Calanques MPA-VULNERABILITY ASSESSMENT

MPA ENGAGE

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IDENTIFICATION

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Description of the deliverable	This report assess the socio-ecological vulnerability of the Calanques MPA to climate change through a common scientific methodology shared with other MPAs. It analyses the ecological vulnerability of species and habitats, but also the social sensitivity and adaptive capacity of users groups in the Calanques MPA to Sea Surface temperature increase and marine heatwaves projected scenarios.
Key words	Vulnerability, exposure, sensitivity, adaptive capacity, social, ecological, users groups, species, habitats, climate change, sea surface temperature, marine heatwaves, RCP scenarios, data, Calanques NP, management plan

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3.3.3 Socio-ecological vulnerability assessment in Calanques MPA	22/12/2020	1	Draft report
3.3.3 Socio-ecological vulnerability assessment in Calanques MPA	22/04/2021	2	Completed report to be updated with future VA tool improvements
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3.3.3 Socio-ecological vulnerability assessment in Calanques MPA	29/10/2021	4	Final report with all parts completed

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1 Summary

The Mediterranean Sea is warming 20% faster than the world's average rate and Marine Protected Areas (MPAs) are already facing climate change impacts with biodiversity and functional alterations. With the MPA Engage project, the Calanques National Park (CNP) starts the process of building an adaptation plan to climate change in four steps: vulnerability assessment, monitoring, citizen science and participatory approach. This report addresses the need of elaborating a socio-ecological vulnerability assessment to climate change in the CNP, taking into account both the ecological and the social systems of the MPA. Characteristics of species, habitats and local stakeholders of the MPA are evaluated through their social and ecological dimensions (indicators of sensitivity and adaptive capacity) according to three projections of carbon emissions scenarios (RCP2.6, 4.5 and 8.5) in the years 2050 and 2100 for two climate change factors of exposure (increase of sea surface temperature and of marine heatwaves). The indicators are then integrated into the vulnerability assessment tool developed in the frame of the MPA Engage project to calculate indices of socio-ecological vulnerability. These indices highlight that the socio-ecological vulnerability will be low in the CNP in all carbon emissions scenarios in 2050 and in RCP 2.6 in 2100. The socio-ecological vulnerability will raise to moderate in RCP4.5 and RCP8.5 scenarios in 2100, mainly because of the increasing ecological vulnerability going from moderate in all scenarios in 2050, to high in RCP4.5 and very high in RCP8.5 scenarios in 2100. Most of the habitats (e.g. *Posidonia oceanica* meadows or coralligenous habitats) and species (e.g. *Paramuricea clavata* or *Epinephelus marginatus*) of the CNP, but also all the users groups (divers, professional fishers, recreational fishers, nautical activities and tourism), will have high to very high vulnerabilities to climate change in the RCP8.5 scenario, which could be lower in the low carbon emissions scenario (RCP2.6). The confidence of the data used in the assessment could be better, with a good data coverage and confidence for ecological vulnerability but variable data coverages and confidences for social sensitivity and social adaptive capacity. The results of this assessment are then discussed regarding their meaning and their quality in order to strengthen the assessment and decrease the socio-ecological or ecological vulnerabilities (e.g. collection of ecological and socio-economic data, or improvements of management efforts and effectiveness) and in the light of other climate change factors at stake in the Mediterranean Sea having cumulative effects (e.g. acidification or sea-level rise). Thus, this socio-ecological vulnerability assessment to climate change in the CNP provides the foundations to guide the design and implementation of management actions, along with the associated monitoring, citizen science and participatory approaches results.

2 Introduction of Calanques National Park

The **Calanques National Park** (CNP) was created in 2012 and is composed of a terrestrial heart (8500 ha) and a marine heart (43 500 ha) with greater protection, and also by two ecological solidarity territories engaged in a sustainable development in partnership with the CNP marine and terrestrial hearts: the adherence area (2600 ha) and the adjacent maritime area (97 800 ha) (Figure1). It covers at the same time continental, marine and island habitats, which form a complex and extraordinary natural environment: bare steep mountains overlooking the sea, narrow creeks, vertiginous cliffs, rocky islands, big marine overhangs and arches, submarine caves, etc. The **character** of the CNP lies in 3 aspects: it is a territory born from the sea and from natural beauties and contrasts, a territory shaped by the man from the antiquity until the 20thcentury, and a territory of contemplation (the infinity within easy reach). One of its most exceptional feature is the presence of an underwater cave, the Cosquer cave, discovered in 1991, whose entry is -37 m deep and whose cave paintings date back to -27 000 to -19 000 years before present (attesting the post-ice age sea level rise).

The CNP is a **suburban MPA**, closed to Marseille, the second bigger city of France (more than 1 million inhabitants), which makes it a natural space isolated between cities, and explains the several years of a battle necessary to make it emerge. The combination of its remarkable landscapes and its close connection with cities has for consequence high human pressures on the natural environment, in particular on the coastline. The CNP **management plan is the charter**, a global and common project of territory, dedicated to environment and heritage protection (regulatory or partnership measures) but also to sustainable development (orientations). 5 cities are part of the CNP: Marseille, Cassis, la Ciotat, Roquefort la Bedoule et Ceyreste.

The CNP benefits from a Mediterranean climate, with low rainfall, high evaporation due to high temperatures, generous sunshine and strong winds. The *courant Liguro-Provencal* (ocean current) interacts with wind currents to define ocean circulation and water bodies' stratification (thermocline). This can induce for instance the spectacular upwelling phenomenon in summer (deep cold water rising up to the surface and enhancing the area with nutrients) where the coastal sea surface temperature in the MPA can go from 20-25° C to 13-15°C in few hours. On the other hand, an increase of sea temperature anomalies along the water column has been recorded these last years in the CNP, a direct climate change sign (Benssoussan *et al.*, 2010).

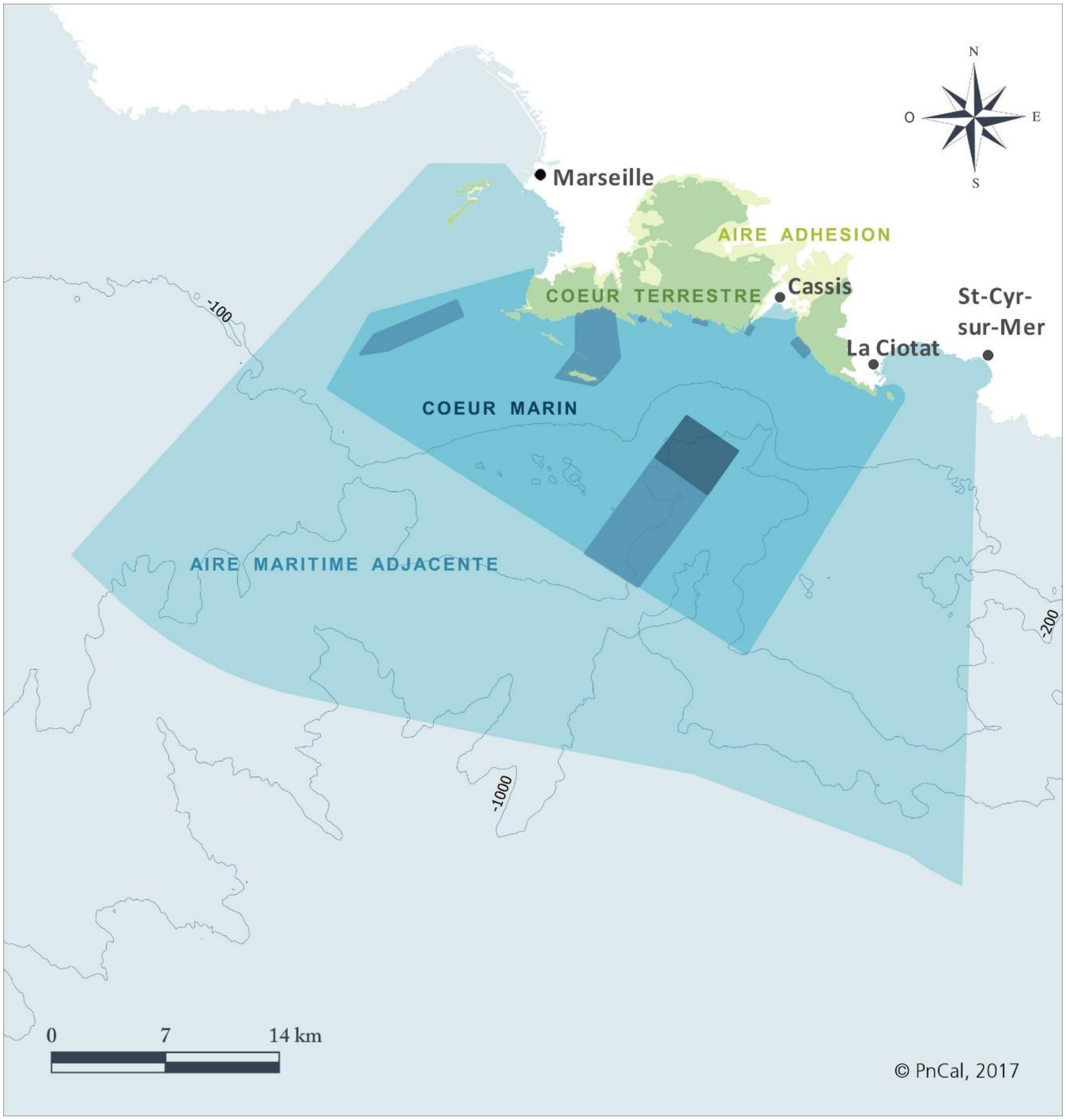
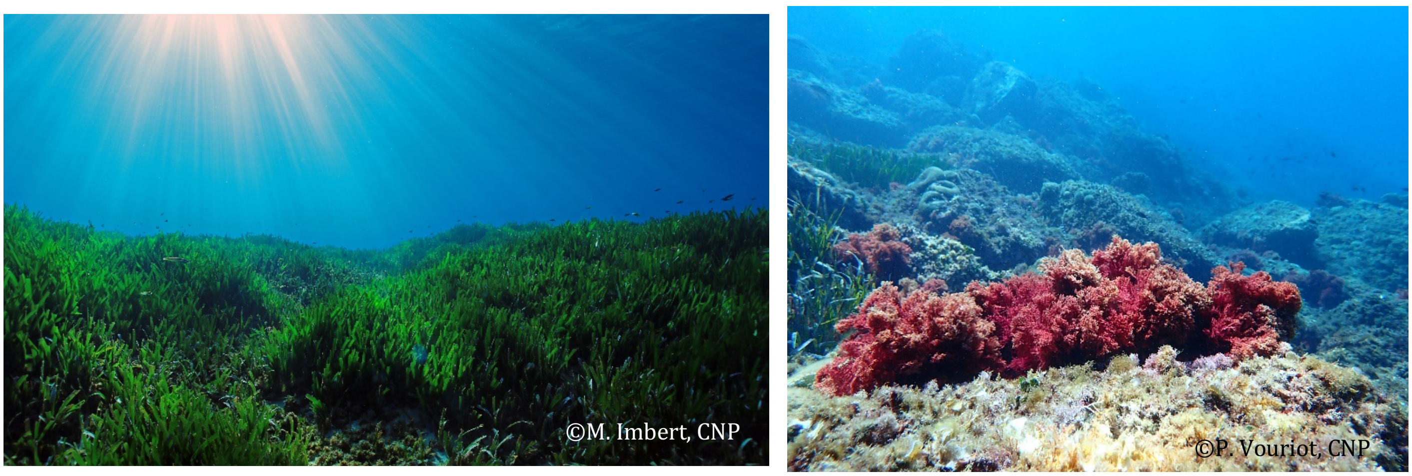


Figure 1: Map of the Calanques National Park

Many Mediterranean marine habitats are represented in the CNP.

- ***Posidonia oceanica* seagrass meadows** play many roles/ecosystem services (primary production, carbon sink, food source, nursery, spawning ground, protection against coastline erosion, etc.) and shelter for various species (*e.g. Pinna nobilis* or *Sarpa salpa*). In regression because of costal building, pollution, trawling and anchoring, their ecological state is stabilising in the CNP (within the 4 water bodies[1] of CNP: 1 in medium general state, 1 in altered ecological functioning and 2 in good ecological status [the ecological functioning is not considered for these water 2 bodies]) (Atlas de synthèse 2020).

Figure 2: Posidonia seagrass meadow (left) & rocky bottoms (right)



- **Infralittoral rocky reefs dominated by algae** are habitats with many functions (spawning, nursey, food supply, etc.) mainly based on the canopy-forming species of the genus Cystoseira. Their ecological state is concerning in the CNP and even deteriorating due to the remaining effects of industrial and wastewater discharges on water quality (3 water bodies of CNP associated with Moderate, Poor or Bad ecological status, according to reef-EBQI, Thibault *et al.*, 2017, and 4 water bodies associated to moderate or good ecological status according to simplified CARLIT index (Blanfuné *et al.*, 2017a).

- ***Cymodocea nodosa* seagrass meadows** are represented by small and spread patches in the CNP that could have several functional roles and that are submitted to many human pressures as *P. oceanica* seagrass meadows. Their ecological state has to be monitored.

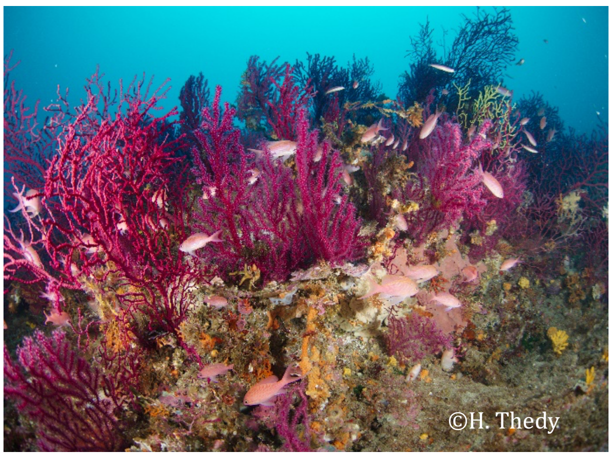
- **Coralligenous habitats**, characterized by encrusting calcareous algae and high biodiversity, are particularly beautiful in the CNP, displaying red coral (*Corallium rubrum)*, gorgonians (*e.g Paramuricea*

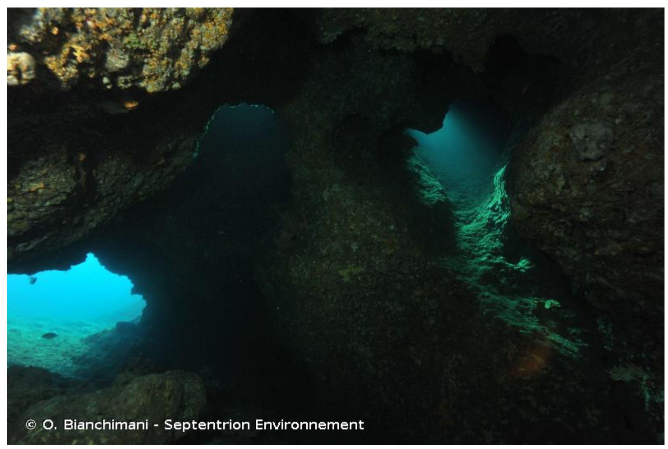
[1] A "water body" is a coherent sub-unit in the river basin (coastal unit for instance here) to which the environmental objectives of the Water Framework Directive must apply. The identification of water bodies is based on geographical and hydrological determinants. In the CNP, there are 4 water bodies: FRDC06b_Pointe d'Endoume - Cap Croisette et Iles du Frioul ; FRDC07a_Iles de Marseille hors Frioul ; FRDC07b_Cap Croisette - Bec de l'Aigle ; FRDC07c_Bec de l'Aigle - Pointe Fauconnière.

clavata), bryozoans, sponges and various fishes (*e.g. Sciaena umbra* or *Epinephelus marginatus*). They furnished many ecosystem services (fishing or harvesting, scientific discoveries or recreational diving, carbon sequestration via coralline algae or water filtration by sponges, refuge or nursery (Thierry de Ville d'Avray *et al.*, 2019). Their ecological state traduces space for improvement (within the 4 water bodies of CNP: 2 in medium general state, 1 in altered ecological functioning and 1 in good to slightly altered general state, according to coralligenous-EBQI) (Atlas de synthèse 2020). Mass mortality events happened in 1999 and 2003 mainly for gorgonians, sponges and bryozoans (Perez *et al.*, 2000, Garrabou *et al.*, 2009).

Figure 3: Coralligenous habitats (left) & submarine caves (right)

- **Marine caves**, which are particular habitats with specific environmental conditions (low hydrologic





circulation, oligotrophy, etc.) and unique biodiversity, are 39 numbered in the CNP. Sea temperature increase has caused the substitution of one *Mysidacea* species to a more thermophilic one in some caves (*Hemimysi margalefi*) (Lejeusne et Chevaldonné, 2005), and also mass mortality event of red coral (Garrabou *et al.*, 2001).

- **Mediolittoral rocky bottoms** are characterized in the CNP by exceptional *Lithophyllum lichenoides* "trottoir", biogenic corbelled constructions of great interest which grow in pure and rough water (exposed to wave actions). Very sensitive to pollution, trampling and sea level variations, their ecological state is not encouraging in the CNP (many dead habitats, in an irreversible way on a human timescale) (Blanfuné *et al.*, 2017b).

Costal detrital sandy bottoms, submarines canyons and open sea habitats are other key habitats in the CNP, also vulnerable to human activities and with a variety of functional roles and high biodiversity. Among the mobile species living in the water column, the bottlenose dolphin (*Tursiops truncatus*), the loggerhead sea turtle (*Caretta caretta*), the sperm whale (*Physeter macrocephalus*) and the fin whale (*Balaenoptera physalus*) are emblematic ones in the CNP.

Figure 4: Lithophyllum lichenoides "trottoir"

Various activities take place in the CNP marine part:

- **Professional fishing** is a traditional activity in the CNP, with fishermen (organized in Prud'homies) using various fishing gears depending on species biological cycles (traps, nets, lines, etc.). They are coastal, versatile and small-scale/artisanal fisheries. Among them, coral and sea urchin fisheries, carried out diving, are characteristic in the region.

- **Recreational fishing** (from boat, from shore or spearfishing) count numerous users, often organized in federations. Recreational fishermen were underestimated for a long time, but are now better comprehended with specific fishing regulations designed for them.

Figure 5: Professional (left) & recreational fishermen (right)

- **A fish farming**, settled decades ago on Frioul Island, is still active and gets the organic farming certification label for the only species farmed, *Dicentrarchus labrax*.

- **Scuba diving** is an historical activity in the CNP (birthplace of diving federations), with various diving clubs and associations generating numerous visits all year long on lots of famous and appreciated diving sites (wreck, underwater remains, caves, etc.).

Figure 6: Scuba diving (left) & boating activities (right)

- **Boating activity** has known an important development in these last decades (several active harbours and high increase of boat rentals) and the Aix-Marseille metropolis has become the first pleasure boating centre in France.

- **Many water sports**, such as sailing, kayaking, windsurfing, etc. have increased their visibility in the meantime, and made the CNP their favourite playground (making recreational activities accessible to the masses).

- **Tourism** also grew up considerably since the CNP creation, with visits linked to many **recreational activities** on/from land (swimming, walk, hiking, climbing, mountain biking, caving, etc.).

- **Passenger sea rides** (guided tours) **or sea transport** (islands services) are well established in the CNP. Their increase has been stopped since the CNP creation and they are now subjected to an authorisation application, but they participate to overcrowding and bottlenecking in specific sites in high season.

Several conflicts of interests between users, and also with CNP, for spatial occupation in the coastal zones are a real challenge for management and form a complicated socio-economical context: competition between users, ignorance of regulations, poaching, speeding, security or confidence in the MPA, are so many topics to deal with.

Figure 7: passenger sea rides and recreational activities at sea

Fishing regulations were set up in the CNP for both recreational and professional fishermen through gear and size restrictions, fishing effort limitation (species minimum size of catch and number of individuals limited), seasonal closures (e.g. for sea urchins or octopus during summer). 7 **No-Take Zones**, covering more than 4 800 ha in the CNP marine heart (biggest zone forbidden to all kinds of fishing in the French metropolitan MPAs), were also established in 2012, at the same time as the MPA creation. They benefit from rigorous regulation and management (to combat poaching for instance) and are at the beginning of their evolution ("reserve effect" already detected). Inevitably, these No-Take Zones had a high impact on professional fishing activities such as they were practised: a higher number of fishers gather in more restricted areas, with more reduced rotation cycles, which create tension on resources and between them, and reluctance to collaborate with the CNP.

Figure 8: Guide for recreational fishermen (left) & No-Take Zones sign (right)

Besides regulations on existing activities of sea transport of passengers, the CNP has implemented in 2019 a new authorisation system on the renting activities of motorised boats in order to **regulate the maritime visits in the MPA heart**. Also, landing on the Riou archipelago and sound diffusion around these islands and inside the inlets ("calanques") are prohibited.

A **diving charter** was created in 2016 with the objective of encouraging divers to adopt or keep eco-behaviours and eco-gestures, which favours the good environmental state of marine diving sites. It is a contractual approach between the diving community and the CNP which aims to limit the potential impacts that the concentration of divers on some sites might have on the marine landscape and associated biocenosis.

Figure 9 Diving charter communication campaign

Finally, 2 master plans built these last years with stakeholders are currently under the process of approval, before implementing the management actions included. The **master plan of anchorage organisation**, which rethinks the reception of nautical activities on the CNP territory in coherence with the reality of these activities and their dynamics, and with the preservation of ecological stakes. The **master plan of recreational activities coherence**, which aims to find a balance between the protection of the CNP fragile territory and the sustainable experiences of all recreational activities (freedom and responsibility).

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 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 205 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.

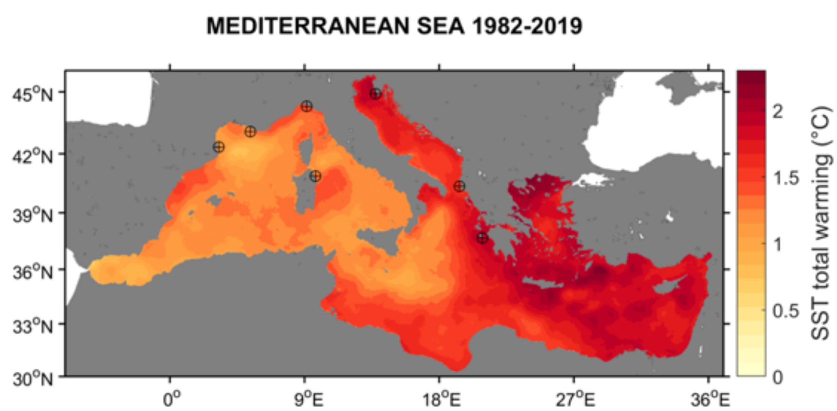
3.2 CLIMATE CHANGE IMPACTS IN THE MPA

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 (Figure 10). 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 11).

Figure 10. Current warming observed in Mediterranean MPAs, period 1982-2019 respect to 1950-1980



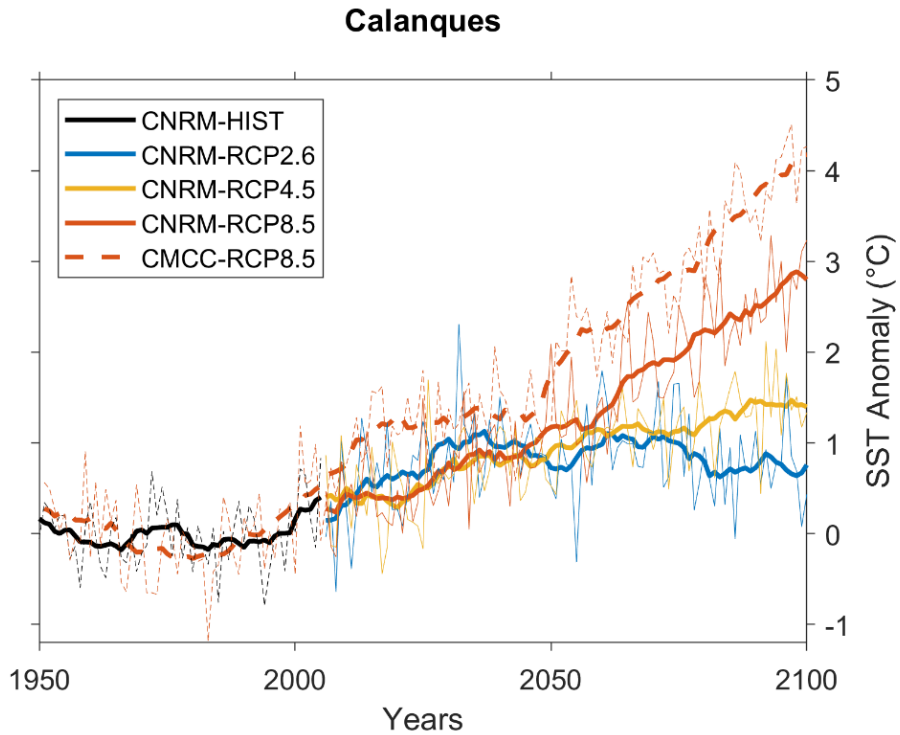


Figure 11. SST99 anomaly projected for the Calanques MPA with climate change scenarios.

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 12).

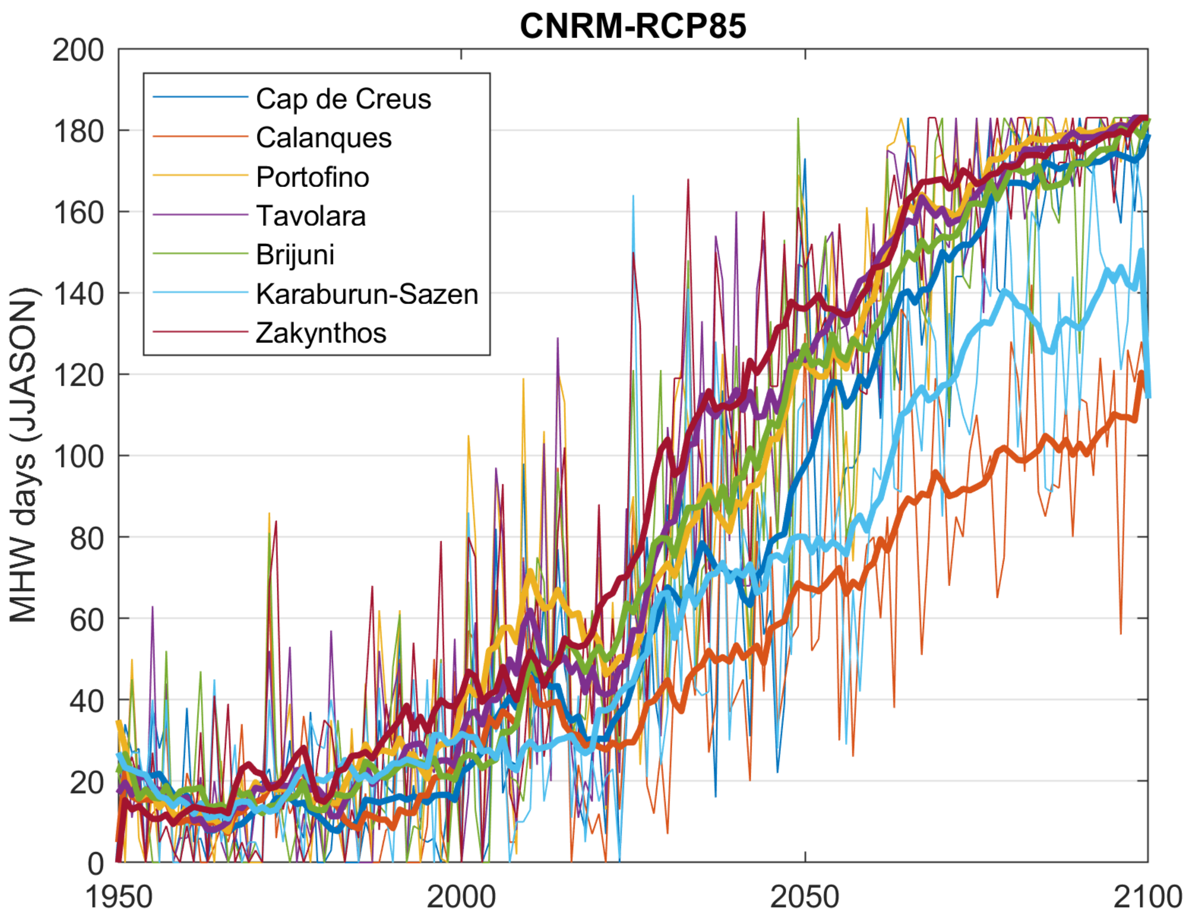


Figure 12. Projected MHW-days over the warm period (JJASON) of each year under climate change scenario 8.5.

Therefore, this assessment does not deal with other climate change impacts, such as sea level rise or acidification, which can add to the MPA socio-ecological vulnerability results presented here.

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 13). 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.

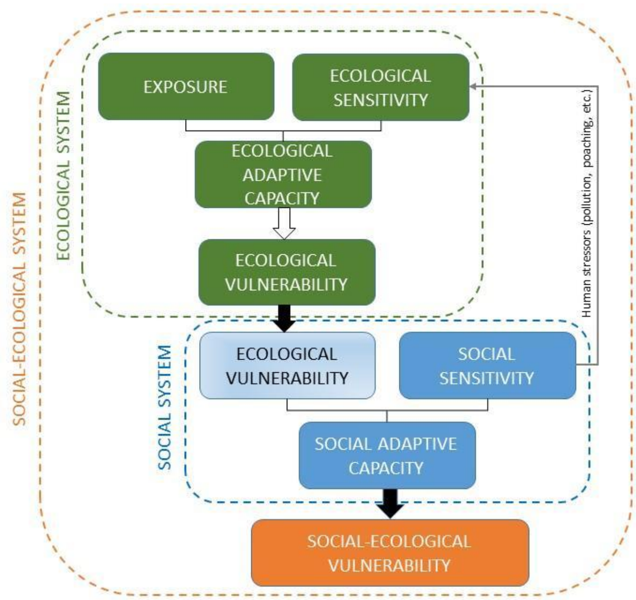


Figure 13. Social-ecological climate Vulnerability framework.

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 5 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, which together form the Vulnerability Index (Figure 14). 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 Annex9.1 tables.

Figure 14. 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), 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):

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

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 (Figure 15).

RANGES				
Low	Intermediate	High	Very high	Extreme

Figure 15. 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 16). Finally, we compare the calculated indexes and categorize them into one of the qualitative categories based on the ranges as defined by the percentiles.

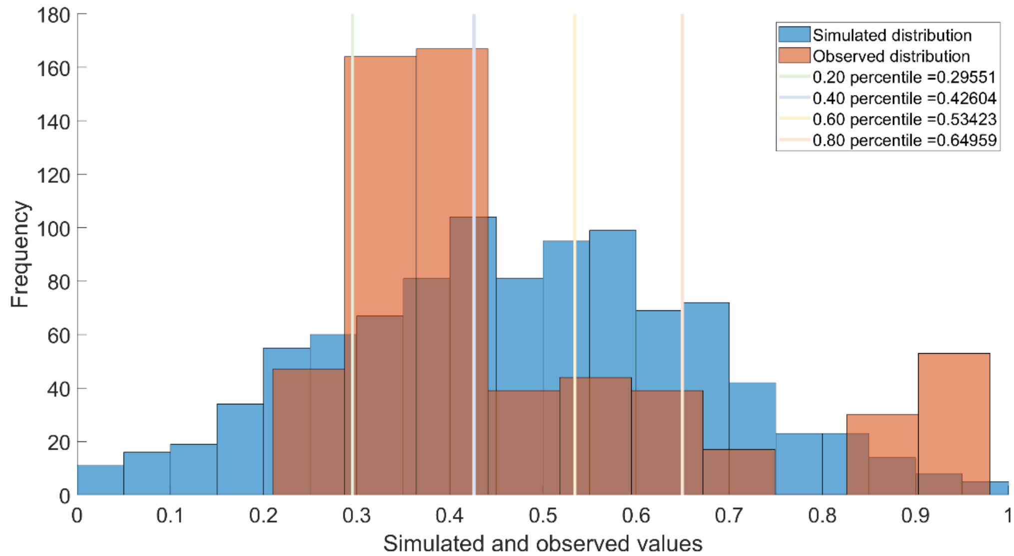


Figure 16: Plot showing the observed and simulated data used to calculate the percentiles to create the qualitative ranges for the exposure dimensions related to the Species Vulnerability Index. The coloured bars in the figure reflect the upper limit of the corresponding category.

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 17). 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				
		Sensitivity	Low	Intermediate	High	Very high	Extreme
	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
		Extreme	Very high	High	High	High	Intermediate
	Intermediate	Low	High	Intermediate	Intermediate	Intermediate	Low
		Intermediate	High	High	Intermediate	Intermediate	Intermediate
		High	High	High	High	Intermediate	Intermediate
		Very high	Very high	High	High	High	Intermediate
		Extreme	Very high	Very high	High	High	High

Figure 17. 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 20 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 Calanques MPA

Posidonia oceanica meadows	Other seagrass meadows	Coralligenous	Infralittoral rocky bottoms dominated by macroalgae	Caves
X	X *Cymodocea nodosa*	X	X	X

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 Calanques MPA

Monitored species	Endangered species	Climate impacted species	Target fishing species	Keystone species	Flagship species

Paramuricea clavata *Epinephelus marginatus* *Corallium rubrum* *Paramuricea clavata*	*Pinna nobilis* *Posidonia oceanica* *Epinephelus marginatus* *Corallium rubrum* *Physeter macrocephalus*	*Corallium rubrum* *Eunicella cavolini* *Paramuricea clavata* *Lithophyllum spp.*	*Octopus vulgaris* *Pagellus bogaraveo* *Mullus surmuletus* *Scorpaeana scrofa* *Sparus aurata*	*Posidonia oceanica* *Coralline calcareous algae* *Cystoseira spp.*	*Epinephelus marginatus* *Sciaena umbra* *Corallium rubrum* *Lithophyllum spp.* *Tursiops truncatus*

In the CNP, were chosen for this assessment:

- Species monitored in the frame of the Water Framework Directive, the wastewater treatment plant effluents (*P.oceanica*), the No Take Zones (*C. rubrum*, *E. marginatus*, citizen sciences programs (*E. marginatus*), and scientific research (sensitivity/resistance/resilience of *P. clavata* or *E. cavolini*);
- Species endangered, whose abundance has decreased these last decades due to human activities such as anchoring, pollution, overfishing, over-harvesting, etc. (*P. oceanica*, *C. rubrum*, *E. marginatus*) or parasites (*P. nobilis*) and with a slow recovery;
- Species affected by marine heatwaves (gorgonians) or sea level rise (*Lithophyllum spp.*);
- Species targeted by recreational fishermen (*O. vulgaris* or *S. aurata*) and also professional fisheries (*P. bogaraveo* in canyons, *M. surmulletus* or *S. scrofa*);
- Species structuring the different marine habitats (*P. oceanica*, Coralline calcareous algae or *Cystoseira spp.*);
- Symbolic species which are regular visitors (*T. truncatus*, *P. macrocephalus*), divers favourite (visible *E. marginatus* or scarcer *S. umbra*), historically important for fisheries and diving (*C. rubrum*) and typical of CNP (*Lithophyllum spp.* « trottoir/corbel »).

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 Calanques MPA

Professional fishers	Recreational fishers	Diving sector	Nautical activities	Tourist sector
X	X	X	X	X

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.

Indicators were selected because of their relevance for the CNP (regarding activities and existing knowledge) and of the data availability from scientific literature, various study reports, and CNP management documents, or directly from stakeholders through questionnaires.

The data collection process went on for several months to gather different types of data:

- Socio-economic data on the different activities/users of the CNP and on the general context/city around the CNP (income, jobs, etc.)
- Geographical and regulatory data on the CNP (area, specific zones for activities, habitats, etc.)
- Ecological data from literature and existing monitoring reports (species abundance, etc.)

More precisely, online questionnaires (with about 20 to 40 questions) targeting 4 groups of stakeholders' representatives (diving clubs, nautical activities companies, institutional actors including tourist offices & recreational fishermen) were created based on UVIGO questionnaires, completed with several questions related to climate change perception, and sent in June and July 2020. The response rate to questionnaires was relatively low:

- ✓ 4 over 26 recreational fishermen
- ✓ 3 tourism offices
- ✓ 8 over 35 diving clubs
- ✓ 23 over 58 nautical activities representatives

Due to differences in the questions wording between the CNP online questionnaires and the UVIGO ones (i.e. different proposed levels of answers: yes/no instead of rating between 1 and 5 or instead of precise number), only some questions (and thus associated responses) from UVIGO questionnaires could be considered to match with online questionnaires (mainly for indicators related to social organisation and recreational activities employment):

- 7 out of 28 questions for diving clubs
- 6 out of 25 questions for nautical activities
- 22 out of 26 questions for recreational fishermen
- 4 out of 23 questions for tourism

This selection was made in order to have harmonized MPAs data that are fitted for the vulnerability assessment tool. Some other responses were then directly given by the CNP managers based on their knowledge (for instance, for indicators related to recreational activities employment, ecosystem and facilities).

For professional fishermen, physical or telephonic interviews were chosen instead of online questionnaires due to the stakeholder specificity and to the MPA context. Nevertheless, an overlap with a major CNP fishing effort study happening at the same time, lead to reduce the ambition of the interviews to just 3 representatives of fishermen (one in each prud'homies: Marseille, Cassis, La Ciotat) in order to avoid excessive requests from CNP managers to fishermen. Due to the low availability of professional fishermen and to the tight schedule, only 1 interview was finally performed in early September 2020.

The CNP managers also replied to a questionnaire designed to collect basic MPA data and perceptions about MPA management and species/habitats ecological state.

A complete list of the data sources per indicator is available in the document "Raw data Calanques vf.xlsx" and the value of each indicator for each scenario in the document "TemplateCalanques_VF".

4.6 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.

Only one person was dedicated to the vulnerability assessment work in the CNP, realising all the activities, which allowed to keep coherence and efficiency, and the position was funded by the MPA Engage project (full-time).

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 3.3.3		
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 3.3.3	Number of stakeholders interviewed for the assessment	Number of staff involved	Number of species, habitats and user groups assessed
Calanques	350	MPA	15	30	30	60	135	NA	47250	1	1	Species: 17 Habitats: 5 Users: 5

Other than the expenses related to the salary of the staff involved in the activity, no supplementary costs were to report as no specific material was necessary for the activity implementation. Additionally, due to the COVID-19 sanitary crisis, most of the travelling to the partner's country for the different trainings was not allowed. Hence all the trainings were followed online (webinars or videoconferences). However, a significant amount of time was spent on emails, chat conversations and video calls to deal with questions and to resolve problems and misunderstandings remotely. This time would have been much lesser if direct and immediate interactions could have been possible through "physical" training (for instance no delayed answers or misunderstandings created by imperfect written wordings). So, it would not be right to deduce from this absence of travel costs, the possibility to remove them from future planning of vulnerability assessment training for other MPAs, as it would be less efficient and might harm the quality of the work.

As for the time allocated to the different vulnerability assessment activities in the CNP, it was difficult to assess precisely as it was split into more or less scattered periods over near 18 months. Thereby, the numbers of days indicated are rough approximations, which can be explained partly by the reason mentioned above (remote continuous work) and by other project activities happening at the same time with only one person in charge, especially for the results interpretation and report writing (more project actions engaged). Specifically, the interview time (30 days) includes preparation and treatment of online questionnaires. However, the time spent on the interviews may be underestimated if the CNP would have rather chosen to carry out physical interviews with the numerous local stakeholders, instead of online questionnaires (representative answers in a heterogeneous context). Besides, the report writing time (60 days) may be over-estimated as the report was written in several periods during the project (3 times) because of the fine-tuning of the tool (corrected and operational) with the feedbacks from MPAs. Thus, the time dedicated to the report might vary for future MPA. In the end, a quite long period of time (8 to 12 months at least) for implementing the vulnerability assessment activities, among other activities being part of the elaboration of the climate change adaptation plan (monitoring, citizen science, communication and raising-awareness), was a good thing to mature these tasks (integration and understanding of the process/ actions/ results) and get a stronger and more confident work.

5 Results

The socio-ecological vulnerability index of the CNP will be low in all carbon emissions scenarios in 2050 and in RCP 2.6 in 2100. It will raise to moderate in RCP4.5 and RCP8.5 scenarios in 2100 (Figure 18). The ecological vulnerability will be driving the overall index variations (social sensitivity and adaptive capacity remaining the same in all scenarios) and will increase from moderate in all scenarios in 2050, to high in RCP4.5 and very high in RCP8.5 scenarios in 2100 (Figure 19). The extreme social adaptive capacity in the CNP will be offsetting the ecological vulnerability and will go along with the low social sensitivity, hence a low socio-ecological vulnerability.

In the CNP, the ecological adaptive capacities are extreme (due to habitats and species recovery potentials, effectiveness and conservation efforts) but the ecological sensitivity is also very high, even extreme in 2100 (due to water conditions, human pressure, and threats to species and habitats integrity). Thus, the ecological vulnerability will increase with the increasing exposure, which goes from moderate to very high in the worst scenario (RCP8.5). It should be noted that in the most optimistic scenario (RCP2.6), the exposure will drop to a low level in 2100.

Regarding the quality of the assessment, the data coverage for the socio-ecological vulnerability is 70%, resulting from good coverage of the ecological vulnerability (see below) and social sensitivity dimensions (respectively 94% and 80%), and from low coverage of the social adaptive capacity one (37%), highlighting a lack of available social data and social monitoring (interviews). The data confidence is medium for the social sensitivity (3.3) and low for the social adaptive capacity (1.9), which results in average confidence in the socio-ecological vulnerability indices presented here (3.2) that could be largely improved. Indeed most of the indicators from social sensitivity and adaptive capacity dimensions are based on qualitative data from a small sample of stakeholders (users' questionnaires for instance) or local experts, which can be variable (low to a high level of agreement) and whose representativeness is average, and from scarce local documentation.

For the ecological vulnerability indices, the data coverage is very good with 100% for exposure and more than 90% for ecological sensitivity and adaptive capacity, and also for the ecological vulnerability (94%). The data confidence is also very good with a maximal score (5) for exposure, and high scores for ecological sensitivity (4), adaptive capacity (4.4) and vulnerability. This means that there are:

- good physical measurements of SST and MHW are available in the CNP, which allow building robust projections of quantitative changes in the future
- many published and quantitative ecological data (time series) to traduce the recovery potentials or the threats to the integrity of habitats and species
- good knowledge of the CNP management aspects with a high level of agreement (effectiveness, conservations efforts and adaptive management).

The ecological vulnerability assessment is thus quite complete and of good quality even if it could still be improved by receiving additional data encompassing some important indicators on selected species and habitats.

Figure 18. Socio-ecological vulnerability index of the Calanques MPA.
Quality indices included for both 2050 and 2100 are the same

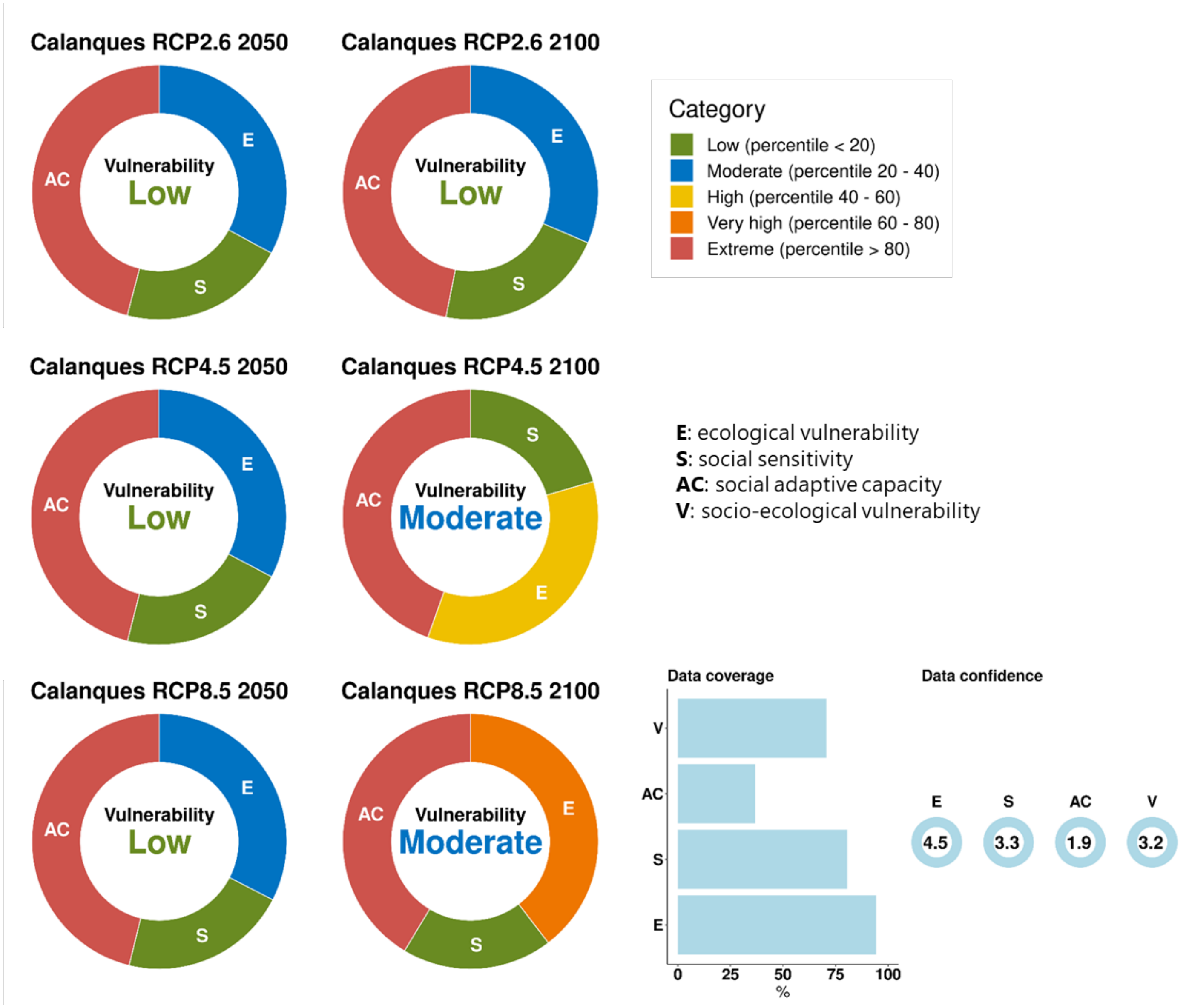
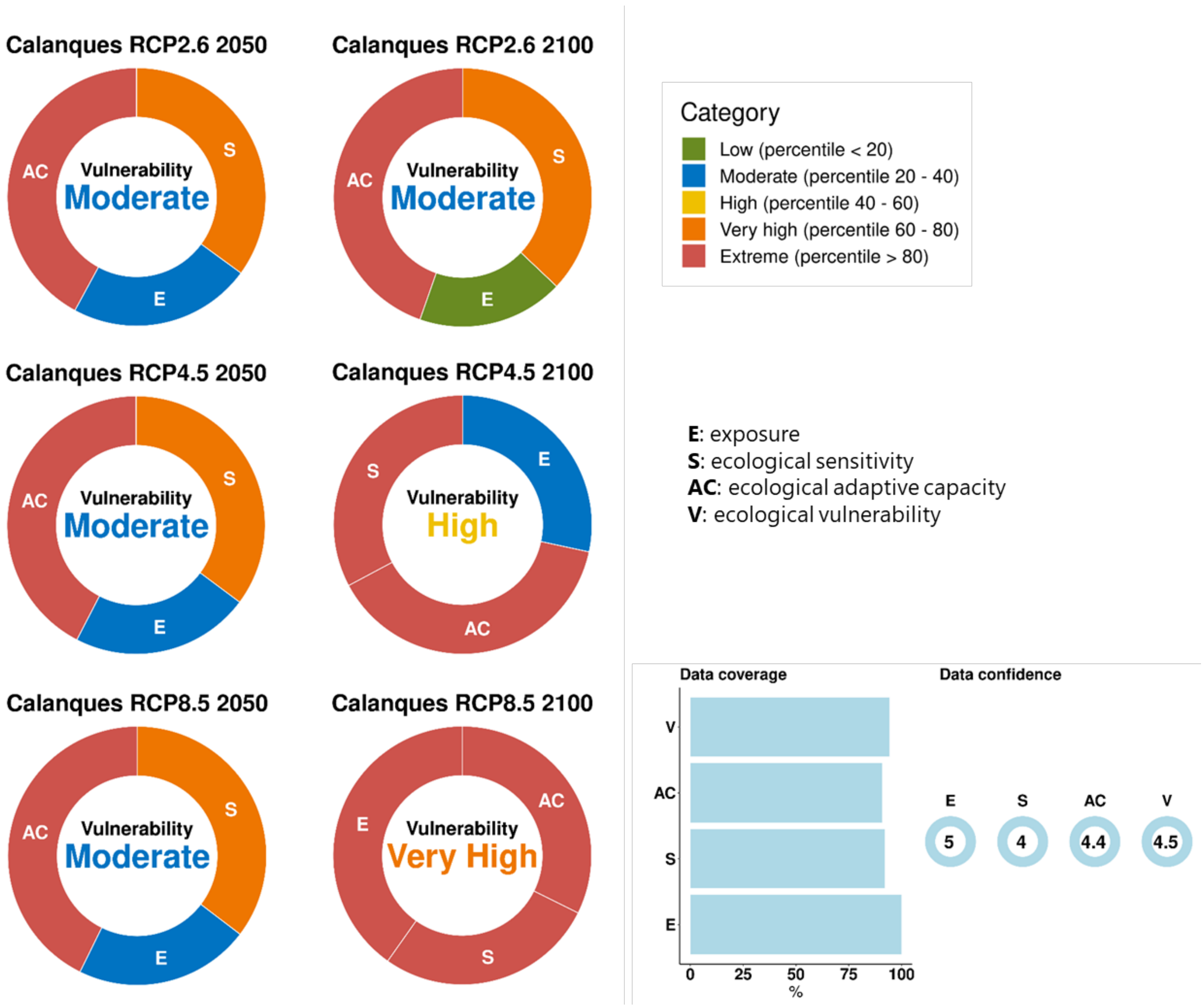


Figure 19. Ecological vulnerability index results



These socio-ecological indices convey the evidence that the CNP will be vulnerable to climate change in the future, admittedly in a low way when considering the social aspect, but still ecologically vulnerable. The indicators contributing to increase the most this ecological vulnerability to climate change (Figure 20) are:

- For exposure indicators: the increase of sea surface temperature (SST) and the multiplication of marine heatwaves (MHW) that species and habitats will handle badly;

- For ecological sensitivity indicators: the water conditions, through deoxygenation (low level of oxygen, DEOX), rather high salinity (SAL) and medium pollution (from close cities), and the human pressure, through a very high coastal population density (the CNP being a suburban MPA, PDEN);
- For ecological adaptive capacity indicators:
    - The lack of habitat redundancy: a suboptimal shape (SHAPE)
    - The lack of habitats recovery potential: low extension of selected habitat because of the large size of the CNP (mainly sandy bottoms and open sea)
    - The lack of some adaptive management: medium water column monitoring (monthly only, WCM) and a medium level of scientific advice on climate change (collaboration on specific occasions only, SCADV).

Regarding the social contribution to climate change vulnerability, the main indicators highlighting the CNP social sensitivity (Figure 20) are:

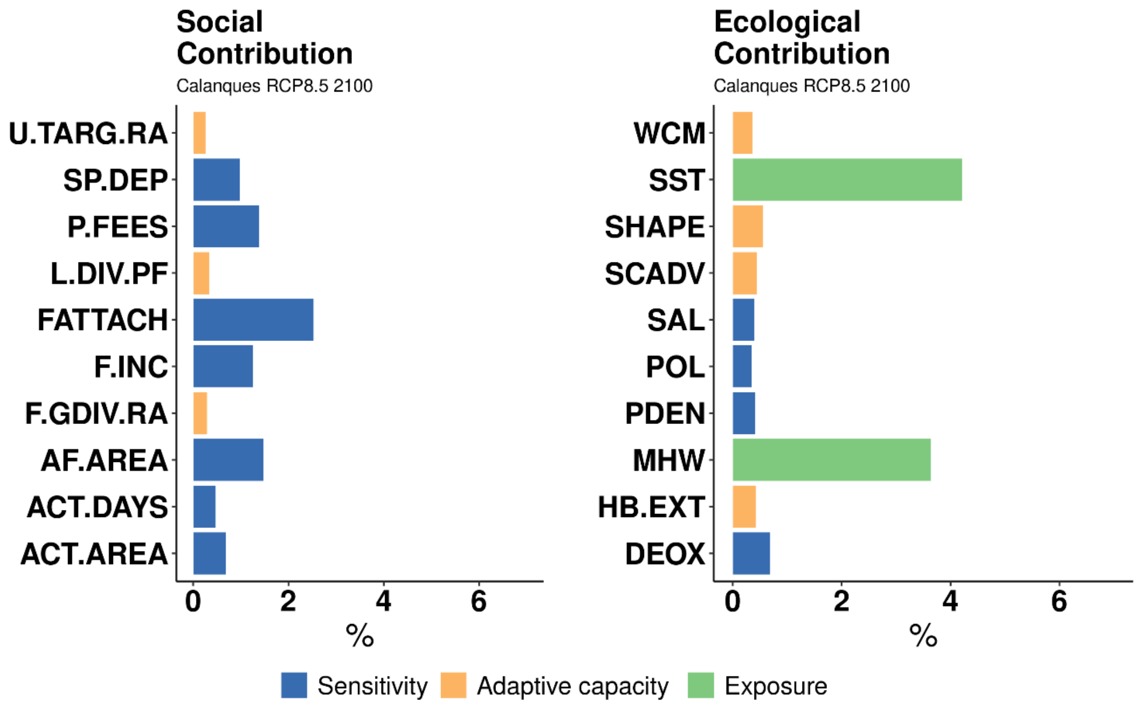
- The moderate professional fisher dependency: medium area still available for fishing (AF.AREA) and moderate species catch dependence (on endemic species, SP.DEP);
- The moderate local dependency on professional fishing: very high attachment of fishers to their occupation (FATTACH) and medium income relative to the average worker (F.INC);
- For recreational activities ecosystem: the very low "beach area" available for tourism (small inlets within the rocky coast which act as bottlenecks) and the medium area allowed to recreational fishing;
- For recreational activities employment: the very low loss of working days due to extreme weather conditions for diving clubs (ACT.DAYS);
- For recreational activities facilities: the medium cost of port mooring fees (P.FEES).

As for the lack of social adaptive capacities that contributes to increasing the vulnerability to climate change, they are expressed mainly through the lack of flexibility of users (Figure 20):

- Low gear diversity (F.GDIV.RA) and low number of targeted species for recreational fishers (U.TARG.RA)
- Very low livelihood diversity for professional fishers (L.DIV.PF).

The extreme social adaptive capacities are then more related to the quite good social organization in the CNP (moderate to good accountability, only some conflict among sectors, moderate to good transparency, medium trust toward the CNP, participation of users by consultation, and a medium level of cooperation within users of a sector) and to the local agency and socio-cultural aspects (medium income of professional fisher and low risk perception of fishers of STT or MHW threat).

Figure 20. Key indicators contributing to vulnerability
(RCP 8.5 for 2100)



In 2100, most of the habitats in the CNP are expected to have a moderate vulnerability in the most optimistic scenario (RCP2.6), and a high vulnerability in the worst scenario (RCP8.5, Figure 21). The other seagrass meadows, constituted by the species *Cymodocea nodosa*, will be the habitat which displays the highest vulnerability, both in 2050 (high in all scenarios) and in 2100 (very high in the RCP8.5 scenario).

The most vulnerable species to future climate change will be the gorgonians in the CNP (*Corallium rubrum*, *Paramuricea clavata* and *Eunicella cavolini*). Their vulnerability is expected to increase from high or very high in 2050, to extreme in the RCP8.5 scenario in 2100 (Figure 22). For all the other species selected in this assessment, the vulnerability will be also very high in 2100 in the RCP8.5 scenario. Thus, climate change represents a big threat, especially for species endemic to the Mediterranean. Coralline calcareous algae, *Lihtophyllum spp.* and *Posidonia oceanica* are the only species whose vulnerability could lower to intermediate by 2100 in case of a low emission scenario (RCP2.6). However, few information is currently available in the literature regarding *Lihtophyllum sp*, hence the vulnerability could be worse.

Figure 21. Habitat vulnerability index
(RCP 8.5 for 2100)

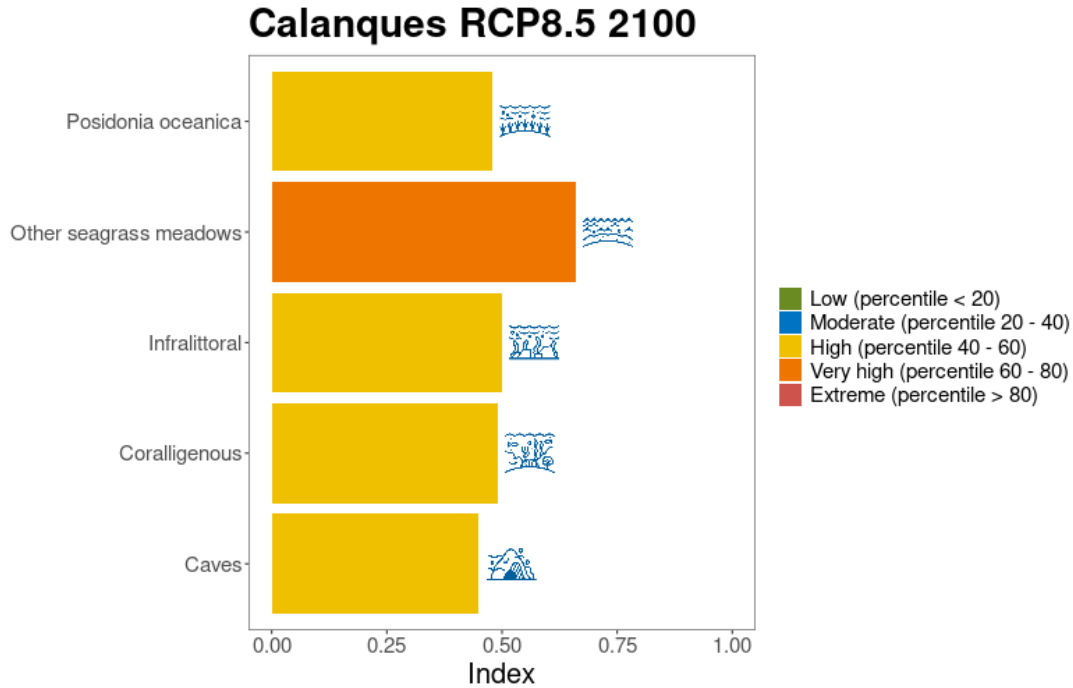
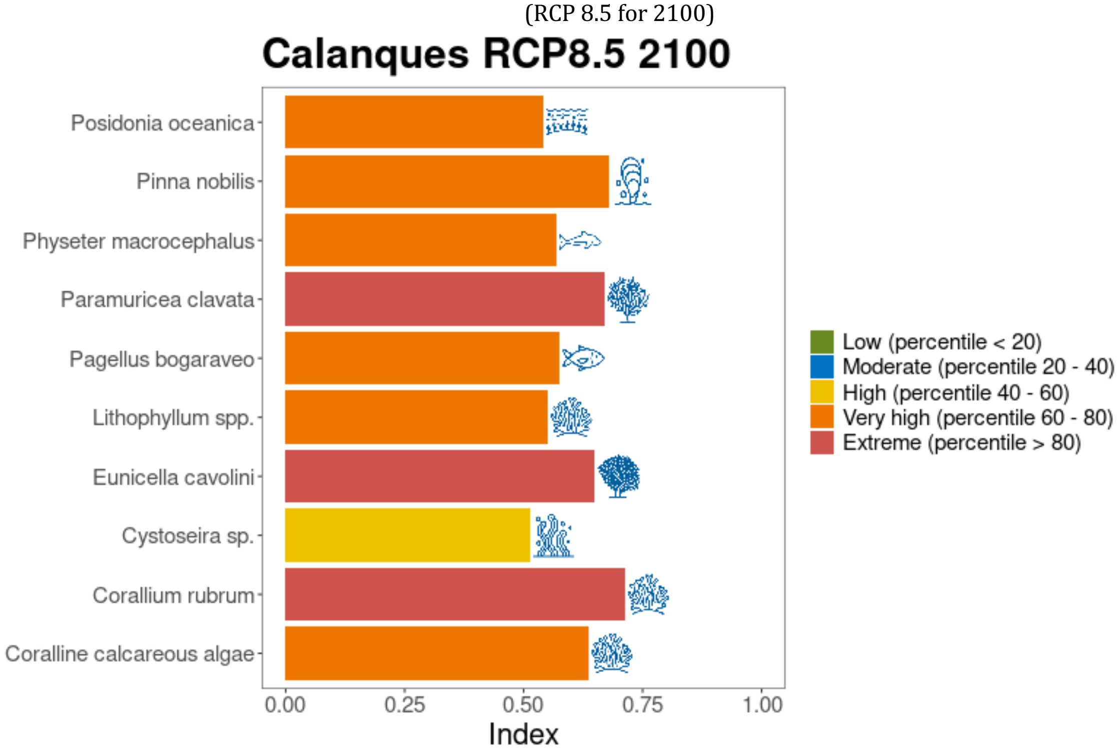
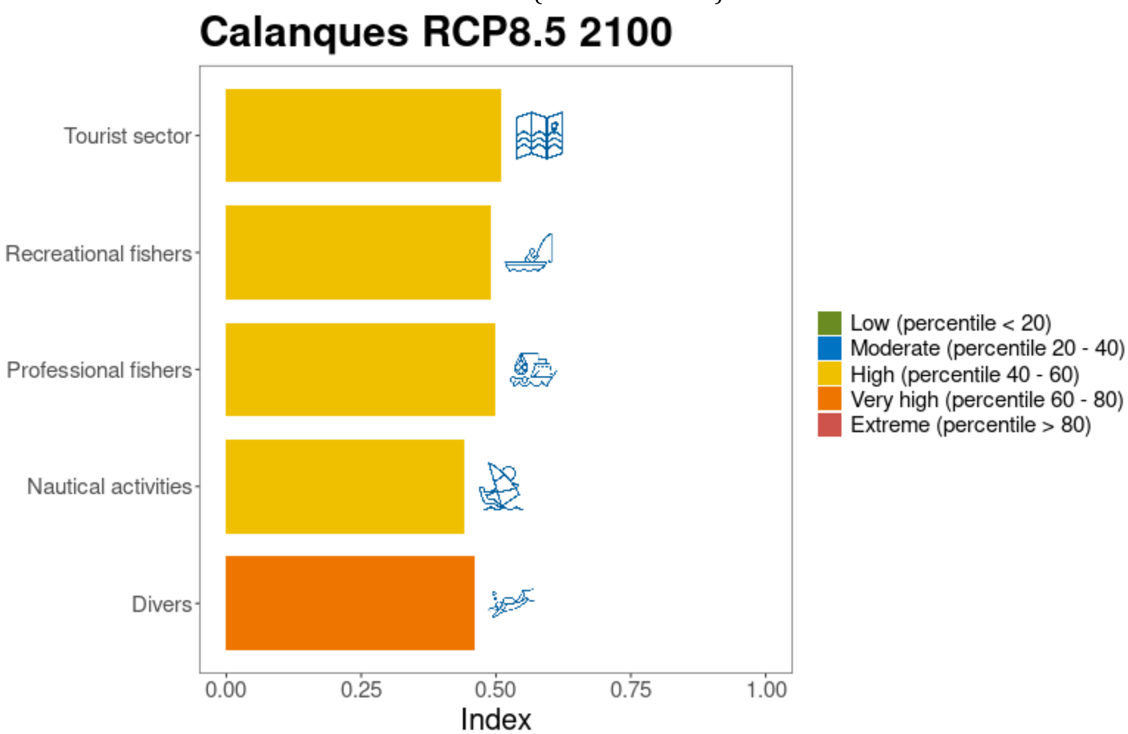


Figure 22. Species Vulnerability Index
(RCP 8.5 for 2100)



Divers will be the most vulnerable users groups to climate change in the future whatever scenarios considered, with a very high vulnerability in RCP8.5 scenario for year 2100, compared to the high vulnerability for the other users groups (Figure 23). However, the vulnerability could remain or become intermediate for all users group in 2100 in case of a low emissions scenario (RCP2.6).

Figure 23. Users Vulnerability Index
(RCP 8.5 for 2100)



All the documents associated with these vulnerability assessment results in the CNP (different figures and tables of values) are available in details in accessible folders on the CNP server, in order to go further into interpretation for one specific topic (e.g. one indicator in one scenario).

6 Discussion and Findings

6.1 WHAT IS THE CNP VULNERABILITY TO CLIMATE CHANGE TELLING US?

This assessment shows that the socioecological vulnerability in Calanques will be low in the mid-term and will increase in the long term with moderate or high emissions scenarios. The exposure indicators constitute the main drivers of the socio-ecological vulnerability indices because of the assessment design itself (high weights attributed to exposure indicators). The only action levers on exposure are linked to the reduction of carbon emissions at a global scale, leading us hopefully to the most optimistic scenario RCP2.6. These results encourage then the CNP management actions to rather focus on decreasing the level of sensitivity and increasing the adaptive capacity, both for social and ecological dimensions when possible, in order to eventually contribute to reducing the global CNP vulnerability to climate change.

The analysis of indicators that contribute the most to the vulnerability also helps identifying which aspects of the vulnerability to focus on, meaning which characteristics of sensitivity and of adaptive capacity determine the local strengths to maintain/improve and the local weaknesses to reduce (non-perfect indicators). For instance, indicators that are at their best values according to the normalisation rules, are considered not to have a margin of improvement and thus not to contribute theoretically to vulnerability (absence of sensitivity or super adaptive capacity): the assessment will not emphasize on them

For the social dimension, the sensitivity appears to be low and the adaptive capacity extreme, so at first sight, few improvements could be made regarding users groups to decrease the socio-ecological vulnerability to climate change. But these results should be taken cautiously because the data coverage and the data confidence for these dimensions are low or medium. This means that social indicators values can be questionable according to the current data input (few available social data and social monitoring) and highlights the need of acquiring sets of robust and quantitative data in the CNP (when it is relevant and possible) in order to strengthen the quality of the vulnerability assessment to climate change, along with the improvements of research and management. It will be also useful as solid evidence for many other purposes.

For the ecological dimension, management actions could focus with confidence on lowering the high to very high sensitivity and on completing the extreme adaptive capacity (covering some important lacking aspects which could be improved). Indeed, both habitats and species of the CNP will display moderate to very high vulnerability to climate change in the future and adaptive management should be adopted from now on to protect them and to reduce the relevant human pressures, in particular to anticipate the case of the worst scenario (RCP8.5).

6.2 ECOLOGICAL AND SOCIO-ECONOMICAL MONITORING ARE NEEDED TO TRADUCE REALISTIC VULNERABILITIES AND HELP DECREASE THEM

6.2.1 WATER CONDITIONS AND HUMAN PRESSURES

The water conditions (mainly pollution and deoxygenation) stands out to be one of the main components contributing the most to the ecological vulnerability, and there is an obvious need for the CNP to trigger and assist the improvement of water quality in order to reduce the ecological sensitivity. Given the CNP geographical situation, at the door of large cities (like Marseille or La Ciotat), the reduction of pollution or the increase of oxygen level constitute then (and for a long time) a big challenge.

In the same way and without surprise, the high coastal population density associated with the suburban situation, represent also one of the main factor contributing to the CNP ecological vulnerability, but as it cannot be changed, the focus will be put on the following human pressures.

As for the fishing pressure, based on the amount of tons of the most caught species in the CNP, as well as the catch rate from CNP or the fishers density, it was not available in the CNP as fisheries data are not available on the territory (small-scale artisanal fisheries are not easy to monitor). That's why a fishing effort study within the CNP based on field interviews (basic fisheries indicators and characteristics), concerning both recreational and professional fishermen, has been planned and has begun in 2021 (even if not all fishermen representatives agree to cooperate). This study will also help to fill data gaps for recreational fishers (e.g. approximate number of recreational fishers, average catch, number of boats, etc.) in order to get a more accurate view of the global fishing pressure (professional + recreational) and to later think about its potential reduction, that could in turn participating in decrease the ecological sensitivity to climate change.

Concurrently, even though surveillance efforts are already deployed over the MPA, poaching activities remain very difficult to monitor, and it is necessary to strengthen this surveillance by building a trustful network of observers/informers and by resorting to photo/video surveillance when possible (e.g. photo trap). Decreasing poaching is still possible through enforcement actions (such as inter-units operations at sea) combined in advance with active communication on the benefits of No Take Zones. In accordance with this, several communication materials (explicative booklet, movable exhibition and online platform) have been created in 2021 on No-Take Zones and will hopefully help raising-awareness among fishermen and convince them to respect the regulations in place.

Regarding ghost nets, they do not appear as main contributors of vulnerability as such, but they are probably largely under-estimated given the importance of fisheries in the large area that the CNP represents, and they have to be kept in mind for effective management actions. The estimation used in this assessment comes from the GHOST MED project, a citizen science programme that aims at creating a dynamic network of sea users in order to evaluate the impacts of lost fishing gears (https://ghostmed.mio.osupytheas.fr/fr). This project allows making an inventory of ghost nets, with their geographical positions and any relevant information to assess the impacts on the habitats and species, which will then trigger their removal or not. Citizen participants, like Palana Environnement association and some diving clubs, help the CNP managers to deal with this pressure and to decrease a little the presence of ghost nets on the territory. This initiative goes along with raising-awareness and responsibility among professional fishers (improvement of material for instance) to gradually solve the issue at the root.

Finally, the precise quantification of the nautical activities impacts (though the annual number of boats in the CNP) is lacking, but it is a common empirical knowledge that there is a huge quantity of boats within the CPN waters, in particular during high season. However, among all boats present, it would be almost impossible to distinguish diving boats, from recreational fishing boats or from private leisure boats, as the CNP cannot control all its territory (ethical and pragmatic issues) and as these activities are often coupled. Only the passengers' sea transport boats are currently monitored (few boats authorized). One solution could be to settle automatic video monitoring at all the key maritime entries of the CNP heart to begin with, as it was done as a test one day in the high season in 2020, to have a rough estimate of the number of boats per day in high and in low season, and thus to estimate in a tangible way the pressure of boating activities. This information would be then used to decide which management or regulation actions to implement given the theoretical load capacity in order to decrease the ecological sensitivity. Indeed this load capacity would result from the recorded or potential impacts on the species and habitats.

6.2.2 SPECIES AND HABITATS INTEGRITY

The species conservation status or the species population indicators are parameters that could be improved in the CNP by management actions in order to decrease the ecological sensitivity, as some species are experiencing a decline in their population (*Pinna nobilis*, *Lithophyllum spp*., *Cystoseira sp*. or *Octopus vulgaris*). Those two indicators are also partly quantitative and exclude some species (*Physeter macrocephlus*, *Sparus aurata* and coralline calcareous algae), as monitoring is missing on several species in the CNP and need clear improvements in order to collect local data series, even though some abundance trends are already detected by observations and local knowledge. In the same way, the condition of benthic communities for most habitats in the CNP is average, and even low for the *Cymodocea nodosa* seagrass meadow, and was evaluated qualitatively by CNP managers deriving from literature and local knowledge. Though, it would have been interesting to use ecosystem-based indicators, such as EBQI (Personnic *et al.*, 2014; Ruitton *et al.*, 2014; Rastorgueff *et al.*, 2015; Thibault *et al.*, 2017), CAI (Deter *et al.*, 2012a,) or CARLIT (Blanfuné *et al.*, 2017a), which can better reflect the ecological state of a particular habitat and the power of complex trophic relationships that can help buffer the effects of climate change. Also, the indicators choice was done to be equivalent between MPAs, but some other indicators, still at the species level, may have been more suitable to the CNP and complementary, when raw data was not existing for the indicators selected, such as the species population. Indicators such as the occurrence of fish species in Underwater Visual Census monitoring (e.g. for *Epinephelus marginatus* Le Direach *et al.*, 2017a), the CPUE in scientific fisheries (e.g. for *Mullus surmuletus*, Le Direach *et al.*, 2017b), the number of vocalizations/calls in passive acoustic monitoring (e.g. for *Sciaena umbra*, Di Iorio *et al.*, 2020) or the encounter rate (for marine mammals, GECEM, 2019), are usually used as proxies of the abundance of mobile species (species population indicator). For benthic invertebrate species, the density per square meter of gorgonian species (e.g. for *Corallium rubrum*, Richaume *et al.*, 2019; for *Paramuricea clavata*, RECOR, 2020), the average roots per square meter at the inferior limit of *Posidonia oceanica* meadows (TEMPO, 2020), or the percentage of rocky coastal length covered by alive *Lithophyllum byssoides* (Blanfuné *et al.*, 2017b), are also alternative indicators that could have been used in this assessment to traduce the species ecological status and thus the ecological sensitivity to climate change.

Gorgonians species, *E. marginatus* and *S. umbra* displayed the highest species sensitivity to SST or to MHW, whereas for *Lithophyllum spp.* (whose one species, *L. byssoides,* constitute exceptional bio-concretion in coastal rocky habitat in the CNP) and for Coralline calcareous algae (the major component of coralligenous habitats) the species sensitivity to STT or MHW was not included in this analysis, as it was not possible to find generic data in the literature for these groups of several species. To overcome this lack of data, a more advanced research could be engaged on the main species considered in this genus in the CNP. Nevertheless, for *L. byssoides*, which lives at the interface between sea and air in high temperature conditions, the thermal tolerance is assumed to be high and thus would not increase the ecological sensitivity. Despite those sensitivities, few mass mortality events have been recorded for now in the CNP.

Monitoring of species indicators of climate change in the CNP (e.g. presence and expansion of warm-water species over temperate and cold-water species in Fish Visual Census protocol) would enhance the knowledge of threats to species and habitats and contribute to anticipating the ecological sensitivity, knowing that the presence of endangered species is moderate in the CNP. As for invasive species, which often benefit from warmer waters that create favourable conditions for developing and settling, their presence is considered to be low in the CNP, as well as the risk of invasive species (low current habitat suitability for 9 known invasive species). Indeed these known invasive species have not arrived yet in the CNP (low invasive status) but the possibility remains and the risk may increase with warming waters. However, other unforeseen invasive species can arrive and be damaging (*e.g.* local invasion of *Rugulopteryx okamurea* occurring in the CNP since 2018 and affecting infralittoral rocky habitats). A rapid detection and monitoring of these potential new non indigenous species are essential to implement through close relationships with local diving clubs (LEK 3 interview), a regular environmental watch through citizen science and also CNP visual monitoring. It allows assessing the extent of invasion and the likely impacts on local species and habitats which can increase the ecological vulnerability to climate change. In the future, a deeper integration of the results of MPA Engage monitoring activities into the tool (through updated indicators) would be useful and help consolidate the vulnerability assessment.

6.2.3 RECOVERY POTENTIAL AND REDUNDANCY

In accordance with the medium conditions of benthic communities, caves and infralittoral rocky bottoms display an average complexity, which was qualitatively by the CNP managers and could be improved by implementing new monitoring methods of 3D cartography, such as photogrammetry, a powerful, accurate and cost-effective photographic tool which can provide indicators related to habitat structure and complexity (Deter *et al.*, 2012b; Palma *et al.*, 2019; Marre *et al.*, 2019). For now, the photogrammetry monitoring initiated in the CNP through MPA Engage will allow acquiring these kinds of data for only coralligenous habitats, whose vulnerability was highlighted in this assessment.

As for the habitat extension or the MPA shape, which stand out as the main indicators contributing to the lack of ecological adaptive capacity, the low values are due to the design of the CNP in itself and are not improvable. Indeed, the CNP is a large MPA which covers not only coastal habitats (the ones selected in this assessment) but also the open sea, including submarine canyons and sandy bottoms (until the EEZ limit), hence the shape. In contrast, the large size of the fully protected area (No Take Zones >46 km2), the high habitat connectivity (for most of them) and the habitat monitoring in place (except for *C. nodosa* segrass meadow), will together contribute to improving the ecological adaptive capacity of the CNP. As a reminder, fully protected areas are the most resilient ones to climate change and constitute the better option to promote.

Regarding species, the recovery potential to climate change is a component to carefully look at to improve the adaptive capacity. Habitat generalist species will be more resilient than habitat specialist species, which are restricted to one habitat that can be severely impacted by climate change. Hence, the focus should be put on more vulnerable specialist species such as gorgonians, *P. nobilis*, *P. oceanica* and algae (*Lithophyllum spp*., *Cystoseira spp*. and coralline calcareous algae). In the same way, priority species to focus on are the ones with a high age of first maturity (fecundity potential), like gorgonians, which are supposed to have more difficulty recovering if an external impact occurs and affect the species. Short or medium larval dispersal ability (*e.g.* low larvae duration) can also be unfavourable for climate change adaptation for these same species (gorgonians, *P. nobilis*, but also *Scorpaena scrofa*, *S. umbra* and *E. marginatus*).

Besides, the species size distribution indicator could be improved by additional monitoring of species targeted by fisheries (e.g. *S. aurata* or *Octopus vulgaris*) and specific flagship species (e.g. *S. umbra* or marine mammals) through underwater visual census or boat observations (large individuals in general synonymous of good population state and fecundity), which could in turn increase the number of monitored species in the CNP and contribute to adapt to climate change.

To resume this part of the discussion, these vulnerability assessment results globally highlight the need to focus the future CNP actions on the following habitats and species to decrease the ecological vulnerability and adapt to climate change: gorgonians (*C. rubrum*, *P. clavata* and *Eunicella cavolini*), *P. nobilis*, *P. oceanica* seagrass meadows and *C. nodosa* seagrass meadow.

6.2.4 USERS SENSITIVITY, ADAPTIVE CAPACITY AND PERCEPTION

Strengthening the data coming from users questionnaires seems important as not enough participation was recorded to be really representative of all the users (there are numerous users in the CNP that have different opinions) and to get a better view of the social organisation (collaboration, participation, trust, transparency, conflict, accountability), of the flexibility (substitute areas, livelihood diversity, gear diversity or number of species targeted) and of the assets available (financial resources) to face climate change, but also of the socio-cultural aspects of stakeholders involved (risk attitudes). Indeed, these components of the social adaptive capacity could be decisive for adaptation to climate change, insuring more or less good acceptance, respect and implementation of the management measures already in place or to be adopted. The CNP needs to make the stakeholders feel they are included in the management process and in the different projects the CNP is participating in. Also, social sensitivity indicators, such as the loss of working or fishing days due to extreme weather conditions, could also be improved with numerous users questionnaires to get a real vision of the sensitivity of each users group (professional fishing, recreational fishing, diving, boating, tourism).

As, it is not planned and advisable, or even possible (beach area), to increase the different areas available for recreational activities (the tendency is even the opposite to protect habitats and species) in order to decrease the social sensitivity, the focus has to be set on other parameters. Likewise, recreational activities facilities might be barely improved in the CNP (good access to ports but moderate port mooring fees that could most certainly not be lowered), and the low local job dependence on fisheries or on recreational activities is already low.

The development of more sustainable and adaptive recreational fisheries would benefit recreational fishermen and increase their adaptive capacity. It could be implemented by increasing the recreational fishing gears used in order to adapt to the different type of species and their temporal variation during the year (presence/absence), and by targeting a higher number of species, either better distributed in the food webs (in particular less known intermediate fish species) or new meridional/tropical species, even though, for now their species dependence is low (no variation detected in their target species).

The social adaptive capacity of professional fishers could be increased by diversifying their activities to add secondary sources of income and then increasing their average global income (decreasing their sensitivity), even though their attachment to fishing is high. Also, as the area available for professional fishing, will not increase (at better for them it will remain stable or potentially decrease), management actions have to persist or to be initiated to improve the population health of endemic species on which they depend (moderate species catch dependence) and the then decrease the social sensitivity of this user group. No–take zones or temporal catch regulations are good examples.

There are no precise and complete economic studies that could depict the dependence of both professional and recreational activities on the CNP ecosystems and resources, for instance regarding the income or employment generated by the CNP, but it would be a lead to explore to better establish the CNP importance in the region. The quantification of ecosystem services provided by the CNP could be used as a proxy and could have many applications beyond this vulnerability assessment. Existing studies on ecosystems service of coralligenous habitats (Thierry de Ville d'Avray *et al.*, 2018) or *Posidonia oceanica* seagrass meadows (Boudouresque *et al.*, 2015; Campagne *et al.*, 2015) are a good working base to be adapted to the surface areas and ecological states of CNP habitats.

6.2.5 CASE OF DIVERS

The diving sector will be the most vulnerable to climate change and the CNP has to work with this users group to anticipate and monitor their potential adaptation to climate change. Indeed, even if the CNP has no data regarding the average number of divers in its area, it is well known that divers are highly active and numerous in the CNP, which lead in 2014 to the establishment of the CNP diving Charter, a rapid tool to settle and support the future objectives. However, despite the fact that, signing this Diving Charter, the diving clubs and associations have an obligation to declare activities parameters (such as number of divers, number of dives, visited sites, etc.) through the mobile application “Mes Calanques”, they don’t do it. The need to improve knowledge on diving activities at local level thus remains.

A diving committee, which should be created in 2022 as the outcome of the master plan of recreational activities coherence, is a second action that would improve the collaboration with the diving stakeholders. It is expected from this committee that they would better understand the necessity of monitoring the diving activity within the CNP and of engaging actions to cleverly frame the practice (*e.g.* designing a decision tree for the choice of diving sites according to the frequentation in real time or to the diving purposes).

6.3 THE MPA MANAGEMENT EFFORTS AND EFFECTIVENESS NEED TO BE BETTER ASSESSED AND ENHANCED

To overcome the lack of current monitoring indicators about the MPA management, it would be possible to set in place a dashboard, which is a simple, detailed and useful tool to monitor and assess the management efforts from real executed actions and numbers (e.g. staff and budget necessities compared to real ones, number of surveillance trips realised, etc.). This dashboard would better traduce the MPA ecological adaptive capacity to climate change and give insights and confidence to this assessment. The CNP charter evaluation, on which the work has been started in 2021, is kind of a global MPA dashboard, updated every 10 years and which gathers monitoring indicators of the actions completed or partly realized since the CNP creation. It is a good tool for long term vision but not useful for daily/yearly management where a more adapted and practical version would be needed.

The CNP display some ecological adaptive capacities, with strengths and weaknesses in its management characteristics, which could for instance be enhanced to reduce the ecological vulnerability by:

- Increasing the budget (currently acceptable but with improvements needed) and the staff capacities (insufficient) in order to fully achieve an effective management in particular for climate change adaptation. One solution could be to resort more to funded projects to develop some activities that have trouble starting and to hire more staff.
- Strengthening the average capacity of enforcement and the average surveillance (but this supposed more staff and budget)
- Implementing efficiently management plans for recreational activities and professional fisheries

- Replacing the marine monitoring as a central objective of the CNP and carrying it out with the available financial, human and material MPA needs (looking for funding for capacities building, planning on short-term and mid-term and staggering the monitoring over time, delegating to subcontracted partner some monitoring and participating into national/ regional monitoring network designed for public policies).
- Discussing, defining and engaging relevant restoration processes in the CNP (when not controversial) to favour better resilience of some marine habitats and species not submitted to certain human pressures anymore.
- Thinking about the possibility of extending the current No-Take zones, representing only 3.28% of the MPA, to some relevant places in the adjacent maritime area (around the Frioul islands for instance).

Additionally, adopting a responsive and adaptive management will greatly help to increase the ecological adaptive capacities. This will be mainly achieved by having access to the existing high frequency water column monitoring (daily) operated by the SOMLIT surveillance network (define the availability of treated data and the kind of collaboration to create) and by enhancing collaboration with scientists on the climate change theme in order to strengthen knowledge and services sharing (through the CNP scientific council sessions or actions, the attendance to relevant symposiums and the implementation of scientific partnerships).

6.4 BROADENING OF THE ASSESSMENT TO OTHER CLIMATE CHANGE FACTORS AND IMPACTS

Due to the limited amount of data available on projections of future climate stressors in the MPAs, this vulnerability assessment focuses only on two climate stressors: sea surface temperature increase and marine heatwaves associated.

6.4.1 SEA TEMPERATURE IN DEEPER LAYER

The sea temperature evolution along the depth gradient (water column stratification and thermocline) and the penetration of marine heatwaves into the deeper layers of the water column (e.g. deep coralligenous habitats and canyons) were not considered in this assessment. Temperature records and projections in the different water masses of the Mediterranean Sea are also available in the scientific literature. For instance, temperature data (time series) is available for several sites in the CNP from 0 m to 45 m depth through the monitoring program T-MEDNet (https://t-mednet.org). Soto-Navarro *et al.* (2020) modelled temperature changes by the end of the century which ranges between 0.81 and 3.71 °C in the upper layer (0–150 m), between 0.82 and 2.97 °C in the intermediate layer (150–600 m) and between 0.15 and 0.18 °C in the deep layer (600 m—bottom) depending on the IPCC scenarios.

Indeed many of the species and habitats selected in this assessment live deeper in the water column and it would have been more accurate and indicative of true sensitivity to assess what will happen along the water column (between 10 and 40m). This approximation would explain partly the low or moderate ecological vulnerability results of this assessment whereas it could be higher in reality. For instance, several benthic species (gorgonians, sponges, coralline algae) living below the usual thermocline are highly sensitive to an extended exposition to high sea temperatures, which have caused previous mass mortality events during deep marine heatwaves (Perez et al., 2000 ; Garrabou et al., 2009). Cold water corals (e.g. Madrepora oculata) living in the canyons of the CNP (Cassidaigne, Planier) are assumed to be extremely sensitive to sea warming as they already live at their upper thermal tolerance limit (13-14°C). However the effect of the concomitant increase in temperature, pCO2 (acidity) and salinity have to be studied to conclude on the potential fate of these cold water coral species in the future as both calcification and respiration reveal a strong acclimation response to temperature (Maier et al., 2019).

Particular hydrodynamics in the CNP due to the regular upwelling phenomenon in the summer (when Mistral blows) could be another reason which explains a lower vulnerability to climate change as it could protect partly the marine ecosystems from lasting marine heatwaves by cooling down the waters.

Also, natural and cyclic phenomena, such as filamentous algae blooms or jellyfish blooms, can also be boosted by water column temperature increases, which offer them suitable conditions to develop and last. For instance, high sea temperature can favour jellyfish reproduction and growth, combined with plastic multiplication at sea (polyp fixing), eutrophication (more plankton for food) and overfishing (removing their direct predators, e.g. sea turtles and tunas, and their competitors, e.g. forage fishes). High jellyfish blooms can deplete the fish biomass by feeding directly on fish larvae but also on the zooplankton prey of these fish larvae (competition).

As for filamentous algae, these seasonal blooms seem to be linked to several factors, including increasing sea temperature and light, nutrients availability and calm water, but disappear with strong wind. Since the ‘80s, this phenomenon is observed to be more frequent and to last longer but for now has still a limited impact (stress caused to organisms that struggle to feed below the thick cover). For instance, within the 4 water bodies of CNP, the filamentous algae bloom indicator (percentage of maximum cover by filamentous algae during the period 2010-2019) is medium in 3 water bodies and good in 1 (Atlas de synthèse, 2020). Combined with the acidification (more dissolved inorganic carbon available), the increase of sea temperature could intensify filamentous algae production (Koch et al., 2013).

Those two phenomena can complete the set of indicators as they could impact the ecological status of the species and habitats and affect the users sensitivity (diving sector for filamentous algae and boating sector or professional fishing for jellyfish blooms).

6.4.2 ACIDIFICATION

The Mediterranean Sea takes up large amounts of anthropogenic CO2 from the atmosphere due to its chemical and current-related properties, which in turn increases the pH and causes its acidification (formation of carbonic acid). Global surface pH has already decreased by more than 0.1 units since preindustrial times (Denman *et al.*, 2011), which means the acidity has increased by 30% in the global ocean. In the bay of Villefranche-sur-Mer, the pH has decreased by 0.0028 units per year during the period 2007-2015 (Kapsenberg *et al.*, 2017). The projections in the Western Mediterranean Sea are a pH decrease of 0.25 (in the most optimistic SRES scenario of the IPCC) to 0.46 (in the most pessimistic SRES scenario of the IPCC) in 2100 (Goyet *et al.*, 2016), which are both higher than the ones forecast for the global ocean (Gattuso *et al.*, 2015).

The Mediterranean Sea acidification will be an increasing factor of exposure to climate change in the future as it reduces the amount of carbonate available, which could create issues for many calcifying marine organisms to build their skeletons/shells and also the carbonate dissolution of these existing skeletons/shells. This phenomenon could be a big threat for coralligenous habitats survival in the CNP, mainly constituted by calcareous organisms (e.g. coralline algae or red coral), and for keystone calcifying species (e.g molluscs or sea urchin). Coccolithophores (abundant phytoplankton in the water column) or foraminifera and pteropods (zooplankton) can see their protective coating disintegrated by too acidic waters and lead to food web/nutrient cycling modifications by cascading effects. Deep-sea animals, such as cold-water corals present in the CNP canyons, are in theory even more sensitive to acidification as they are built from aragonite form of calcium carbonate which is more soluble than regular calcite from, and as the calcium carbonate is more soluble in high pressure and cold water of the canyons. However, some experiments showed a high resilience of these species which may be able to maintain calcification and respiration rates constant in more acidic waters (Maier *et al.*, 2019). As for sea urchin and starfish, they build their shell-like parts from high-magnesium calcite, a type of calcium carbonate that dissolves even more quickly than the aragonite form of calcium carbonate that corals use. This means a weaker shell for these organisms, increasing the chance of being crushed or eaten, and thus modifications in their density (Asnaghi *et al.*, 2013). Indicators related to sensitivity to acidification of these species/habitats would increase the ecological vulnerability.

Moreover, marine organisms could experience changes in growth, development, abundance, and survival in response to ocean acidification (Kroeker *et al.*, 2013). Most species seem to be more vulnerable in their early life stages. Acidification may also cause direct acidity issues to sensitive organisms (inside their internal fluids, e.g. acidosis) and alter sensory systems and behaviour in fish and some invertebrates.

6.4.3 SEA LEVEL RISE

Worldwide, the global mean sea level from tide gauges and altimetry observations has increased from 1.4 mm per year over the period 1901–1990, to 2.1 mm per year over the period 1970–2015, to 3.2 mm per year over the period 1993–2015, to 3.6 mm per year over the period 2006–2015 (Oppenheimer *et al.*, 2019). By 2100, the global mean sea level will rise depending on IPCC scenarios between 0.43 m (0.29–0.59 m, likely range; RCP2.6) and 0.84 m (0.61–1.10 m, likely range; RCP8.5) relative to 1986–2005 (Oppenheimer *et al.*, 2019).

Averaged across the Mediterranean Basin, the mean sea level has risen by 1.4 mm per year during the 20th century (Wöppelmann & Marcos, 2012) and has accelerated to 2.8 mm per year recently (1993–2018) (Cazenave and WCRP Global Sea Level Budget Group, 2018). The Mediterranean mean sea level will likely be 37 to 90cm higher than at the end of the 20th century, with a small probability to be above 110 cm. The sea level rise is thus accelerating due to climate change and the main drivers are terrestrial ice melting (glaciers and ice sheets) and the North-eastern Atlantic dynamics (in addition to thermal expansion) (Jordà *et al.*, 2020). These predictions are subjected to variations depending on the prediction models used. In parallel, a reduction of the average number of positive storm surges is forecast throughout the 21st century as well as a general reduction of the mean significant wave height field over the Mediterranean Sea (Lionello et al., 2017).

In the area of Marseille, the sea level has risen 20 cm since 1870, with a rhythm of 1.40 mm per year over the period 1909-1980 and 2.6 mm per year over the period 1980-2012 (Wöppelmann *et al.*, 2014).

The sea level rise is already responsible for coastal erosion and floods (known impacts on rocky cliffs and beaches) and this phenomenon will increase in frequency and intensity in the future. In particular, the coastline retreat and the role *Posidonia oceanica* banquettes to slow down the process have to be considered within the CNP coasts as an adaptation to climate change measures. Marine submersion is also predictable along with seal level rise: it will cause the loss of the *Lithophyllum byssoides* bio-constructions, a coastal habitat of high interest in the CNP and thus highly vulnerable to climate change. The Cosquer cave is another CNP important feature threatened by the sea level rise and highly vulnerable to climate change. The scientific team working on the cave topographic mapping has noted that inside the cave, the sea could rise several tens of centimetres since 2011, due to the multiplication of high atmospheric pressure episodes in the Northern Mediterranean basin. This phenomenon would already have submerged and damaged some of the most famous cave paintings. In parallel, some harbour infrastructures would need to be raised to support the future sea level rise and the foreseen seawater intrusions into coastal aquifers would have to be studied. These vulnerabilities have to be taken into account as social adaptive capacity into the climate change adaptation planning strategy of the cities near the CNP.

The platform « Mon littoral Provence-Côte d'Azur» was created in 2020 with a prototype in the Var French department, which will be followed to an extension to other departments of the regional coast (https://www.monlittoral.fr). It aims to develop a regional observatory of the coastline over the regional coast (Stratégie nationale de gestion intégrée du trait de côte, 2012) and to enhance the knowledge on coastal risks management and climate change adaptation. To complete this tool, the citizen science application « Rivages » was initiated by the CEREMA to monitor the coastline evolution and erosion. These 2 tools will contribute to better understand the local changes and local vulnerabilities to sea level rise.

6.4.4 INCREASE OF SALINITY AND CURRENTS DYNAMICS

An increase of salinity in the intermediate (200-600 m) and deeper layer (>600 m) was recorded in the Western Mediterranean Sea over the period 1945-2000 (Vargas-Yáñez et al., 2012). The French SOMLIT network for monitoring of coastal environment also recorded an increase of salinity from 1997 to 2016 at the Frioul station (Lheureux et al. 2021) in the CNP.

Nevertheless, the future evolution of the sea surface density of the Western Mediterranean Sea remains uncertain due to the opposite effects of an increase in sea surface temperature and sea surface salinity. In all the simulations, the salinity will increase due to the increase of the freshwater deficit (i.e. the excess of evaporation over precipitation and river runoff) and the related increase in the net salt transport at the Gibraltar Strait (inflowing waters from the Atlantic). Adloff et al. (2015) projected an increase of salinity of+0.48 to +0.89 for the 2070-2099 period compared to 1961-1990 depending on IPCC scenarios, which could be under-estimated (much stronger evaporation, Skliris et al., 2018). More recently, Soto-Navarro et al. (2020) projected salinity changes per water masses by the end of the century for the whole basin : they range between 0 and 0.34 psu in the upper layer, between 0.08 and 0.37 psu in the intermediate layer and between − 0.05 and 0.33 in the deep layer depending on IPCC scenarios.

Generally, pessimistic scenarios project a decrease in surface density at the end of the 21st century (temperature increase prevails on salinity increase) which will be associated with an increase in vertical stratification of the water column. But an increase in density (and a decrease in stratification) is still possible in optimistic scenarios with a low level of warming (Adloff *et al.*, 2015). There is a model consensus that the intensity of the deep water formation (dive of dense and cold-water surface masses) in the Gulf of Lions is expected to decrease in the future (Soto-Navarro *et al.*, 2020). These future shifts in marine currents dynamics, which are powerful climate regulators, may have strong consequences on food web dynamics and on food availability, in particular for deep ecosystems (e.g. canyons) with the increasing stratification acting like a density barrier for the vertical mixing of nutrients and oxygen (coming from the primary production). The modifications of the Mediterranean thermohaline circulation, combined with the sea warming (which decreases the oxygen solubility) and eutrophication (nutrients enrichment), may cause oxygen depletion of the deep water masses in the future, even if it should not be severe (Powley *et al.*, 2016). Indeed, the enhanced primary and secondary production in surface waters would increase the delivery rate of degradable organic matter to deep waters, where microbial decomposition by aerobic respiration consumes oxygen. More, generally, changes of communities and of species repartition (for instance of organisms whose movement depend on marine currents such as fish and crustacean larvae), as well as cascades of physiological responses, could be expected. All these future changes may increase the future ecological vulnerability of many species to climate change (sensitivity to current dynamics).

6.5 LESSONS LEARNT AND DIFFICULTIES THROUGHOUT THE PROCESS

During the various vulnerability assessment activities, difficulties arose and the following paragraph goes back on the main lessons learnt in the CNP, which will be useful for future work on the subject. First, the data collection was quite difficult to carry out in the CNP due to the lack and the scarcity of some type of data in this young MPA (in particular social data) and to the absence of a marine database gathering all relevant ecological indicators related to habitats and species (big bibliographic work).

Secondly, the number of indicators included in this assessment was quite high to be representative of the CNP heterogeneity and of the different aspects of the climate change vulnerability (social and ecological). Even though it was optimised by UVIGO team, this high level of data required has in turn made more complex the assessment and more difficult the right understanding of the indicators and components results per dimension. The interpretation in details of this vulnerability assessment requires then lots of time and expertise.

Finally, the process of fine-tuning the tool after testing it in the different MPAs was essential to detect errors/weirdness (in indices design, in aggregation formula applied or in programming the tool) and to be sure that the averaging and weighting of dimensions, component or indicators does not smooth the real vulnerabilities. For instance, the CNP help solving mistakes linked to the figures/report display or to the different vulnerability indices values. The MPA feedbacks were then important to revise the tool and make it operational (confident socio-ecological vulnerability indices) and transferable to other MPAs at the end of the project.

However some limitations remain, as the impossibility for the MPA manager to update directly the data template (with new collected) and to upload it into the tool (right now it is necessary to go through UVIGO team). Likely, work has to be planned and realized in a near future by UVIGO team to integrate MPA Engage monitoring indicators, as well as proposed indicators available in the CNP that could better reflect the ecological or social components selected. Besides, in the mid-term, some work would be necessary to integrate also other climate change stressors (local or regional projections) and associated indicators.

7 Conclusion

This report is the first attempt to assess the future socio-ecological vulnerability of the CNP to climate change, taking into account both the ecological and the social systems. It was built using the vulnerability assessment tool developed in the framework of the MPA Engage project, which considers projections of specific climate change exposure factors (SST & MHW) and characteristics of species, habitats and user groups of the MPA through their social and ecological dimensions (sensitivity and adaptive capacity).

Thus, the socio-ecological vulnerability will be low in the CNP in all carbon emissions scenarios in 2050 and in RCP 2.6 in 2100. It will raise to moderate in RCP4.5 and RCP8.5 scenarios in 2100, mainly because of the increasing ecological vulnerability, going from moderate in all scenarios in 2050, to high in RCP4.5 and very high in RCP8.5 scenarios in 2100. The extreme social adaptive capacity in the CNP will be offsetting the ecological vulnerability and will go along with the low social sensitivity, hence a low socio-ecological vulnerability. As for the ecological vulnerability, it will increase with the increasing exposure, which goes from moderate to very high in the worst scenario (RCP8.5), given its extreme ecological adaptive capacities and its high to extreme ecological sensitivity. Most of the habitats and species of the CNP, but also all the users groups, will have high to very high vulnerabilities to climate change in the RCP8.5 scenario, which could be lower in the low carbon emissions scenario (RCP2.6).

The quality of the assessment reveals that the data coverage and confidence is good for ecological vulnerability and could be improved for social sensitivity and social adaptive capacity in order to refine the indicators and strengthen the vulnerability assessment. Indeed, the lack of monitoring and studies, either on some ecological aspects or on the socio-economical components of the CNP, stands out of this assessment, but will help the CNP managers to better target their future monitoring priorities (data acquisition to finance). In addition, the vulnerability assessment tool remains useful, as it could be fed up with additional data over the next years to continuously consolidate and update the indicators and thus the socio-ecological vulnerability results. However, the tool would need to be broadened in a near future to other climate change factors projections (acidification, sea-level rise, etc.) which will have cumulative effects (synergetic or not) and that could not be set aside to depict the more realistic vulnerabilities to climate change. Ultimately, the risk is that climate change worsens the existing or forthcoming human pressures on species and habitats, which would be already weakened by their vulnerability to climate change, and vice versa, particularly in a suburban MPA such as the CNP with multiple pressures to cope with.

This socio-ecological vulnerability assessment constitutes the first step in the process of elaborating the adaptation plan to climate change of the CNP, providing the basic material to guide the design and implementation of management measures during participatory approaches, along with the associated monitoring and citizen science results. An adaptive management of the CNP is the key to facing present and future climate change impacts, given its socio-ecological vulnerability, by restoring or maintaining essential functions and services of the marine ecosystems (re-establishing ecological corridors, restoring specific affected environment, supporting selective and sustainable fisheries, improving wastewater treatment, setting up and managing No Take Zones, organising and framing sustainable and reasoned recreational activities, etc.).

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9 Annexes

9.1 ANNEX 1 – LISTS OF INDICATORS

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.MH W	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 the average income of an artisanal fishers working within the country EEZ in relation to the average worker income in the region. The indicator aims to assess the average earning of fishers in relation to the average regional income.
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.

9.2 ANNEX 2 – STRUCTURE OF THE INDEX

Table9.2. 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
EX RE	SST threat	SST increase	SST	O			O		
	MHW threat	Marine heatwaves	MHW	O			O		
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			0			
		Invasive status	INV.ST			0			
		Species population size	SP.POP	0		0			
ECO ADA CAP	Habitat redundancy	Habitat diversity within the MPA	DIVHB	0					
		MPA shape	SHAPE	0					
		Fully protected area	SAREA	0					
	Habitat Recovery potential	Habitat complexity	HB.COM	0	0				
		Habitat extension	HB.EXT	0	0				
		Habitat connectivity	HB.CON	0	0				
		Habitat depth	HB.DEPTH	0	0				
		Habitat monitoring	HB.MON	0	0				
	Species Recovery potential	Larval dispersal capacity	SP.DISP			0			
		Species habitat specificity	SP.HB			0			
		Fecundity potential	FECUN			0			
		Species size distribution	SP.SIZE	0		0			
		Species monitoring	SP.MON	0		0			
	Effectiveness	Polycentric Governance	PGOV	0					

		Budget capacity	BUDG	0					
		Staff capacity	STAFF	0					
		Presence of a management plan with professional fishers	M.PLAN.PF	0				0	
		Presence of a management plan for recreational activities	M.PLAN.RA	0					0
		Capacity of enforcement	ENFOR	0					
	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
SO AD	Flexibility	Substitute areas outside the MPA	U.SUBS	0				0	0

E CA Y		Number of targeted species	U.TARG	0				0	0
		Livelihood diversity	L.DIV	0				0	
		Gear diversity	F.GDIV	0				0	0
		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
		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
	Social Organization	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

9.3 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:

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

(d)

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 $(HB.SEN.SST_{j,i})$, habitat sensitivity to marine heatwaves $(HB.SEN.MHW_{j,i})$, 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 ($HI_{j,i}$) 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)

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

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)

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

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:

(6)

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

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]) giving equal weights to each dimension but ensuring that the values range from 0 to 1 following the equation:

$$PF.VULN_i = \frac{(E_i + PF.SEN_i - PF.AC_i) - (-1)}{2 - (-1)} \quad (8)$$

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:

$$PF.SEN_i = \omega_m * F.DEP_i + \omega_m * F.EFF_i + \omega_m * LOCAL.DEP_i + \omega_m \quad (9)$$

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:

S (15)

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

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:

$$4.EMP_{u,i} = \omega_c * ACT.DAYS_{u,i} + \omega_c * ACT.DEP_{u,i} + \omega_c * ACT.COMP_{u,i} \quad (21)$$

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:

$$RA.EC_{u,i} = \omega_c * ACT.AREA_{u,i} + \omega_c * USERS_{u,i} + \omega_c * RF.SPDEP_i \quad (22)$$

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

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

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) $$\text{R}G_{u,i} = \omega_c * U.COLW_{u,i} + \omega_c * U.COLA_{u,i} + \omega_c * U.PART_i + \omega_c * U.TRUST_{u,i} + \omega_c * U.TRANS_{u,i} + \omega_c * U.ACCO_{u,i} + \omega_c * U.CONFW_{u,i} + \omega_c * U.CONFA_{u,i}$$

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)

$$HP_i = \omega_c * PDEN_i + \omega_c * POA.PF_i + \omega_c * POA.RF_i + \omega_c * GNET_i + \omega_c * FGEAR.PF_i + \omega_c * FGEAR.RF_c + \omega_c * FPRES_i + \omega_c * IMP_i,$$

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)

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

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:

$$EF_i \quad (40) \quad PGOV_i + \omega_c * BUDG_i + \omega_c * STAFF_i + \omega_c * M.PLAN.PF_i + \omega_c * M.PLAN.RA_i + \omega_c * ENFOR_i$$

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:

$$AM_i = \omega_c * WCM_i + \omega_c * SCADV_i \quad (42)$$

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.

9.3.1 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:

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

(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

(49)

$$FLEX_i = \sum_u \omega_u * FLEX_{u,i},$$

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) 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

(50)

$$S.ORG_i = \sum_u \omega_u * S.ORG_{u,i},$$

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 $\sum_u \omega_u = 1$.

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)

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

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 $\sum_u \omega_u = 1$.

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)

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

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 $\sum_u \omega_u = 1$.

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

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

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 $\sum_u \omega_u = 1$.

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)

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

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 $\sum_u \omega_u = 1$.