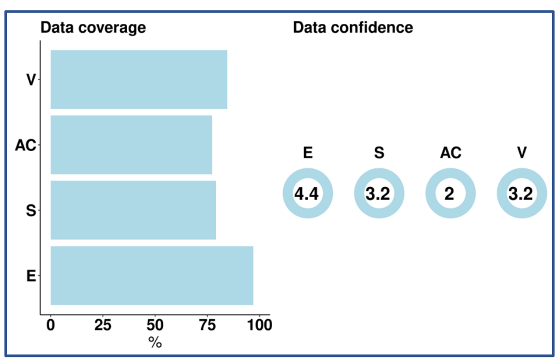
Four people were involved in the vulnerability assessment activity counting both MPA staff and external contractors. Since the implementation of the activity didn't involve any costs related to travelling or materials, the total costs refer to the salary of the MPA staff involved, plus the costs of hiring the external contractor. The data collection and writing the report were the activities that required a higher number of days, respectively 9 and 7 days, while the preparation and the interview activities required less time, 1,5 and 3 days. In total 5 stakeholders were interview during the process. It is important to stress that even though all the persons spent time working in the activity, not all people dedicated the same number of hours.

5 Results

Figure 9. Socio-ecological vulnerability index of the Cap de Creus MPA.

Quality indices included for both 2050 and 2100 are the same



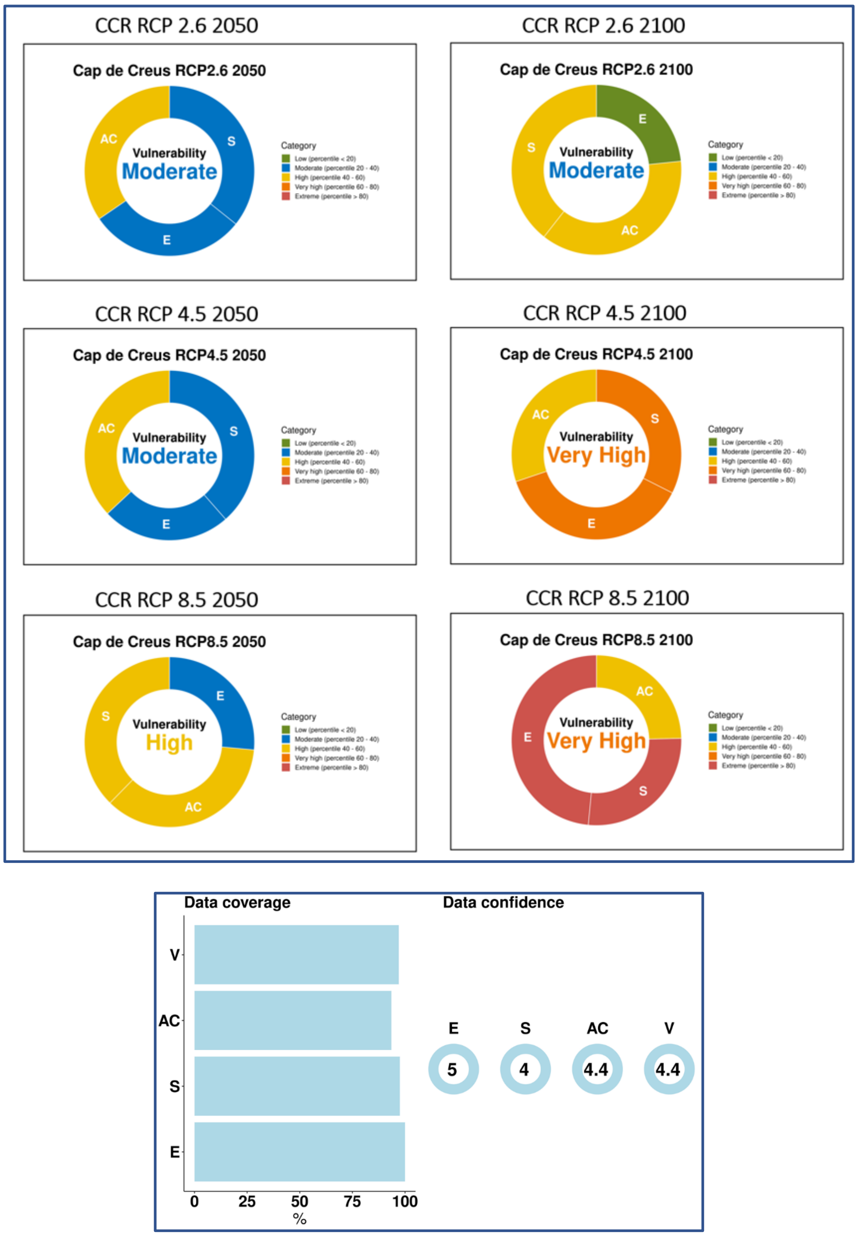


The socio-ecological vulnerability index combines three dimensions: ecological vulnerability (the degree to which the ecological side of the system is susceptible to the impacts of climate change), social sensitivity (degree to which the social aspect of the system could be damaged), and adaptive capacity (the social capacity to reduce its disturbance by taking actions to enhance resilience).

Cap de Creus's Socio-ecological vulnerability will be high in all scenarios reaching a very high vulnerability in the intermediate and worst scenarios of 2100. Social sensitivity is moderate while the social adaptive capacity is low resulting in high and very high levels of vulnerability.

The data coverage that provides the information on the amount of data measured in the assessment is around 80% in total. It is necessary to improve adaptive capacity data and social sensitivity data. Generally, the confidence level of the data used to measure the indicators is medium with a score of 3,2 and a low score for adaptive capacity.

Figure 10. Ecological vulnerability index results.



The ecological vulnerability index combines three dimensions: ecological sensitivity (the degree to which the ecosystem could be damaged), exposure (direct impacts of the changing climate on the system), and adaptive capacity (capacity to reduce its disturbance by taking actions to enhance resilience).

Cap de Creus Ecological vulnerability is mainly moderate but it will increase over time specifically in RCPs 4.5 and 8.5 2100, the intermediate and worst scenarios. Ecological sensitivity is increasing over time reaching an extreme value while the ecological adaptive capacity is high.

The data coverage that provides the information on the amount of data measured in the assessment is close to 100% in total. Generally, the confidence level of the data used to measure the indicators is high with a score of 4,45.

Figure 11. Key indicators contributing to vulnerability
(RCP 8.5 for 2100)

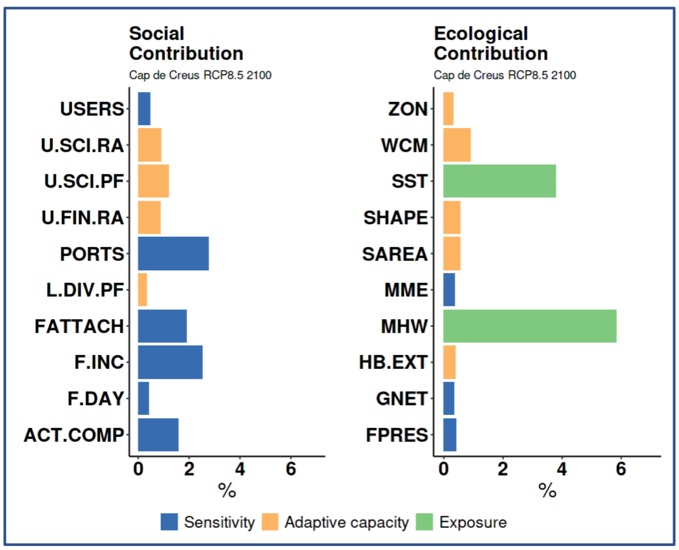
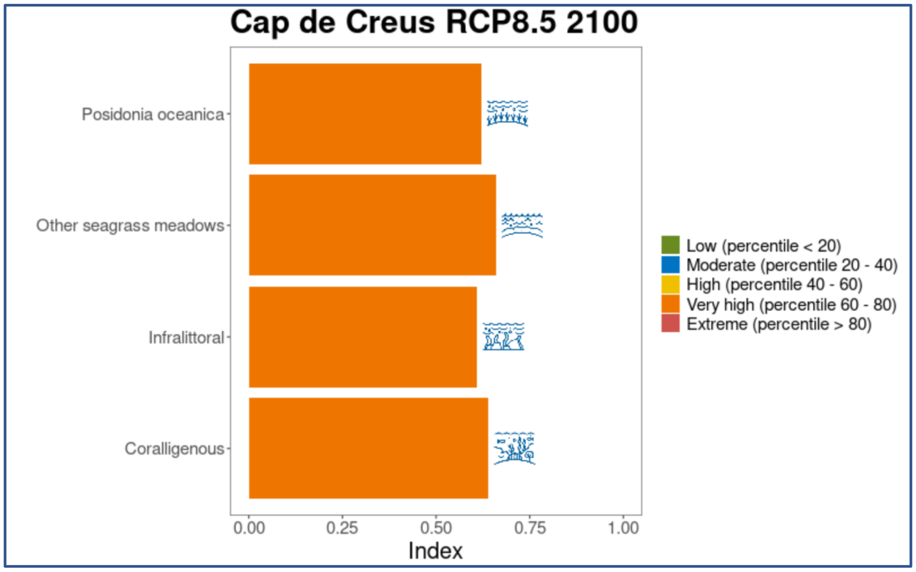


Figure 11 shows the top 10 social and ecological indicators of Exposure (green), Sensitivity (blue) and Adaptive Capacity (orange) that most contribute to the socio-ecological vulnerability of the marine area.

Regarding the key indicators contributing to vulnerability, in the scenario RCP 8.5 for the year 2100, exposure indicators: “marine heatwaves” and “SST increase” are the two which will contribute the most to vulnerability, which is logical because they are the indicators related to climate impacts.

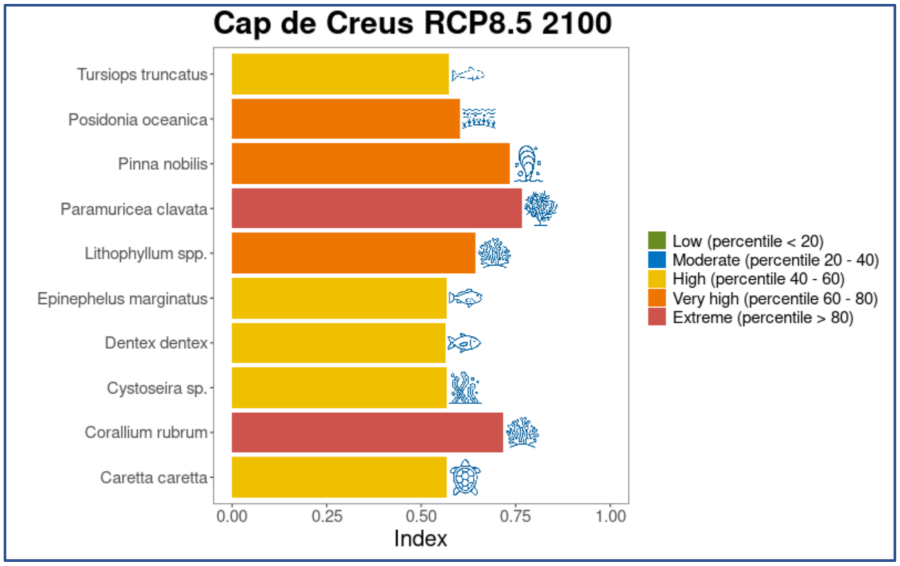
Figure 12. Habitat vulnerability index
(RCP 8.5 for 2100)



Cap de Creus's Habitats vulnerability is going to increase when considering the RCPs 4.5 and 8.5 2100, the intermediate and worst scenarios. *Coralligenous* and *Posidonia oceanica* are the two habitats that are going to experience the worse level of vulnerability in the intermediate scenario. Nevertheless, in scenarios RCPs 4.5 and 8.5 2100 all habitat vulnerabilities will be either high and very high.

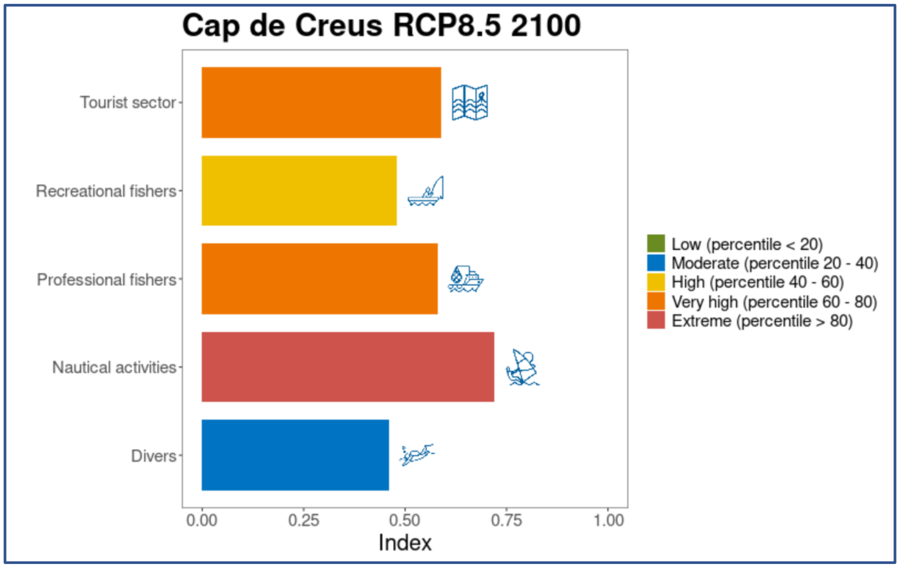
Figure 13. Species Vulnerability Index*

(RCP 8.5 for 2100)



Generally, Cap de Creus Species vulnerability is going to increase over time specifically in RCPs 4.5 and 8.5 2100, the intermediate and worst scenarios. Out of 15 species analysed, most of them will experience a high vulnerability, while *Corallium rubrum* and *Paramuricea clavata*'s vulnerability will reach an extreme level. In scenarios RCPs 4.5 and 8.5 2100 all species vulnerabilities will be either high, very high or extreme except for the *Octopus vulgaris* and the invasive species *Caulerpa* and *Fistularia commersonii*.

Figure 14. Users Vulnerability Index*
(RCP 8.5 for 2100)



Cap de Creus User's vulnerability is quite different between sectors, however it is generally increasing in scenarios with RCPs 4.5 and 8.5 2100. The diving sector is the least vulnerable group while the nautical sector is the most vulnerable reaching an extreme vulnerability. Very high vulnerability is going to be experienced by professional fishers and the tourist sector.

6 Discussion and Findings

In general, once the methodology has been implemented, the results showed in the graphs for the Cap de Creus MPA are of concern, as the values for socio-ecological vulnerability remain high or very high in all the cases. This result shows that there is an urgent hazard to face right now. So, it highlights the need to take action soon.

For the calculation of the socio-ecological vulnerability index (Figure 9) we have an acceptable quality of the data, although it could be better if the monitoring system of the MPA would cover more indicators, especially those related to socioeconomic aspects. Data coverage is good, being the ecological vulnerability the strongest dimension with 5 years of data series, and the adaptive capacity the weakest part with any periodicity. The results for this index show vulnerabilities between high (0,45) to very high (0,52) for all the scenarios, being the ecological vulnerability the highest value in all of them, which means that there is an emergency scenario of climate hazard right now. So, it's necessary to take measures as soon as possible in order to avoid a worse situation in the near future, especially regarding the improvement of the ecological vulnerability of the ecosystem. This dimension needs a long-term recovery, as it is mostly related to the natural conditions of the environment, but some of its indicators, as fishing conditions, ghost nets, recreational activities or illegal activities as poaching are susceptible to be changed in the short-term and depend directly on the MPA's management. Moreover, some other indicators as resources monitoring, surveillance or habitat and species restoration, are also important objectives to improve in Cap de Creus MPA. In this sense, it must be considered that the management body of Cap de Creus MPA, being a Natural Park, has a certain ability to make decisions quickly, one of which is the PRUG (as it is mentioned in the introduction).

The ecological vulnerability index (Figure 10) is calculated with a better quality of the data, as data coverage is close to 100%. The results for this index show vulnerabilities between moderate (0,43) and high (0,45) in most of the cases, being the ecological sensitivity the highest value, but the scenario RCP 8.5 for the year 2100 has a value of 0,63, which means a very high index of vulnerability. This is due mainly to the exposure dimension, which includes Sea Surface Temperature increase and Marine Heatwaves, both direct effects of climate change. As said before, the management of the MPA can improve the indicators of ecological vulnerability in the short-term with rapid and direct actions on the management and activities developed in the area in order to face these future climate effects.

Regarding the key indicators contributing to vulnerability in the scenario RCP 8.5 for the year 2100 (Figure 11), "marine heatwaves", alongside "SST increase" and "ports mooring fees (all users except tourist)" are the main ones with scores between 0,028 and 0,058. Is a must to pay attention to the indicators related to users, as it depends on the direct management of the MPA authorities and public administration.

The Habitat Vulnerability Index (Figure 12) shows a very high vulnerability in the scenario RCP 8.5 for the year 2100 for all kind of habitats present at Cap de Creus MPA, with scores between 0,61 (infralittoral) and 0,66 (other seagrass meadows). Similar values are found for the Species Vulnerability Index (Figure 13), with more than 0,7 for *Paramuricea clavata* and *Corallium rubrum*. These extreme vulnerabilities must be interpreted as a warning to pay attention to these species and habitats and keep on improving the monitoring systems and the conservation measures.

Users Vulnerability Index (Figure 14) evidences again that nautical activities are the most affected, showing an extreme vulnerability (0,72) in the scenario RCP 8.5 for the year 2100, which highlights the need action quickly. There is an increasing number of nautical users in the Park and, therefore, in addition to the data that show that nautical activities are the most vulnerable, it is observed that the impact on the environment of so much nautical activity creates a significant negative synergy added to climate change, on marine habitats and ecosystems. So, nautical activity is a sector that must be better regulated in Cap de Creus MPA. Professional fishers and the tourist sector are also of concern with a very high vulnerability. On the other hand, diving shows a moderate vulnerability (0,46). Regarding recreational fishing, with a high vulnerability, it must be borne in mind that has a special controversy among users and it has to be better supervised.

A total of 89 indicators have been selected to feed the tool. In view of the results, once the tool has been adjusted, we can guess that the results of the vulnerabilities throughout this century in general can be adjusted to reality. This main conclusion can be reached if we compare the results obtained with the existing literature on climate impacts on Mediterranean marine ecosystems, as well as with the results obtained once the standardized monitoring protocols have been implemented within the framework of the project.

However, this study has also detected the urgent need to carry out continuous monitoring over time, beyond the life of the project, and with the maximum number of possible indicators to feed the tool, in order to be able to refine the results and make them more robust and adjusted to reality. In fact, this monitoring is already being carried out in terms of environmental monitoring -species and habitats- and therefore, the trends of the populations of species and habitats in the Park are known. Maybe it would be interesting to adjust some indicators. This will allow us to have a good knowledge base to be able to plan the actions to be implemented in the MPAs so that they can adapt to the impacts of climate change, especially considering that there is evidence that the Mediterranean Sea is it is warming at a faster rate than the rest of the oceans (Medec, 2020).

7 Conclusion

The results of the analysis reveal that there is an imminent hazard to face, and highlight the need to start working on climate change issues from now, which is consistent with the fact that Catalonia has declared the “climate emergency” in all its territory in 2019. The final results of the socio-ecological vulnerability assessment in Cap de Creus MPA indicate that the ecosystem has a very high vulnerability in the face of climate change future impacts, in scenarios with RCP 4.5 and 8.5 at 2100.

First, the analysis has considered the ecological aspects of the protected area, selecting specific marine habitats and species. The results show that it is necessary to pay attention to the ecosystems management from now on. Improving protection and restoration plans for these specific habitats and species is a must that should be included within the priorities of the MPA.

The other aspect analysed is the vulnerability of the MPA users. The results have underlined an extreme vulnerability value for nautical activities, which seems to be the most affected group of users. Behind them, professional fishers and the tourist sector are the next groups at risk, with a very high vulnerability. There is an urgent necessity of management regarding nautical activities. More control and surveillance is needed in order to avoid illegal activities as well as a management plan which includes the nautical activities as an important indicator to evaluate the vulnerability of the MPA. In this sense, the Master Plan for the Use and Management of the marine environment of the Cap de Creus Natural Park (PRUG) is currently being drafted and all these issues will be taken into account.

Regarding the key vulnerability factors, apart from exposure indicators as the most important ones, it is necessary to emphasize the role of the users in general. On one side, its implication in citizen science is low and they don't feel engaged with the decisions related to the MPA at all, although it is necessary to take into account the involvement of local entities in environmental awareness and environmental education tasks, as well as the role of local and municipal administrations in these latter issues. By the other side, the collaboration among users within a sector is also a weakness that should be improved within the MPA management board possibilities. The governance model of the MPA has to facilitate public engagement in the decision-making processes as a key factor in order to assure the participation of all the users' groups.

To conduct better vulnerability assessments in the future, it is necessary to have the quality of the data as good as possible. In that sense, it is necessary to broaden the monitoring system in order to get more data, especially those regarding the socioeconomic indicators, and also to increase the frequency of the monitoring. Nevertheless, it should be considered that this methodology of Vulnerability Assessment is a new one, and it should be tested in different MPAs, conditions, periods, etc. to keep improving it.

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9 Annexes

1.1 ANNEX 1

Table 9.1A List of indicators of ecological exposure and ecological sensitivity. The table below indicates the "code" used to identify each indicator and for the Vulnerability index calculation, the "indicator name" and a description of the indicator.

Code	Indicator Label	Description
SST	SST Increase	Quantitative change in sea surface temperature projected under climate change scenarios, relative to baseline period
MHW	Marine heatwaves	Quantitative change in the frequency and duration of MHW in the projected scenarios, relative to a baseline period.
POL	Water ecological status	Measures the quality elements for the classification of ecological surface water status in coastal waters based on the EU Water Framework Directive 2000/60/EC, page 49 considering the *Physico -chemical quality elements* of the section "1.2.4 Definition for high, good, moderate ecological status in coastal waters".
SAL	Salinity	Measures the annual mean water salinity in the MPA.
DEOX	Deoxygenation	Measures the annual average level of oxygen of in the MPA.
PDEN	Coastal population density	Measures the density of people living in the adjacent areas of the MPA. Can include population density within a MPA-10Km radius OR, the population density of the city council where the MPA is located.
POA.PF	Poaching professional fishers	Measures the level of poaching event and/or illegal fishing estimated inside the MPA waters done by professional fishers.
POA.RF	Poaching recreational fishers	Measures the level of poaching event and/or illegal fishing estimated inside the MPA waters done by recreational fishers.
GNET	Ghost nets	Evaluates the impact of lost fishing gears that are found at the sea bottom.
FGEAR.PF	Fishing gear restrictions professional fishers	Evaluates the type of fishing gears that are used for professional fishing activities in MPA waters. Following a classification system for marine protected areas and gears from the literature, we will assign a value for the indicator, based on the gears used.

FGEAR.RF	Fishing gear restrictions recreational fishers	Evaluates the type of fishing gears that are used for recreational fishing activities in MPA waters. Following a classification system for marine protected areas and gears from the literature, we will assign a value for the indicator, based on the gears used.
FPRES	Fishing pressure	measures the amount of tons of the species most caught in the MPA.
IMP	Nautical activities impact	Measures the level of nautical activities, quantifying the annual number of boats in the area of the MPA where nautical activities are allowed.
HB.SEN.SST	Habitat sensitivity to SST	Measures the level of sensitivity of the habitat to the effects of climate change (SST) in the MPA using a qualitative scale based on expert assessment.
HB.SEN.MHW	Habitat sensitivity to MHW	Measures the level of sensitivity of the habitat to the effects of climate change (MHW) in the MPA using a qualitative scale based on expert assessment.
HB.BENT	Condition of the benthic community	Measures the current condition of the benthic community in the habitat, using a qualitative scale based on expert assessment and the monitoring experience in the project.
END.SP	Presence of endangered species	Number of endangered and threatened species present in the MPA based on IUCN, SPAMI and Habitat Directive Annex 4 lists.
HB.INV	Invasive species presence	Evaluates the diversity of invasive species present in the MPA at the habitats level.
RISK.INV	Risk of invasive species	Measure the risk of 9 new coming invasive species in the MPA area in the next 30 years due to the favorable water conditions, considering the most optimistic and most pessimistic scenario (RCP 2.6 and 8.5 by 2050).
WARMW	Warm water species	Measure the presence and expansion of warm-water species over temperate and cold-water species in the MPA water.
MME	Mass mortality events	Measure the range of abrupt events that cause the sudden mortality of a great number of marine organisms due to alteration of the water conditions The indicator measures both the MME experiences by a species considered in the assessment as well as the total number of MME occurred in the MPA in the last 5 years.

SP.SEN.SST	Species sensitivity to climate hazard (SST)	Measure the level of sensitivity of the species to climate hazards (SST increase) in the MPA using a qualitative scale based on expert assessment.
SP.SEN.MHW	Species sensitivity to climate hazard (MHW)	Measure the level of sensitivity of the species to climate hazards (MHW) in the MPA using a qualitative scale based on expert assessment.
SP.DIS	Species distribution	Total area of distribution of *a species* in the Mediterranean basin. If the studied species is restricted to a narrow area, it results more sensitive to abrupt changes compared to species that have broader distributional ranges. In fact these species have a higher chance to come back and repopulate an area if there is a perturbation in the system.
MME.SP	Species Mass mortality Events	Measures the number of MME events experienced by the species considered in the Vulnerability Assessment in the last 5 years
SP.POP	Species population size	Measures abundance of individuals of a *species* in the MPA
SP.ST	Species conservation status	Measure if the species considered in the assessment is still present and is healthy in the area and the likelihood of the group to become extinct in the near future.
END.ST	Endangered status	Measures if the *species* considered in the MPA assessment is an endangered or threatened species based on IUCN, SPAMI and Habitat Directive Annex 4 lists.
INV.ST	Invasive species status	Measure if the species considered in the assessment is an invasive species.

Table 9.1B List of indicators of Ecological adaptive capacity. The table below indicates the "code" used to identify each indicator and for the Vulnerability index calculation, the "indicator name" and a description of the indicator.

code	Indicator Label	Description
DIVHB	Habitat diversity within the MPA	Number of different habitats inside de MPA, using the MPA-ENGAGE habitat list (coralligenous, Posidonia oceanica meadows, other seagrass meadows, caves, infralittoral rocky bottoms with macroalgae).
SHAPE	MPA shape	Shape of the MPA prioritizing simple shapes (squares or rectangles), compared to elongated or convoluted ones, to minimize edge effects.
SAREA	Fully protected area	Size of the area in the MPA that is fully protected. Implementing fully protected areas at least twice the size of target species' home ranges would ensure ecological benefits at the local population scale. The area should be greater than twice the size of the largest individual home range assessed. A spatial area of 3.6km2 should be considered as a minimal threshold that has been seen to increase the density of local populations of the species in MPAs.
HB.COM	Habitat complexity	Level of complexity of each habitat present in the MPA (coralligenous, Posidonia oceanica meadows, other seagrass meadows, caves, infralittoral rocky bottoms with macroalgae) using a qualitative scale based on expert assessment.
HB.EXT	Habitat extension	Current area of each habitat type inside the MPA.
HB.CON	Habitat connectivity	Distance between a habitat type inside the MPA and the nearest patch outside the MPA.
HB.DEPTH	Habitat depth	Maximum depth of each of the MPA habitat types. (Deeper habitats are considered to have higher recovery potential as they are less disrupted).
HB.MON	Habitat monitoring	Measure if the habitat considered in the assessment is part of a monitoring program.
SP.DISP	Larval dispersal capacity	Evaluates the larval dispersion ability of a species.
SP.HB	Species habitat specificity	Recovery potential of a species based on its habitat restriction. Habitat generalist species are more resilient as they are present in different habitat types. Habitat specialist species are more sensitive as they are restricted to one habitat.
FECUN	Fecundity potential	Measures the reproductive capacity of a stock species considering the length of first maturity.

SP.SIZE	Species size distribution	Measure the occurrence of large individuals which indicate a more even size-spectra and an increase in fecundity using the underwater visual census technique.
SP.MON	Species monitoring	Measure if the species considered in the assessment is part of a monitoring program.
PGOV	Polycentric Governance	Measure whether the MPA has established a multiple governing bodies approach that interact to make and enforce rules to improve the MPA functionality (Central government, Local institutions, Local NGOs, Local users groups, etc.).
BUDG	Budget capacity	Status of the annual economic budget that the MPA has access to, for the management of the MPA. A higher budget capacity increases the opportunity to meet a more effective management of the MPA.
STAFF	Staff capacity	Measures the current status of the staff employed that is actively working in the MPA. A higher and adequate staff capacity and presence increases the opportunity to meet a more effective management of the MPA.
M.PLAN.PF	Presence of a management plan for professional fishers	Presence of a formal or informal arrangement between MPA management body and professional fishermen which details the agreed objectives for the fishery and specifies the management rules and regulations which apply to it.
M.PLAN.RA	Presence of a management plan for recreational activities	Measure the presence of a formal or informal arrangement between MPA management body and the different recreational activities performed in the MPA. The arrangement details the agreed objectives for the recreational activities and specifies the management rules and regulations which apply to them.
ENFOR	Capacity of enforcement	Measures the enforcement capacity and consistency that the MPA has to improve its effectiveness through legislations and regulations.
MON.NSP	Species monitoring number	Evaluates the number of species monitored by the MPA management and specify which of the species considered in the assessment are under a monitoring program. The higher the number of vulnerable species and/or habitats that are monitored the higher their recovery potential.
MON.NHB	Habitat monitoring number	Evaluates the number of habitats monitored by the MPA management and specify which of the habitats considered in the assessment are under a monitoring program. The habitat in the following list (coralligenous, Posidonia oceanica meadows, other seagrass meadows, caves, infralittoral rocky bottoms with macroalgae) are the habitats considered in the assessment.

SUR	Surveillance	Level of surveillance in the MPA to control poaching and illegal activities such as boat accessing or diving in restricted areas, poaching, collecting endangered species, etc.
HB.REST	Habitat restoration	Measures the existence of restoration actions in the MPA targeting at specific habitats of the following list (coralligenous, Posidonia oceanica meadows, other seagrass meadows, caves, infralittoral rocky bottoms with macroalgae).
SP.REST	Species restoration	Measures the existence of restoration actions in the MPA targeting specific species.
ZON	MPA Zoning	MPAs are divided in different levels based on access and activities restrictions where zone A represents the zone of very strict protection, no-take/no-use zone. The greater the % of area of full protection the higher the potential of recovery of the area.
WCM	Water column monitoring	Measures if the MPA is implementing activities to monitor physical and chemical properties of the water column (including temperature, pH, Salinity, Oxygen, etc.).
SCADV	Level of climate scientific advice	Measures if the MPA is working in collaboration or is regularly receiving training by climate scientist regarding the effects of climate change in MPAs.

Table 9.1C List of indicators of Social sensitivity. The table below indicates the "code" used to identify each indicator and for the Vulnerability index calculation, the "indicator name" and a description of the indicator.

code	Indicator Label	Description
AF.AREA	Available fishing area	Measures the percentage of the MPA area where fishing is allowed.
SP.DEP	Species catch dependence	Level of occurrence of endemic species from which fishers have been depending historically within the last 10 years.
F.DAY	Fishing days	Loss in fishing days due to the extreme weather conditions within the last 10 years.
F.DEN	Fishers density	Measure the density of fishermen that can harvest in allowed fishing areas of the MPA.
FATTACH	Attachment to occupation	Measures the eventuality of giving up fishing for another job in the face of the increasing climate change impacts.
F.INC	Local income dependence on fishing	Measure the percentage of income in the region that comes from artisanal fisheries activities carried out within the country EEZ .
LOC.F.DEP	Local job dependence on fisheries	Measure the percentage of population in the region that works in the fishery sector over the total working population.
ACT.DAYS	Working days	Loss in working days due to the extreme weather conditions within the last 10 years.
ACT.DEP	Local job dependence	Measure the percentage of population in the region that works in the sector considered over the total working population.
ACT.COMP	Number of companies	Measures the number of companies of the sector working in the MPA.
ACT.AREA	Activity area	Percentage or area in the MPA area where the user's activity is allowed For diving sector: Diving sites in the MPA where diving is allowed.
USERS	Users number	Measures the average number of users of the sector visiting the MPA per year, in the last 5 years

RF.SPDEP	Species dependence (Recreational fishers)	Level of change in the last 5 years in the occurrence of species from which recreational fishers are targeting.
PORTS	Ports access (all users except tourist)	Measure the number of ports that stakeholders can use for their activities
P.FEES	Ports mooring fees (all users except tourist)	Evaluates the average boat mooring fees that users pay for their activities.

Table 9.1D List of indicators of Social Adaptive capacity. The table below indicates the "code" used to identify each indicator and for the Vulnerability index calculation, the "indicator name" and a description of the indicator.

code	Indicator Label	Description
U.SUBS	Substitute areas outside the MPA (all users groups)	Measures if the activities performed inside the MPA can also be performed in the surrounding areas, maintaining the quality/satisfaction level of the activity.
U.TARG	Number of targeted species	Number of species that are considered most important to an activity inside the MPA. Most important species for fishing (i.e. represent 80% of the catch), for tourism (flagship species), for diving, etc.
L.DIV	livelihood diversity	Level of professional fishermen that have additional sources of income from secondary jobs or activities.
F.GDIV.PF	Gear diversity professional fishers	Amount of gears that fishers in the area have license for to fishing within the MPA.
F.GDIV.RA	Gear diversity recreational fishers	Amount of gears that fishers in the area have license for to fishing within the MPA.
U.COLW	Collaboration within sectors	Measures the level of cooperation of users within a sector.
U.COLA	Collaboration among sectors	Measures the level of cooperation of users across sectors.
U.PART	Participation in decision making	Measures the level of users' participation in the decision-making of the MPA management such as monitoring activities, regulation enforcement, training activities,
U.TRUST	Level of trust	Measures the users level of trust towards local leaders in the MPA management.
TRANS	Transparency	Measures the level of access to the information about the MPA management decision-making process.
U.CONFW	User conflict within sectors	Measures the perception about increasing conflicts within the users of a sector due to the impacts of climate change.

U.CONFA	User conflict among sectors	Measures the perception about increasing conflicts, due to the impacts of climate change, between a user group and the other user groups within the MPA.
ACCO	Accountability	Measure how easy is for users to identify to whom they should report if any issues arises in relation to the management of the MPA.
U.SCI	Users engagement in citizen science	Measures the level of integration of users in scientific activities to advance the MPA scientific research and increase the users' understanding of science (e.g monitoring programs).
U.FIN	Financial resources of users	Measure if users can have access to credit from formal institutions or other mean (i.e. Insurances, bank loans, subsidies, etc.).
U.RISK.SST	Risk attitudes in user groups to SST	Measures the user risk perception level regarding sea surface temperature increase (SST).
U.RISK.MHW	Risk attitudes in user groups to MHW	Measures the user risk perception level regarding the occurrence of marine heatwaves (MHW).
U.INC	Fishers income	Measures the income status of fishers for the activities performed in the MPA waters compared to their cost of living.
U.JUST	Access to justice	Measure the effectiveness of a mechanism that addresses disagreements or conflicts that may arise between user groups and the MPA management.

1.2 ANNEX 2

Table 9.2. Structure of the Index. List of indicators defining the degree of resolution of measurement of each indicator expressed in the columns MPAs, habitats (HB), species (SP), climate scenario (SC), professional fishers (PF) and recreational activities (RA). Color legend, blue: MPA, green: habitat, red: species, purple: climate scenario, orange: professional fishers, brown: recreational activities.

D	C	indicator	ABREV.	MPA	HB	SP	SC	PF	RA
EXRE	SST threat	SST increase	SST	0			0		
	MHW threat	Marine heatwaves	MHW	0			0		

EC CA SE VI	water cond.	Water ecological status	POL	O					
		Salinity	SAL	O					
		Deoxygenation	DEOX	O					
	human pressure	Coastal population density	PDEN	O					
		Poaching Professional fishers	POA.PF	O				O	
		Poaching Recreational fishers	POA.RF	O					O
		Ghost nets	GNET	O					
		Fishing gear restrictions professional fishers	FGEAR.PF	O				O	
		Fishing gear restrictions recreational fishers	FGEAR.RF	O					O
		Fishing pressure	FPRES	O					
		Nautical activities impact	IMP	O					
	habitat integrity	Habitat sensitivity to SST	HB.SEN.SST		O		O		
		Habitat sensitivity to MHW	HB.SEN.MHW		O		O		
		Condition of the benthic community	HB.BENT	O	O				

		Presence of endangered species	END.SP	O	O				
		Invasive species presence	HB.INV	O	O				
		Risk of invasive species	RISK.INV	O			O		
		Warm-water species	WARMW	O					
		Mass mortality events	MME	O					
	species integrity	Species sensitivity to SST hazard	SP.SEN.SST			O	O		
		Species sensitivity to MHW	SP.SEN.MHW			O	O		
		Species distribution	SP.DIS			O			
		Species mass mortality events	MME.SP	O		O			
		Species conservation status	SP.ST	O		O			
		Endangered status	END.ST			O			
		Invasive status	INV.ST			O			
		Species population size	SP.POP	O		O			
ECO ADA CAP	Habitat redundancy	Habitat diversity within the MPA	DIVHB	O					
		MPA shape	SHAPE	O					
		Fully protected area	SAREA	O					

	Habitat Recovery potential	Habitat complexity	HB.COM	O	O					
		Habitat extension	HB.EXT	O	O					
		Habitat connectivity	HB.CON	O	O					
		Habitat depth	HB.DEPTH	O	O					
		Habitat monitoring	HB.MON	O	O					
	Species Recovery potential	Larval dispersal capacity	SP.DISP			O				
		Species habitat specificity	SP.HB			O				
		Fecundity potential	FECUN			O				
		Species size distribution	SP.SIZE	O		O				
		Species monitoring	SP.MON	O		O				
	Effectiveness	Polycentric Governance	PGOV	O						
		Budget capacity	BUDG	O						
		Staff capacity	STAFF	O						
		Presence of a management plan with professional fishers	M.PLAN.PF	O					O	
		Presence of a management plan for recreational activities	M.PLAN.RA	O						O
		Capacity of enforcement	ENFOR	O						

	Conservation efforts	Species monitoring number	MON.NSP	0		0			
		Habitats monitoring number	MON.NHB	0	0				
		Surveillance	SUR	0					
		Habitat restoration	HB.REST	0					
		Species restoration	SP.REST	0					
		MPA zoning	ZON	0					
	Adaptive management	Water column monitoring	WCM	0					
		Level of climate scientific advice	SCADV	0					
SO SE VI	Professional fishing dependency	Available fishing area	AF.AREA	0				0	
		Species catch dependence	SP.DEP	0				0	
	Professional fishing effort	Fishing days	F.DAY	0				0	
		Fishers density	F.DEN	0				0	
	Professional fishing local dependence	Attachment to occupation	FATTACH	0				0	
		Local income dependence on fishing	F.INC	0				0	
		Local job dependence on fisheries	LOC.F.DEP	0				0	

	Recreational activities employment	Working days	ACT.DAYS	0					0
		Local job dependence	ACT.DEP	0					0
		Number of companies	ACT.COMP	0					0
	Recreational Activities ecosystem	Activity area	ACT.AREA	0					0
		Users number	USERS	0					0
		Species dependence	RF.SPDEP	0					0
	Recreational Activities facilities	Ports access	PORTS	0					0
		Ports mooring fees	P.FEES	0					0
	Flexibility	Substitute areas outside the MPA	U.SUBS	0				0	0
		Number of targeted species	U.TARG	0				0	0
		Livelihood diversity	L.DIV	0				0	
		Gear diversity	F.GDIV	0				0	0
	Social Organization	Users collaboration within a sector	U.COLW	0				0	0
		Users collaboration among sectors	U.COLA	0				0	0
		Level of participation of users in decision making	U.PART	0				0	0
SO AD E CA Y		Level of trust	U.TRUST	0				0	0

		Transparency	TRANS	0				0	0
		Users conflict within a sector	U.CONFW	0				0	0
		Users conflict among sectors	U.CONFA	0				0	0
		Accountability	ACCO	0				0	0
	Learning	Users engagement in citizen science	U.SCI	0				0	0
	Assets	Financial resources of users	U.FIN	0				0	0
	Agency and cultural aspects	Risk attitudes to SST in user groups	U.RISK.SST	0			0	0	0
		Risk attitudes to MHW in user groups	U.RISK.MHW	0			0	0	0
		Income of fishers	U.INC	0				0	
		Access to justice	U.JUST	0				0	0

1.3 ANNEX 3 – INDEX CALCULATIONS

The Social-Ecological Vulnerability index presented within this framework has an overall social-ecological vulnerability value per MPA, but is also calculated at different scales (A-H). Here is a summary of all the Index outputs that are generated:

A. HABITATS VULNERABILITY INDEX

Calculation of the Vulnerability Index to the impacts of climate change on 5 specific habitats. The habitats selected in the current framework are: Posidonia oceanica meadows, coralligenous, infralittoral rocky bottoms dominated by macroalgae, other seagrass meadows and caves. Habitats vulnerability is calculated for each MPA.

B. SPECIES VULNERABILITY INDEX

Calculation of the Vulnerability Index to the impacts of climate change on selected species. In the current framework species are selected from a multi-category list which considered endangered species, climate impacted species, target fishing species, monitored species, keystone species and flagship species. Between 14 and 24 species have been selected and analysed in the different assessments. Species vulnerability is calculated for each MPA.

C. PROFESSIONAL FISHERS' VULNERABILITY INDEX

Calculation of the Vulnerability Index to the impacts of climate change on Professional fishers. We split this user group as many indicators are specific to professional fishers. The vulnerability is calculated at the MPA level.

D. RECREATIONAL ACTIVITIES VULNERABILITY INDEX

Calculation of the Vulnerability Index to the impacts of climate change on the groups of recreational activities. These groups include four different activities: recreational fishing, diving, nautical and the tourist sectors (U=4). The recreational activities vulnerability is calculated at the MPA level.

E. ECOLOGICAL VULNERABILITY INDEX

Calculation of the Ecological Vulnerability Index. This index just accounts for the ecological indicators and therefore on the ecological aspect of the MPA.

F. SOCIAL ECOLOGICAL VULNERABILITY INDEX

This is the composite social-ecological vulnerability index at the MPA level. The calculation considers both the social and ecological dimensions of the MPA vulnerability.

All the indicators presented in the calculation listed in Table 8 have been carefully defined and measured as explained in tables 9.2A, 9.2B, 10 and 10B (Annex9.2).

Below a general section describing the equations used for the aggregation of dimensions, components and indicators is presented.

General equations

In this section of the methodology we describe how to aggregate the indicators, components and dimensions to build up the Social-Ecological Vulnerability Index at the MPA level. Each indicator is coded following the acronyms used in Table 8.

Vulnerability Index

The vulnerability index (VI_i) is calculated by aggregating Exposure (E_i) with sensitivity (SEN_i) and subtracting the adaptive capacity (AC_i). In order to keep the Vulnerability Index value between 0 and 1 we are including in the following equation its normalization by using the following formula:

(b)
$$VI_i = \frac{(E_i + SEN_i - AC_i) - (-1)}{2 - (-1)}$$

Dimensions

In general, each of these dimensions d , for MPA i, is calculated as the weighted linear combination of components, m . Each of the dimension is calculated as follows:

(c)
$$Dimension_{d,i} = \sum_{m}^{M} \omega_m * component_{mi}$$

where $component_{mi}$ denotes the individual component in dimension d for MPA i, M denotes the total number of components in dimension d , and ω_m denotes the individual weight associated to each individual component m *in dimension* d.

Components

In general , individual components belonging to a dimension d , for MPA i, are calculated as a weighted average of a linear combination of indicators, denoted by x. Each of the components is calculated as follows:

(d)
$$Component_{mdi} = \sum_{c}^{C} \omega_c * x_{cmdi}$$

where x_{cmdi} denotes the indicator c for component m, and dimension d at MPA i. C denotes the total number of indicators in the corresponding component and dimension at MPA i. The weight ω_c denotes the individual weight associated to each individual indicator c *in component* m *and dimension* d.

Indicators

In some instances, indicators measure a single attribute of the MPA, such as the case of pollution, thus x_i denotes the value of the indicator x at MPA i. In some other cases, an indicator measures the attributes of several habitats, species, or user groups (see section 3-4-5-6). When more than one habitat, species, or user group exits at a single MPA, we calculate the indicator at the MPA level as follows:

(e)
$$x_{cmdi} = \sum_{k}^{K} \omega_k * x_{k,cmdi}.$$

When several species exits in the MPA i, x_{cmdi} denotes the values of the indicator c, for component m, dimension d, and species k. $\omega_k = 1/K$ are the individual weights for each of the species, and K denotes the total number of species in the MPA i. We replace the subscript k, for j and u when an MPA indicator is calculated by aggregating values for habitats and user groups respectively.

HABITAT VULNERABILITY INDEX (A)

Habitat vulnerability ($HB.VULN_{i,j}$) is an index output that is calculated by adding *Exposure* (E_i) to *Habitat sensitivity* ($HB.SEN_{j,i}$) and subtracting *Habitat adaptive capacity* ($HB.AC_{j,i}$), giving equal weights to each dimension but ensuring that the values range from 0 to 1.The Index is provided at the habitat (*j*) and MPA level (*i*), that is:

(1)
$$HB.VULN_{i,j} = \frac{\left(E_i + HB.SEN_{j,i} - HB.AC_{j,i}\right) - (-1)}{2 - (-1)}$$

where *Exposure,* E_i, varies per MPA (*i*) level and is calculated adding the components SST threat ($SSTthreat_i$) and MHW threat ($MHWthreat_i$). and it is found following the equation:

(2)
$$E_i = \omega_m * SSTthreat_i + \omega_m * MHWthreat_i$$

where ω_m denotes the individual weight associated to each component. The component *SST threat* ($SSTthreat_i$) corresponds to the single indicator sea surface temperature increase (SST_i) , thus $SSTthreat_i = SST_i$ and the component MHW threat ($MHWthreat_i$) corresponds to the single indicator marine heatwaves (MHW_i) that is $MHWthreat_i = MHW_i$.

The *Exposure equation* (2) will be the same for the calculation of the indices of habitat, species, professional fishers, recreational activities and ecological vulnerability (A, B, C, D and E from list of index outputs). Note that exposure varies per climate scenario (RCP and timeframe).

Habitat sensitivity ($HB.SEN_{j,i}$) correspond to the only component of *Habitat Integrity* ($HI_{j,i}$) and it varies per MPA (*i*) and per habitat type (*j*) for *J* habitats, thus $HB.SEN_{j,i} = HI_{i,i}$.

Habitat Integrity ($HI_{j,i}$) is calculated considering the following indicators: habitat sensitivity to sea surface temperature $\left(HB.SEN.SST_{j,i}\right)$, habitat sensitivity to marine heatwaves $\left(HB.SEN.MHW_{j,i}\right)$, condition of the benthic community ($HB.BENT_{j,i}$), presence of endangered species ($END.SP_i$), invasive species presence $\left(HB.INV_{j,i}\right)$, risk of invasive species ($RISK.INV_i$), warm water species ($WARMW_i$) and mass mortality events (MME_i). The indicators used for the calculation of ($HI_{j,i}$) vary per MPA (*i*) and per habitat type (*j*) for *J* habitats except: species ($END.SP_i$), invasive species presence ($HB.INV_i$), risk of invasive species ($RISK.INV_i$), warm water species ($WARMW_i$) and mass mortality (MME_i) . Habitat Integrity at the habitat level, is calculated as follows:

– (3)

$$HI_{j,i} = \omega_c * HB.SEN.SST_{j,i} + \omega_c * \ HB.SEN.MHW_{j,i} + \omega_c * HB.BENT_{j,i} + \omega_c * END.SP_i + \omega_c * HB.INV_i + \omega_c * RISK.INV_i + \omega_c * WARMW_i + \ + \omega_c * MME_i,$$

where $\omega_c = 1/C$ is the weight of each indicator in habitat sensitivity and C is the total number of indicators that enter the calculation. At the habitat level, *habitat integrity* for MPA i (HI_{ij}) incorporates C=8 indicators. Note that each MPA can have a set of habitats, so *J* varies with *i*.

Habitat Adaptive Capacity *(HB.AC)* correspond to the only component of *Habitat recovery potential* $(HRP_{j,i})$and it varies per MPA (*i*) and per habitat type (*j*) for *J* habitats, , thus $HB.AC_{j,i} = HRP_{i,i}$.

Habitat recovery potential ($HRP_{j,i}$) is calculated considering the indicators habitat complexity ($HB.COM_{j,i}$), habitat extension ($HB.EXT_{j,i}$), habitat connectivity ($HB.CON_{j,i}$), habitat depth ($HB.DEPTH_{j,i}$) and habitat monitoring ($HB.MON_{j,i}$). The indicators used for the calculation of *HB.AC* vary per MPA (*i*) and per habitat type (*j*) for *J* habitats. Habitat Adaptive Capacity is calculated as follows:

(4)

$$H_{j,i} \quad \omega_c * HB.COM_{j,i} + \omega_c * HB.EXT_{j,i} + \omega_c * HB.CON_{j,i} + \omega_c * HB.DEPTH_{j,i} + \omega_c * HB.MON_{j,i},$$

where $\omega_c = 1/C$ is the weight of each indicator in habitat sensitivity.

At the habitat level, *Habitat recovery potential* ($HRP_{j,i}$) incorporates C=5 indicators. Note that each MPA can have a set of habitats so *J* varies with *i*.

SPECIES VULNERABILITY INDEX (B)

Species vulnerability ($SP.VULN_{k,i}$) is an index output that is calculated adding Exposure (E_i) and *Species sensitivity* ($SP.SEN_{k,i}$) and subtracting *Species adaptive capacity* ($SP.AC_{k,i}$) giving equal weights to each dimension but ensuring that the values range from 0 to 1. The Index is provided at the species (k) and MPA level (i) and it is calculated following the equation:

(5)

$$SP.VULN_{i,j} = \frac{\left(E_i + SP.SEN_{k,i} - \ SP.AC_{k,i}\right) - (-1)}{2 - (-1)}$$

Species sensitivity *($SP.SEN_{k,i}$)* correspond to the only component of *Species Integrity* ($SI_{k,i}$) and it varies per MPA (*i*) and per species type (k) for *k* species , thus $SP.SEN_{k,i} = SI_{k,i}$.

Species Integrity $(SI_{k,i})$ is calculated considering the indicators species sensitivity to sea surface temperature $(SP.SEN.SST_{j,i})$, species sensitivity to marine heatwaves $(SP.SEN.MHW_{j,i})$, species distribution $(SP.DIS_{k,i})$, species mass mortality events $(MME.SP_{k,i})$, species conservation status $(SP.ST_{k,i})$, endangered status $(END.ST_{k,i})$, invasive status $(INV.ST_{k,i})$ and species population size $(SP.POP_{k,i})$. The indicators used for the calculation of $SI_{k,i}$ vary per MPA (i) and per species (k) for k species, except $SP.DIS_k, END.ST_k, and\ INV.ST_k$ that only vary per species (k). Species Integrity is calculated as follow:

$$S\,[illegible]\,\omega_c * SP.SEN.SST_{k,i} + \omega_c * SP.SEN.MHW_{k,i} + \omega_c * SP.DIS_k + \omega_c * MME.SP_{k,i} + \omega_c * SP.ST_{k,i} + \omega_c * END.ST_k + \omega_c * INV.ST_k + \omega_c * SP.POP_{k,i}, \quad (6)$$

where $\omega_c = 1/C$ is the weight of each indicator. At the species level, *Species Integrity* (SI_i) incorporates C=8 indicators. Note that each MPA can have a set of species, so K varies with *i*.

Species Adaptive Capacity $(SP.AC_{i,k})$ correspond to the only component of *Species recovery potential* $(SRP_{k,i})$ and it varies per MPA (i) and per species type (k) for k species , thus $SP.AC_{k,i} = SRP_{k,i}$.

For the calculation of *Species recovery potential* $(SRP_{k,i})$ denotes an individual species recovery potential for each of the species found in MPA(i). It is calculated considering the indicators: larval dispersal capacity $(SP.DISP_k)$, species habitat specificity $(SP.HB_k)$, fecundity potential $(FECUN_k)$, species size distribution $(SP.SIZE_{k,i})$ and species monitoring $(SP.MON_{k,i})$. The indicators used for the calculation of *SP.AC* vary per MPA (i) and per species (k) for k species, except $SP.DISP_k, SP.HB_k, and\ FECUN_k$ that only vary per species (k). Species recovery potential at the species level, is calculated as follows:

$$SRP_{k,i} = \omega_c * SP.DISP_k + \omega_c * SP.HB_k + \omega_c * FECUN_k + \omega_c * SP.SIZE_{k,i} + \omega_c * SP.MON_{k,i}, \quad (7)$$

where $\omega_c = 1/C$ is the weight of each indicator in the species adaptive capacity calculation. At the species level, *Species recovery potential* $(SRP_{k,i})$incorporates C=5 indicators.

PROFESSIONAL FISHERS' VULNERABILITY INDEX (C)

Professional fishers' Vulnerability $(PF.VULN_i)$ is an index output that is calculated adding *Exposure* (E_i) wit[illegible]essional fishers sensitivity* $(PF.SEN_i)$ and subtracting *Professional fishers adaptive capacity* (*SI*[illegible] (8) giving equal weights to each dimension but ensuring that the values range from 0 to 1 following the equation:

$$PF.VULN_i = \frac{(E_i + PF.SEN_i - PF.AC_i) - (-1)}{2 - (-1)}$$

Professional fishers sensitivity $(PF.SEN_i)$ varies per MPA (i), and it is calculated adding the components professional fishers dependence $(F.DEP_i)$, professional fishers effort $(F.EFF_i)$, professional fishers local dependence $(LOC.F.DEP_i)$, following the equation:

(9)

$$PF.SEN_i = \omega_m * F.DEP_i + \omega_m * F.EFF_i + \omega_m * LOCAL.DEP_i + \omega_m$$

where ω_m denotes the individual weight associated to each component.

Professional fishers' dependence $(F.DEP_i)$ for professional fishers in MPA (i) is calculated aggregating the indicators: available fishing area $(AF.AREA_i)$ and species catch dependence $(SP.DEP_i)$ as follows:

(10)

$$F.DEP_i = \omega_c * AF.AREA_i + \omega_c * SP.DEP_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *professional fishers dependence* where *C*=2 indicators.

Professional fishers' effort $(F.EFF_i)$ for professional fishers in MPA (i) is calculated aggregating the indicators: fishing days $(F.DAY_i)$ and fishers density $(F.DEN_i)$ as follows:

(11)

$$F.EFF_i = \omega_c * F.DAY_i + \omega_c * F.DEN_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *professional fishers effort* where *C*=2 indicators.

Professional fishing local dependence $(LOCAL.DEP_i)$ for MPA (i) is calculated aggregating indicators: attachment to occupation $(FATTACH_i)$, local income dependence on fishing $(F.INC_i)$, and local job dependence on fisheries $(LOC.F.DEP_i)$ and it is done following the equation:

(12)

$$LOCAL.DEP_i = \omega_c * FATTACH_i + \omega_c * F.INC_i + \omega_c * LOC.F.DEP_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *professional fishing local dependence* where C=3 indicators.

Professional fishers Adaptive Capacity $(PF.AC_i)$ for professional fishers varies per MPA (i), and it is calculated adding the components flexibility $(FLEX_i)$, social organization $(S.ORG_i)$, learning (LRN_i), assets $(ASTS_i)$, and agency and socio cultural aspects$(AG.CUL_i)$ and it is found following the equation:

(13)

$$PF.AC_i = \omega_m * FLEX_i + \omega_m * S.ORG_i + \omega_m * LRN_i + \omega_m * ASTS_i + \omega_m * AG.CUL_i$$

where ω_m denotes the individual weight associated to each component.

Flexibility $(FLEX_i)$ for professional fishers in MPA (i) is calculated summing up the indicators: substitute areas outside the MPA$(U.SUBS_i)$, number of targeted species $(U.TARG_i)$, livelihood diversity $(L.DIV_i)$, gear diversity $(F.GDIV_i)$ and it is found following the equation:

(14)

$$FLEX_i = \omega_c * U.SUBS_i + \omega_c * U.TARG_i + \omega_c * L.DIV_i + \omega_c * F.GDIV_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *Flexibility* where C=4 indicators.

Social Organization $(S.ORG_i)$ for professional fishers in MPA (i) is calculated aggregating the indicators: users collaboration within a sector $(U.COLW_i)$, users collaboration among sectors $(U.COLA_i)$, level of participation of users in decision making $(U.PART_i)$, level of trust $(U.TRUST_i)$, transparency $(U.TRANS_i)$, accountability $(U.ACCO_i)$, users conflict within a sector $(U.CONFW_i)$, and users conflict among sectors $(U.CONFA_i)$ and it is described in the following equation:

(15)

$$S = \omega_c * U.COLW_i + \omega_c * U.COLA_i + \omega_c * U.PART_i + \omega_c * U.TRUST_i + \omega_c * U.TRANS_i + \omega_c * U.ACCO_i + \omega_c * U.CONFW_i + \omega_c * U.CONFA_i$$

Where $\omega_c = 1/C$ is the weight of each indicator in *Social Organization* where C=8 indicators

Learning (LRN_i) for professional fishers in for MPA (i), corresponds to the single indicator of users engagement in citizen science ($U.SCI_i$) and it is found following the equation:

(16)

$$LRN_i = \omega_c * U.SCI_i$$

where ω_c denotes the weight associated to the indicator $U.SCI_i$ which equals to 1.

Assets ($ASTS_i$) for professional fishers in MPA (i), corresponds to the single indicator of financial resources of users ($U.FIN_i$) and it is found following the equation:

(17)

$$ASTS_i = \omega_c * U.FIN_i$$

where ω_c denotes the weight associated to the indicator $U.SCI_{u,i}$ which equals to 1.

Agency and socio cultural aspects ($AG.CUL_i$) for professional fishers in MPA (i), is calculated aggregating the indicators risk attitudes to SST in user groups ($U.RISK.SST_i$), risk attitudes to MHW in user groups($U.RISK.MHW_i$), income of fishers ($U.JUST_i$), and access to justice ($U.JUST_i$) and it is found following the equation:

(18)

$$AG.CUL_{u,i} = \omega_c * U.RISK.SST_i + \omega_c * U.RISK.MHW_i + \omega_c * U.INC_i + \omega_c * U.JUST_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *Agency and socio cultural aspects* where C=4 indicators.

RECREATIONAL ACTIVITIES VULNERABILITY INDEX (D)

Recreational activities *groups* include four different activities: recreational fishing, diving, nautical and tourist sectors (U=4).

For each group the Vulnerability Index is calculated adding *Exposure* (E_i) to the *Recreational activity sensitivity* ($RA.SEN_{u,i}$) and subtracting the *Recreational activity adaptive capacity* ($RA.AC_{u,i}$) giving equal weights to each dimension but ensuring that the values range from 0 to 1. Hence, the Index is provided at the user (u) and MPA level (i) and it is found following the equation:

(19)

$$RA.VULN_{u,i} = \frac{\left(E_i + RA.SEN_{u,i} - RA.AC_{u,i}\right) - (-1)}{2 - (-1)}$$

Recreational activity sensitivity ($RA.SEN_{u,i}$) is provided at the MPA (i) level and it is calculated adding the components: recreational activity employment ($RA.EMP_i$), recreational activity ecosystem ($RA.EC_i$) and recreational activities facilities ($RA.FAC_i$) and it is found following the equation:

$$RA.SEN_{u,i} = \omega_m * RA.EMP_i + \omega_m * RA.EC_{u,i} + \omega_m * RA.FAC_{u,i}$$

(20)

wh … denotes the individual weight associated to each component.

Recreational activities employment ($RA.EMP_{u,i}$) is a components at the MPA (i) level, and also by recreational activities user types (u), for U total users. It is calculated by aggregating the indicators: working days ($ACT.DAYS_i$), local job dependence ($ACT.DEP_i$), and number of companies ($ACT.COMP_i$), and it is calculated following the equation:

(21)

$$A.EMP_{u,i} = \omega_c * ACT.DAYS_{u,i} + \omega_c * ACT.DEP_{u,i} + \omega_c * ACT.COMP_{u,i}$$

where $\omega_c = 1/C$ is the weight of each indicator in *recreational activities employment* where C=3 indicators.

Recreational activities ecosystem ($RA.EC_{u,i}$) for MPA (i) per recreational activity user type (u) for U total users, is calculated aggregating the indicators activity area ($ACT.AREA$), users number ($USERS_{u,i}$) and species dependence ($RF.SPDEP_i$) as follow:

(22)

$$RA.EC_{u,i} = \omega_c * ACT.AREA_{u,i} + \omega_c * USERS_{u,i} + \omega_c * RF.SPDEP_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *Recreational activity ecosystem* where C=3 indicators. Note that the indicator $RF.SPDEP_i$ applies only to Recreational fishers.

Recreational activity facilities $(RA.FAC_{u,i})$ for MPA (i) per recreational activity user type (u) for U total users it is calculated aggregating the indicators ports access $(PORTS_{u,i})$ and ports mooring fees $(P.FEES_{u,i})$ as follow:

$$RA.FAC_i = \omega_u * PORTS_{u,i} + \omega_u * P.FEES_{u,i} \quad (23)$$

where $\omega_c = 1/C$ is the weight of each indicator in *Recreational activity facilities* where C=3 indicators. Note that $PORTS_{i,u}$ *and* $P.FEES_{i,u}$ are only applied to Diving, Nautical and recreational fishers activities.

Recreational activity adaptive capacity $(RA.AC_{u,i})$is provided at the MPA (i) level per recreational activity user type (u) for U total users and it is calculated adding the components flexibility $(FLEX_i)$, social organization $(S.ORG_i)$, learning (LRN_i), assets $(ASTS_i)$, and agency and socio cultural aspects$(AG.CUL_i)$ and it is found following the equation:

$$(24) \quad \text{l}.AC_{u,i} = \omega_m * FLEX_{u,i} + \omega_m * S.ORG_{u,i} + \omega_m * LRN_{u,i} + \omega_m * ASTS_{u,i} + \omega_m * AG.CUL_{u,i}$$

where ω_m denotes the individual weight associated to each component.

Flexibility $(FLEX_{u,i})$ for MPA (i) per user type (u) for U total users, is calculated summing up the indicators: substitute areas outside the MPA$(U.SUBS_{u,i})$, number of targeted species $(U.TARG_{u,i})$, gear diversity $(F.GDIV_{u,i})$ and it is found following the equation:

$$(25) \quad FLEX_{u,i} = \omega_c * U.SUBS_{u,i} + \omega_c * U.TARG_{u,i} + \omega_c * F.GDIV_{u,i}$$

where $\omega_c = 1/C$ is the weight of each indicator in *Flexibility* where C=3 indicators

Note that $F.GDIV_{u,i}$applies to Recreational fishers.

Social Organization $(S.ORG_{u,i})$ for MPA (i) per user type (u) for U total users, is calculated aggregating the indicators: users collaboration within a sector $(U.COLW_{u,i})$, users collaboration among sectors $(U.COLA_{u,i})$, level of participation of users in decision making $(U.PART_i)$, level of trust $(U.TRUST_{u,i})$, transparency ($U.TRANS_{u,i}$), accountability ($U.ACCO_{u,i}$), users conflict within a sector ($U.CONFW_{u,i}$), and users conflict among sectors ($U.CONFA_{u,i}$) and it is described in the following equation:

(26)
$$RG_{u,i} = \omega_c * U.COLW_{u,i} + \omega_c * U.COLA_{u,i} + \omega_c * U.PART_i + \omega_c * U.TRUST_{u,i} + \omega_c * U.TRANS_{u,i} + \omega_c * U.ACCO_{u,i} + \omega_c * U.CONFW_{u,i} + \omega_c * U.CONFA_{u,i}$$

Where $\omega_c = 1/C$ is the weight of each indicator in *Social Organization* where C=8 indicators

Learning ($LRN_{u,i}$) for MPA (i) per user type (u) for U total users, corresponds to the single indicator of users engagement in citizen science ($U.SCI_{u,i}$) and it is found following the equation:

(27)
$$LRN_{u,i} = \omega_c * U.SCI_{u,i}$$

where ω_c denotes the weight associated to the indicator $U.SCI_{u,i}$ which equals to 1.

Assets ($ASTS_{u,i}$) for MPA (i) per user type (u) for U total users, corresponds to the single indicator of financial resources of users ($U.FIN_{u,i}$) and it is found following the equation:

(28)
$$ASTS_{u,i} = \omega_c * U.FIN_{u,i}$$

where ω_c denotes the weight associated to the indicator $U.SCI_{u,i}$ which equals to 1.

Agency and socio cultural aspects ($AG.CUL_{u,i}$) for MPA (i) per user type (u) for U total users, is calculated aggregating the indicators risk attitudes to SST in user groups ($U.RISK.SST_{u,i}$), risk attitudes to MHW in user groups($U.RISK.MHW_{u,i}$), income of fishers ($U.JUST_i$), and access to justice ($U.JUST_{u,i}$) and it is found following the equation:

(29)
$$AG.CUL_{u,i} = \omega_c * U.RISK.SST_{u,i} + \omega_c * U.RISK.MHW_{u,i} + \omega_c * U.JUST_{u,i}$$

where $\omega_c = 1/C$ is the weight of each indicator in *Agency and socio cultural aspects* where C=3 indicators.

ECOLOGICAL VULNERABILITY INDEX (E)

The ecological vulnerability index of MPA (i), $V.ECOL_i$ is calculated by summing Exposure, (E_i)and Ecological sensitivity ($EC.SEN_i$) and subtracting Ecological Adaptive Capacity ($EC.AC_i$) giving equal weights to each dimension but ensuring that the values range from 0 to 1 following the equation:

(30)
$$V.ECOL_i = \frac{(E_i + EC.SEN_i - EC.AC_i) - (-1)}{2 - (-1)}$$

where *Exposure* E_i is provided in equation 2 section A.

Ecological Sensitivity

Ecological sensitivity ($EC.SEN_i$) is provided at the MPA (*i*) level and it is calculated adding the components water conditions (WC_i), human pressure (HP_i), species integrity (SI_i) and habitat integrity (HI_i), and it is calculated following the equation:

(31)
$$EC.SEN_i = \omega_m * WC_i + \omega_m * HP_i + \omega_m * SI_i + \omega_m * HI_i$$

where ω_m denotes the individual weight associated to each component.

Water conditions (WC_i) for MPA *i* is calculated summing water ecological status (POL_i), salinity (SAL_i) and deoxygenation ($DEOX_i$). The indicators used for the calculation of *Water conditions* vary per MPA (i), and it is calculated:

$$WC_i = \omega_c * POL_i + \omega_c * SAL_i + \omega_c * DEOX_i,$$
(32)

where $\omega_i = 1/C$ is the weight of each indicator in *Water condition* where C=3 indicators.

Human pressure (HP_i) for MPA *i* is calculated aggregating coastal population density ($PDEN_i$), poaching for professional fishers ($POA.PF_i$), poaching for recreational fishers ($POA.RF_i$), ghost nets ($GNET_i$), fishing gear restrictions for professional fishers ($FGEAR.PF_i$), fishing gear restrictions for recreational fishers

($FGEAR.RF_i$), fishing pressure ($FPRES_i$) and nautical activities impact (IMP_i). The indicators used for the calculation of *Human pressure* vary per MPA (i), and it is calculated as:

(33)

$$H \quad {}_c * PDEN_i + \omega_c * POA.PF_i + \omega_c * POA.RF_i + \omega_c * GNET_i + \omega_c * FGEAR.PF_i + \omega_c * FGEAR.RF_c + \omega_c * FPRES_i + \omega_c * IMP_i,$$

Where $\omega_c = 1/C$ is the weight of each indicator in Human pressure where C=8 indicators.

Species Integrity (SI_i) for MPA i is calculated by aggregating the *Species Integrity* for the species considered in the assessment within the MPA excluding the invasive species (from section B). Thus, the equation to calculate the *Species integrity* component for an MPA i is given by:

(34)

$$SI_i = \sum_k \omega_k * SI_{k,i},$$

where each species weight, ω_k, equals $1/k$ and k is the total number of species in MPA i.

List of invasive species included in the Vulnerability assessment: *Siganus luridus, Siganus rivulatus, Fistularia commersonii, Caulerpa cylindracea, Pterois miles, Pomatomus saltatrix, Balistes capriscus and Sphyraena sphyraena*

Habitat integrity for MPA i is calculated summing up the *Habitat Integrity* of all habitats within the MPA (from section A). Thus, the equation to calculate the *Habitat integrity* component for an MPA i is given by

(35)

$$HI_i = \sum_j \omega_j * HI_{j,i},$$

where each habitat weight, ω_j, equals $1/J$ and J is the total number of habitats in MPA i.

Ecological adaptive capacity

Ecological Adaptive Capacity ($EC.AC_i$) is provided at the MPA (i) level and it is calculated aggregating habitat redundancy(HR_i), habitat recovery potential (HRP_i), species recovery potential (SRP_i), effectiveness (EF_i), conservation (CE_i) and adaptive management (AM_i) and it is calculated following the equation:

(36) $$EC.AC_i = \omega_m * HR_i + \omega_m * HRP_i + \omega_m * SRP_i + \omega_m * EF_i + \omega_m * CE_i + \omega_m * AM_i$$

where ω_m denotes the individual weight associated to each component.

Habitat redundancy (HR_i) for MPA i is calculated aggregating habitat the indicators: diversity within the MPA ($DIVHB_i$), MPA shape ($SHAPE_i$) and fully protected area ($SAREA_i$). The indicators used for the calculation of *Habitat redundancy* vary per MPA (i), and it is given by the equation:

(37)
$$HR_i = \omega_c * DIVHB_i + \omega_c * SHAPE_i + \omega_c * SAREA_i,$$

where $\omega_i = 1/C$ is the weight of each indicator in *Habitat redundancy* where C=3 indicators

Habitat recovery potential (HRP_i) for MPA i is calculated summing up the *Habitat recovery potential* of all habitats within the MPA (from section A). Thus, the equation to calculate the *Habitat integrity* component for an MPA i is given by

(38)

$$HRP_i = \sum_j \omega_j * HRP_{j,i},$$

where each habitat weight, ω_j, equals $1/J$ and J is the total number of habitats in MPA i.

Species recovery potential (SRP_i) for MPA i is calculated summing up the *Species recovery potential* of all species within the MPA except invasive species (from section B). Thus, the equation to calculate the *Species integrity* component for an MPA i is given by:

(39)

$$SRP_i = \sum_k \quad \omega_k * SRP_{k,i},$$

where each species weight, ω_k, equals $1/k$ and k is the total number of species in MPA i.

Effectiveness (EF_i) for MPA i is calculated aggregating the indicators: polycentric governance ($PGOV_i$), budget capacity ($BUDG_i$), staff capacity ($STAFF_i$), presence of management plan with professional fishers ($M.PLAN.PF_i$), presence of management plan with recreational fishers ($M.PLAN.RF_i$), and capacity of enforcement ($ENFOR_i$). The indicators used for the calculation of *Effectiveness* vary per MPA (i), and the calculation is given by the equation:

(40)

$$EF_i \quad PGOV_i + \omega_c * BUDG_i + \omega_c * STAFF_i + \omega_c * M.PLAN.PF_i + \omega_c * M.PLAN.RA_i + \omega_c * ENFOR_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *Effectiveness* where C=6 indicators

Conservation (CE_i) for MPA i is calculated aggregating the indicators: species monitoring number ($MON.NSP_i$), habitat monitoring number($MON.NHB_i$), surveillance (SUR_i), habitat restoration ($HB.REST_i$), species restoration ($SP.REST_i$), and MPA zoning (ZON_i). The indicators used for the calculation of *Conservation* vary per MPA (i), as given by the equation:

(41)

$$CE_i = \omega_c * MON.NSP_i + \omega_c * MON.NHB_i + \omega_c * SUR_i + \omega_c * HB.REST_i + \omega_c * SP.REST_i + \omega_c * ZON_i$$

where $\omega_c = 1/C$ is the weight of each indicator in *Conservation* where C=6 indicators

Adaptive management (AM_i) for MPA i is calculated summing water column monitoring (WCM_i) and level of climate scientific advice ($SCADV_i$) and these 2 indicators vary per MPA (i). The *Adaptive management* component is given by the equation:

$$AM_i = \omega_c * WCM_i + \omega_c * SCADV_i$$

(42)

where $\omega_c = 1/C$ is the weight of each indicator in *Adaptive management* where C=2 indicators.

SOCIAL-ECOLOGICAL VULNERABILITY INDEX (F)

The social-ecological vulnerability index of MPA i, $V_{Soc.Ecol}$, is calculated by adding Ecological Vulnerability ($V.ECOL_i$) to social sensitivity ($S.SEN_i$), and subtracting social adaptive capacity, $S.AC_i$ giving equal weights to each dimension but ensuring that the values range from 0 to 1. Thus, we can write the Social-ecological vulnerability index for MPA i as:

(43)

$$V_{Soc.Ecol} = \frac{(V.ECOL_i + S.SEN_i - S.AC_i) - (-1)}{2 - (-1)}$$

where $V.ECOL_i$ is explained in the equation 30 section D.

In the assessment we considered a total of 5 user groups (U): professional fishers, recreational fishers, diving, nautical and tourist sector. These last 4 user groups (i.e. excluding professional fishers) are combined into a mayor group named: *recreational activities* group. In the next sections the component of Social sensitivity and social adaptive capacity will be calculated separately for *Professional fishers* and the *Recreational activities* group. The main reason for this is that the indicators for professional fishers' sensitivity are different than the indicators for other user groups, which are almost the same across groups.

Social sensitivity

Social sensitivity ($S.SEN_i$) is provided at the MPA (i) level and it is calculated adding the components: professional fishers dependence ($F.DEP_i$), professional fishers effort ($F.EFF_i$), professional fishers local dependence ($LOC.F.DEP_i$), recreational activity employment ($RA.EMP_i$), recreational activity ecosystem ($RA.EC_i$) and recreational activities facilities ($RA.FAC_i$) and it is found following the equation:

(44)

$$S.SEN_i = \omega_m * F.DEP_i + \omega_m * F.EFF_i + \omega_m * LOCAL.DEP_i + \omega_m * RA.EMP_i + \omega_m * RA.EC_i + \omega_m * RA.FAC_i$$

where ω_m denotes the individual weight associated to each component.

Professional fishers' dependence ($F.DEP_i$), *Professional fishers' effort* ($F.EFF_i$) and

Professional fishing local dependence ($LOCAL.DEP_i$) for MPA (i) are calculated in the same way as expressed respectively in the equations 10, 11 and 12 of section C.

Recreational activities employment ($RA.EMP_i$) for MPA (i) is calculated aggregating the *Recreational activities employment* ($RA.EMP_{u,i}$) for all recreational users within the MPA (section D). Thus, the equation to calculate the *Recreational activities employment* component for an MPA i is given by

(45)

$$RA.EMP_i = \sum_u \omega_u * RA.EMP_{u,i},$$

where each user weight, ω_u, equals $1/U$ and U is the total number of users in MPA i.

Recreational activities ecosystem ($RA.EC_i$) for MPA (i) is calculated aggregating the *Recreational activities ecosystem* ($RA.EC_{u,i}$) of all recreational users within the MPA(section D). Thus, the equation to calculate the *Recreational activities ecosystem* component for an MPA i is given by:

(46)

$$RA.EC_i = \sum_u \omega_u * RA.EC_{u,i},$$

where each user weight, ω_u, equals $1/U$ and U is the total number of users in MPA i.

Recreational activities facilities ($RA.FAC_i$) for MPA (i) it is calculated aggregating the *Recreational activities ecosystem* ($RA.FAC_{u,i}$) of all recreational users within the MPA (sectionD). Thus, the equation to calculate the *Recreational activities facilities* component for an MPA i is given by:

(47)

$$RA.FAC_i = \sum_u \omega_u * RA.FAC_{u,i},$$

where each user weight, ω_u, equals $1/U$ and U is the total number of users in MPA i.

1.3.1 SOCIAL ADAPTIVE CAPACITY

Social adaptive capacity ($S.AC_i$) is provided at the MPA (i) level and it is calculated adding the components flexibility ($FLEX_i$), social organization ($S.ORG_i$), learning (LRN_i), assets ($ASTS_i$), and agency and socio cultural aspects($AG.CUL_i$) and it is found following the equation:

$$S.AC_i = \omega_m * FLEX_i + \omega_m * S.ORG_i + \omega_m * LRN_i + \omega_m * ASTS_i + \omega_m * AG.CUL_i \quad (48)$$

where ω_m denotes the individual weight associated to each component.

Flexibility ($FLEX_i$) for MPA (i) is calculated summing up the *Flexibility* ($FLEX_{u,i}$) of all users (professional fishers and recreational activities from section C&D) within the MPA. Thus, the equation to calculate the *Flexibility* component for an MPA i is given by

$$FLEX_i = \sum_u \omega_u * FLEX_{u,i}, \quad (49)$$

where $\omega_u = 1/2$ for professional fishers and for recreational activities users $\omega_u = \left(\frac{1}{2}\right) * \frac{1}{n}$ where n indicates the total number of recreational activities in MPA (i) so that $\sum_u \omega_u = 1$. This set of weights places reflect a relative higher importance to the professional fisher's indicator compared to the recreational activities users' indicator.

Social Organization ($S.ORG_i$) for MPA (i) it is calculated summing up the *Social organization* ($S.ORG_{u,i}$)of all users (professional fishers and recreational activities section C&D)within the MPA. Thus, the equation to calculate the *Social organization* component for an MPA i is given by

$$S.ORG_i = \sum_u \omega_u * S.ORG_{u,i}, \quad (50)$$

where $\omega_u = 1/2$ for professional fishers and for recreational activities users $\omega_u = \left(\frac{1}{2}\right) * \frac{1}{n}$ where n indicates the total number of recreational activities in MPA (i) and where $\sum_u \quad \omega_u = 1$.

Learning $(LRN_{u,i})$ for MPA (i) it is calculated summing up *Learning* $(LRN_{u,i})$ of all users (professional fishers and recreational activities from section C&D)within the MPA. Thus, the equation to calculate the *Learning* for an MPA i is given by

(51)

$$LRN_i = \sum_u \quad \omega_u * LRN_{u,i},$$

where $\omega_u = 1/2$ for professional fishers and for recreational activities users $\omega_u = \left(\frac{1}{2}\right) * \frac{1}{n}$ where n indicates the total number of recreational activities in MPA (i) and where $\sum_u \quad \omega_u = 1$.

Assets $(ASTS_{u,i})$for MPA (i) it is calculated summing up *Assets* $(ASTS_{u,i})$of all users (professional fishers and recreational activities from section C&D)within the MPA. Thus, the equation to calculate the *Assets* for an MPA i is given by

(52)

$$ASTS_i = \sum_u \quad \omega_u * ASTS_{u,i},$$

where $\omega_u = 1/2$ for professional fishers and for recreational activities users $\omega_u = \left(\frac{1}{2}\right) * \frac{1}{n}$ where n indicates the total number of recreational activities in MPA (i) and where $\sum_u \quad \omega_u = 1$.

Agency and socio cultural aspects ($AG.CUL_i$) for MPA (i) it is calculated summing up the *Agency and socio cultural aspects* ($AG.CUL_{u,i}$) of all users (professional fishers and recreational activities from section C&D)within the MPA. Thus, the equation to calculate the *Agency and socio cultural aspects* for an MPA i is given by

$$AG.CUL_i = \sum_u \omega_u * AG.CUL_{u,i}, \quad (53)$$

where $\omega_u = 1/2$ for professional fishers and for recreational activities users $\omega_u = \left(\frac{1}{2}\right) * \frac{1}{n}$ where n indicates the total number of recreational activities in MPA (i) and where $\sum_u \omega_u = 1$.

VULNERABILITY INDEX TO SEA SURFACE TEMPERATURE (G)

The *Vulnerability Index* of MPA (i), $V_{Soc.Ecol}$, to the impact of sea surface temperature is calculated using the same formulas used for the calculation of the Social-ecological Vulnerability Index presented in equation 43 in section F. However, some components and dimensions differ as we are only including indicators specific to SST, in the cases where we had both indicators of SST and MHW.

For the *Vulnerability Index to SST* we are adding Ecological vulnerability , ($V.ECOL_i$) to Social sensitivity, ($S.SEN_i$), and subtracting Social adaptive capacity, ($S.AC_i$) giving equal weights to each dimension but ensuring that the values range from 0 to 1 following the equation:

$$V_{Soc.Ecol} = \frac{(V.ECOL_i + S.SEN_i - S.AC_i) - (-1)}{2 - (-1)}$$

Ecological vulnerability of MPA (i) $V.ECOL_i$ is calculated using the same formula used for the calculation of the Ecological Vulnerability index as previously explained in the equation 30 in section E where we are summing Exposure, E_i and Ecological sensitivity $EC.SEN_i$ and subtracting Ecological adaptive capacity $EC.AC_i$. The formula is reported below:

$$V.ECOL_i = E_i + EC.SEN_i - EC.AC_i$$

where *Exposure* E_i is provided at the MPA (i) level and it is calculated considering only the component of sea surface temperature threat ($SSTthreat_i$) and it is found following the equation:

(54)
$$E_i = \omega_m * SSTthreat_i$$

where ω_m denotes the weight associated to the component $SSTthreat_i$ which equals to 1 and the component *Sea surface temperature threat* ($SSTthreat_i$) corresponds to a the single indicator surface temperature increase (SST_i) , thus $SSTthreat_i = SST_i$.

Ecological Sensitivity

Ecological sensitivity ($EC.SEN_i$) is provided at the MPA (i) level and it is calculated applying the same formula used for the calculation of Ecological sensitivity in section E in equation 31 described below.

$$EC.SEN_i = \omega_m * WC_i + \omega_m * HP_i + \omega_m * SI_i + \omega_m * HI_i$$

where ω_m denotes the individual weight associated to each component.

The components Water conditions (WC_i) and Human pressure (HP_i) are calculated in the same way as expressed in the equations 32 and 33 of section E while Species Integrity (SI_i) and Habitat integrity (HI_i) *are* calculated as it is explained below.

Species Integrity (SI_i) for MPA i is calculated by summing up the *Species Integrity* of all species within the MPA. Thus, the equation to calculate the *Species integrity* component for an MPA i is given by:

(55)
$$SI_i = \sum_k \omega_k * SI_{k,i},$$

where each species weight, ω_k, equals $1/k$ and k is the total number of species in MPA i.

Species integrtity ($SI_{k,i}$) varies per MPA (i), per species type (k) for K total species and it is calculated considering the indicators: species sensitivity to sea surface temperature ($SP.SEN.SST_{j,i}$), species distribution ($SP.DIS_{k,i}$), species mass mortality events ($MME.SP_{k,i}$), species conservation status ($SP.ST_{k,i}$), endangered status ($END.ST_{k,i}$), invasive status ($INV.ST_{k,i}$) and species population size ($SP.POP_{k,i}$). The indicators used for the calculation of *SP.SI* vary per MPA (i) and per species (k) for k species except $SP.DIS_k, END.ST_k, and\ INV.ST_k$ that only vary per species (k). Species Integrity at the species level, is calculated as follow:

(56)

$$SP.SI_{k,i} = \omega_c * SP.SEN.SST_{k,i} + \omega_c * SP.DIS_k + \omega_c * MME.SP_{k,i} + \omega_c * SP.ST_{k,i} + \omega_c * END.ST_k + \omega_c * INV.ST_k + \omega_c * SP.POP_{k,i},$$

where $\omega_c = 1/C$ is the weight of each indicator. At the species level, *Species integrity* (SI_i) incorporates C=7 indicators. Note that each MPA can have a set of species, so K varies with i.

Habitat integrity (HI_i) for MPA (i) is calculated aggregating up the *Habitat integrity* of all habitats within the MPA. Thus, the equation to calculate the *Habitat integrity* component for an MPA i is given by

(57)

$$HI_i = \sum_j \omega_j * HI_{j,i},$$

where each habitat weight, ω_j, equals $1/J$ and J is the total number of habitats in MPA i.

Habitat Integrity ($HI_{j,i}$) varies per MPA (i) and per habitat type (j) for J habitats and it is calculated considering the indicators: habitat sensitivity to sea surface temperature ($HB.SEN.SST_{j,i}$), condition of the benthic community ($HB.BENT_{j,i}$), presence of endangered species ($END.SP_i$), invasive species presence ($HB.INV_{j,i}$), risk of invasive species ($RISK.INV_i$), warm water species ($WARMW_i$) *and mass mortality events* (MME_i). The indicators used for the calculation of *HB.SEN* vary per MPA (i) and per habitat type (j) for J habitats except species ($END.SP_i$), invasive species presence ($HB.INV_i$), risk of invasive species ($RISK.INV_i$), warm water species ($WARMW_i$) *and mass mortality events* (MME_i) that only vary per MPA (i). Habitat integrity at the habitat level, is calculated as follow:

(58)

$$HI_{j,i} = \omega_c * HB.SEN.SST_{j,i} + \omega_c * HB.BENT_{j,i} + \omega_c * END.SP_i + \omega_c * HB.INV_i + \omega_c * RISK.INV_i + \omega_c * WARMW_i + + \omega_c * MME_i,$$

where $\omega_c = 1/C$ is the weight of each indicator in habitat integrity measure and C is the total number of indicators that enter the calculation. At the habitat level, *habitat integrity* for MPA i (HI_{ij}) incorporates C=7 indicators. Note that each MPA can have a set of habitats, so J varies with i.

Ecological adaptive capacity

Ecological Adaptive Capacity ($EC.AC_i$) is provided at the MPA (i) level and it is calculated as explained in equation 36 in section E, aggregating habitat redundancy(HR_i), habitat recovery potential (HRP_i), species recovery potential (SRP_i), effectiveness (EF_i), conservation (CE_i) and adaptive management (AM_i) and the formula is reported below:

$$EC.AC_i = \omega_m * HR_i + \omega_m * HRP_i + \omega_m * SRP_i + \omega_m * EF_i + \omega_m * CE_i + \omega_m * AM_i$$

where ω_m denotes the individual weight associated to each component.

Social sensitivity

Social sensitivity ($S.SEN_i$) is provided at the MPA (i) level and it is calculated as explained in equation 44 in section F adding the components: professional fishers dependence ($F.DEP_i$), professional fishers effort ($F.EFF_i$), professional fishers local dependence ($LOC.F.DEP_i$), recreational activity employment ($RA.EMP_i$), recreational activity ecosystem ($RA.EC_i$) and recreational activities facilities ($RA.FAC_i$) and it is found following the equation:

$$S.SEN_i = \omega_m * F.DEP_i + \omega_m * F.EFF_i + \omega_m * LOCAL.DEP_i + \omega_m * RA.EMP_i + \omega_m * RA.EC_i + \omega_m * RA.FAC_i$$

where ω_m denotes the individual weight associated to each component.

Social adaptive capacity

Social adaptive capacity ($S.AC_i$) is provided at the MPA (i) level and it is calculated as explained in equation 48 in section F adding the components flexibility ($FLEX_i$), social organization ($S.ORG_i$), learning (LRN_i)and assets ($ASTS_i$), and agency and socio cultural aspects($AG.CUL_i$) and it is found following the equation:

$$S.AC_i = \omega_m * FLEX_i + \omega_m * S.ORG_i + \omega_m * LRN_i + \omega_m * ASTS_i + \omega_m * AG.CUL_i$$

where ω_m denotes the individual weight associated to each component.

Flexibility ($FLEX_i$), Social Organization ($S.ORG_i$) learning (LRN_i) and assets ($ASTS_i$) are calculated as expressed respectively in equations 49, 50, 51 and 52 from section F while Agency and socio cultural aspects ($AG.CUL_i$) is found following the equation below.

Agency and socio cultural aspects ($AG.CUL_i$) for MPA (i) per user type (u) for U total users, is calculated aggregating the indicators: risk attitudes to SST in user groups ($U.RISK.SST_{u,i}$), income of fishers ($U.JUST_i$), and access to justice ($U.JUST_{u,i}$) and it is found following the equation:

(59)
$$AG.CUL_{u,i} = \omega_c * U.RISK.SST_{u,i} + \omega_c * U.INC_i + \omega_c * U.JUST_{u,i}$$

where $\omega_c = 1/C$ is the weight of each indicator in *Agency and socio cultural aspects* where C=3 indicators. Note that $U.INC_i$ only apply to Professional fishers

Agency and socio cultural aspects ($AG.CUL_i$) for MPA (i) it is calculated aggregating the *Agency and socio cultural aspects* of all users (professional fishers and recreational activities) within the MPA. Thus, the equation to calculate the *Agency and socio cultural aspects* for an MPA i is given by

(60)
$$AG.CUL_i = \sum_u \omega_u * AG.CUL_{u,i},$$

where $\omega_u = 1/2$ for professional fishers and for recreational activities users $\omega_u = \left(\frac{1}{2}\right) * \frac{1}{n}$ where n indicates the total number of recreational activities in MPA (i) and where $\sum_u \omega_u = 1$.