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Assessing the effectiveness of marine nature-based solutions with climate risk assessments

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Abstract

Prospective risks from climate change impacts in ocean and coastal systems are urging the implementation of nature-based solutions (NBS). These are climate-resilient strategies to maintain biodiversity and the delivery of ecosystem services, contributing to the adaptation of social-ecological systems and the mitigation of climate-related impacts. However, the effectiveness of measures like marine restoration or conservation is not exempt from the impacts of climate change, and the degree to which they can sustain biodiversity and ecosystem services remains unknown. Such uncertainty, together with the slow pace of implementation, causes decision-makers and societies to demand a better understanding of NBS effects. To address this gap, in this study, we use the risk mitigation capacity of marine NBS as a proxy for their effectiveness while providing a toolset for the implementation of the method. The method considers environmental data and relies on expert elicitation, allowing us to go beyond current practice to evaluate the effectiveness of NBS in reducing habitat or species risks under different future socio-political and climate-change scenarios. As a result, we present a ready-to-use tool, and supporting materials, for the implementation of the Climate Risk Assessment method and an illustrative example considering the application of the NBS "nature-inclusive harvesting" in two shellfisheries. The method works as a rapid assessment that guarantees comparability across sites and species due to its low data or resource demand, so it can be widely incorporated to adaptation policies across the marine realm.

KEYWORDS
climate change, climate-risk assessments, effectiveness, future scenarios, nature-based solutions, species risk

1 | INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC, 2022a), the consequences of the current climate crisis will be felt for decades even if global emissions were to cease completely today. Future scenarios projecting a 2°C increase predict a higher frequency of catastrophic events (floods, hurricanes, or droughts), pushing environmental and social systems toward possible tipping points with uncertain consequences (IPCC, 2022a). Far from lowering, however, emissions keep increasing, with global CO_2

emissions from fossil fuels reaching a 36.6 billion tons record in 2021 (Friedlingstein et al., 2022). In this context, and due to the incapability of the socio-political system to rapidly swift and reduce emissions, mitigation and adaptation strategies (IPCC, 2022b) have become fundamental components in the fight against the potential consequences of climate change and, consequently, an important focus of attention of the scientific community in recent years (e.g., Fawzy et al., 2020; Owen, 2020; Salgueiro-Otero et al., 2022).

The benefits provided by nature-based solutions (NBS; IUCN, 2012), directed to improve climate mitigation and adaptation capabilities in social-ecological systems, have recently started to be acknowledged (Macready et al., 2021; Seddon et al., 2021). NBS are defined by the European Environment Agency (2021) as "*solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient and systemic interventions*." The idea behind the application of NBS to mitigate the effects of climate change is that by promoting the integrity and natural functioning of ecosystems (e.g., protected areas, restoration activities), and integrating them more fully into our social system, their natural capacity to regulate the environment and buffer environmental impacts will lower the risks derived from climate change (European Commission, 2022). In this context, the present research proposes a novel approach to quantify the climate risk reduction potential of NBS.

The investment of countries in the application and study of the benefits provided by NBS has increased in the last few years (Calliari et al., 2022). However, more investment in conservation and restoration is needed at different levels, from the European Union to a global scale, in order to implement the Kunming-Montréal Global Biodiversity Framework (https://www.cbd.int/gbf/targets/) and the EU Biodiversity strategy for 2030 (European Commission, 2021a). In the case of marine NBS, some successful applications can be found related to marine protected areas contributing toward the resilience of ecological and social systems by acting as biodiversity refugia and nursery grounds, thus contributing toward food security from a human perspective (Gissi et al., 2022). Restoration of eelgrass meadows or kelp forests has also been demonstrated to benefit the provision of ecosystem services such as global organic carbon sequestration, fish schooling, or other cultural or leisure aspects (Ruiz-Frau et al., 2017). Similarly, other types of NBS such as sustainable or nature-inclusive harvesting are increasingly considered as valuable tools with the potential to improve the adaptability and resilience of socioecological systems, encompassing the conservation of nature with sensitive social and cultural aspects (Roy et al., 2022). Because of this accumulation of evidence, the paradigm in conservation is shifting from hard engineering to more adaptive approaches that care for social identities, local knowledge, or gender inclusion (Cooley et al., 2022; Faivre et al., 2017).

Despite their potential application on decision and policy making, NBSs still lack well-established protocols for measuring their effectiveness, especially under climate change scenarios. Different approaches (and definitions of effectiveness) have been proposed and are still under discussion (European Commission, 2021b). To date, most attempts rely on indicators developed considering the different environmental challenges faced by the systems under evaluation (Murillas-Maza, 2023), and whose temporal evaluation (area covered by seagrass meadows in a bay, for instance) needs specific monitoring protocols that must be maintained through time (Aoki et al., 2020; Blanco et al., 2021). On the other hand, NBS effectiveness has been measured as the capability of these measures to decrease risk on a given system. This perspective has been mostly applied in the context of natural disasters (disaster risk reduction (DRR); Sahani et al., 2019; Tyllianakis et al., 2022) such as floods, hurricanes, and other extreme events in densely populated areas. The approach to the effectiveness of NBS as tools for DRR is focused on the physical/economic effects of NBS in the face of natural disasters and often sets aside the co-benefits of NBS in the environmental, social, and cultural domains.

In addition, the degree to which climate change impacts on the ecosystems can compromise the effectiveness of NBS remains a key question for policy and practice. By changing the physical conditions of the environment, or disrupting the functioning of the ecosystems, climate change may lower (totally or partially) the effectiveness of NBSs (Seddon et al., 2020). These failures would probably be gradual and noticeable only at mid-term temporal scales, which complicates forecasting the future scenarios of adaptation. However, several marine ecosystems are already highly disrupted by climate change, such as tropical coral reefs, temperate kelp forests or seagrass meadows, which will reach non-return ecosystem tipping points within a decade or two (Cooley et al., 2022).

Here, we present a method that applies the concept of NBS as a tool for DRR (Tyllianakis et al., 2022) in the context of climate risk reduction. The methodology intends to be replicable and universal to estimate the effectiveness of marine NBSs. The method can be applied for different units of analysis including species, habitats, ecosystem services, or social groups, albeit here we will focus on species and habitats for simplification. Here, the effectiveness of NBS will be approached as the amount of risk reduced, for the unit of analysis under consideration, as a result of the application of the NBS. Hence, the method relies on the application of two climate-risk assessments (CRA): one considering the application of the NBS (hereafter "NBS ON"), and the other considering that the NBS is not implemented ("NBS OFF"). CRA are indicator-based approach used to characterize and quantify the main components of risk: hazards, exposure, and vulnerability (IPCC, 2014). In addition, CRA results are visual and easy to understand, which makes them optimal communication products for interacting with managers and decision-makers. Results from this approach can address questions such as: is the NBS effective in reducing climate risks for a given species? Is the NBS able to reduce the climate hazard, exposure, or vulnerability for a given species? Under which scenarios?

Since CRAs are often constructed considering future environmental conditions (scenarios) or time frames, the risk of the system (and so the NBS effectiveness) can be estimated for specific periods or scenarios (e.g., Bueno-Pardo et al., 2021). This provides managers with valuable information on the future level of risk under different potential conditions (hence the potential effectiveness of NBS), facilitating the design of adaptation pathways (e.g., Hanger-Kopp et al., 2022). A further application of this method could infer potential losses of effectiveness of NBS (Seddon et al., 2020) when results are compared across large geographic scales or environmental, political, and social conditions, opening the door to explore new insights on the limits of NBS.

2 | METHODS

The proposed methodology relies on the concept of NBS as a tool for DRR (Sahani et al., 2019; Tyllianakis et al., 2022) to infer the amount of climate risk that is reduced due to the application of a given marine NBS. The application of the method is specific to the unit of analysis (i.e., species, habitats, etc.), implying that a separate assessment should be carried out specifically for each unit. To quantify the amount of risk reduced by an NBS, two CRAs are conducted: one considering the application of the NBS ("NBS ON"), and another with no application of the NBS ("NBS OFF"). Hence, the difference of risk estimated in both CRA is seen as the potential NBS effectiveness, always from the perspective of the unit of analysis considered (Equation 1):

$$\text{NBS effectiveness} = \text{Risk}_{\text{NBS OFF}} - \text{Risk}_{\text{NBS ON}} \tag{1}$$

Due to the challenge of obtaining relevant time series or data to evaluate the CRA indicators corresponding to the NBS ON or OFF situations, the method relies on expert elicitation for the evaluation of some indicators. In addition, each indicator is also accompanied by a confidence estimate. Figure 1 summarizes the conceptual framework that we propose. The following sections provide details on the CRA framework, its relationship with NBS, and its implementation.

The method can potentially be applied to assess the effectiveness of any NBS, albeit it has been specifically developed under the framework of the European H2020 project FutureMARES (https://www.futuremares.eu/) where three marine NBSs were proposed: (1) active restoration of habitat-forming species that can act as "climate rescuers," (2) effective conservation strategies considering the impacts of climate change on habitat suitability for flora and fauna, and (3) sustainable harvesting of seafood from fisheries and aquaculture encompassing flexible, adaptive, managed on ecosystem basis.

2.1 | CRA framework for marine NBS

The CRA approach on which this theoretical framework relies follows the premises of the 5th Assessment Report (AR5) of the IPCC (IPCC, 2014). Following this approach, the climate-related risk of a given unit of analysis results from the combination of three dimensions: hazard, exposure, and vulnerability (Figure 2). The hazard of a system is related to the potential occurrence of natural or human physical events or conditions that may cause loss or degradation of some level of biodiversity, provisioning of any ecosystem service, or

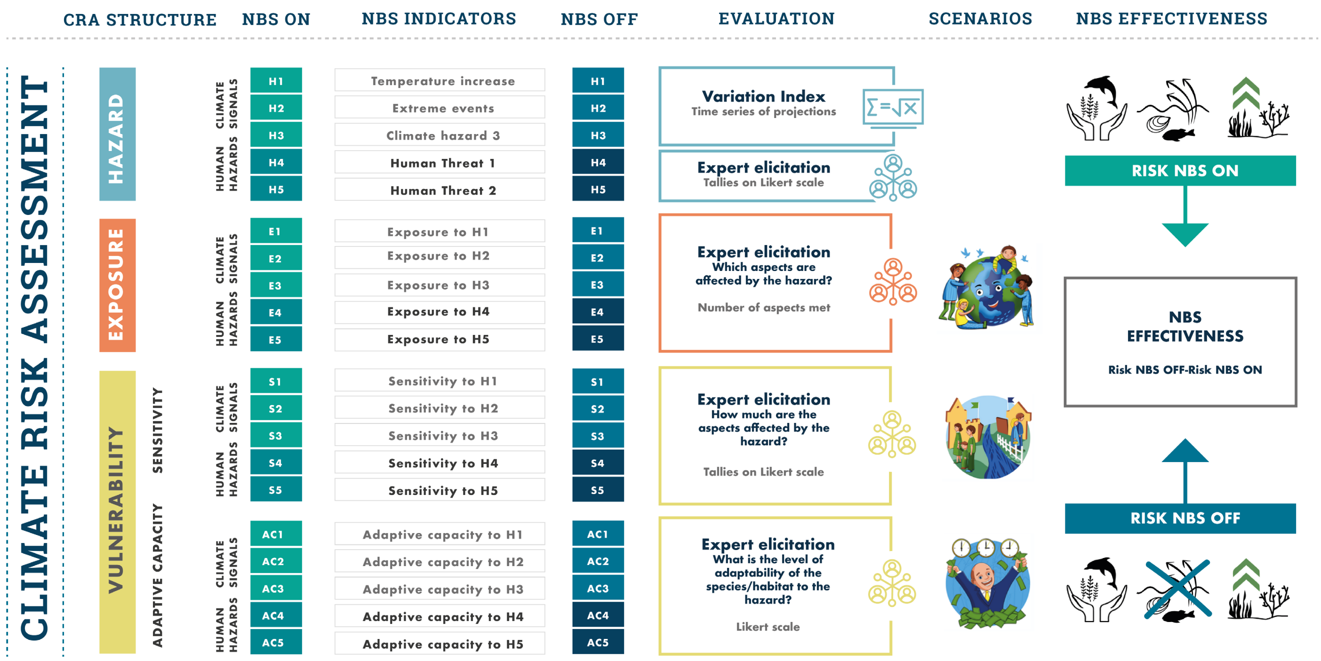

FIGURE 1 Summary figure representing the approach used to estimate NBS effectiveness based on climate risk assessments. From left to right, the figure shows the CRA structure, the different types of indicators capturing the NBS ON and OFF concept, the type of evaluation carried out for the indicators, the integration of different future scenarios, and the final estimate of the effectiveness.

human livelihoods; the exposure relates to the interaction (physical or procedural) between the hazard and the unit of analysis; finally, the vulnerability is composed by two subdimensions: (1) the sensitivity which captures the degree to which the hazard affects the subject of analysis and typically refers to inherent characteristics of the unit and (2) the adaptive capacity, which represents the way in which an exposed and sensible system is able to cope with the harm suffered to recover or maintain its status quo. For clarification, in this work, we will consider as adaptive capacity the external conditions, techniques, or measures related to the system promoting its resilience to climate change impacts. More detailed definitions of these dimensions are provided in the SROCC report (IPCC – AR5; Pörtner et al., 2019).

NBS can potentially affect the three dimensions of risk (Figure 2) and so, all the indicators in the assessment include the NBS ON and NBS OFF versions. The integration of the NBS ON indicators through the respective dimensions gives the overall estimate of risk under NBS ON conditions ($risk_{NBS\ ON}$), and the same happens for the version NBS OFF ($risk_{NBS\ OFF}$). The full description of the indicators of the CRA can be found in Data S1 and S2, for species and habitats respectively.

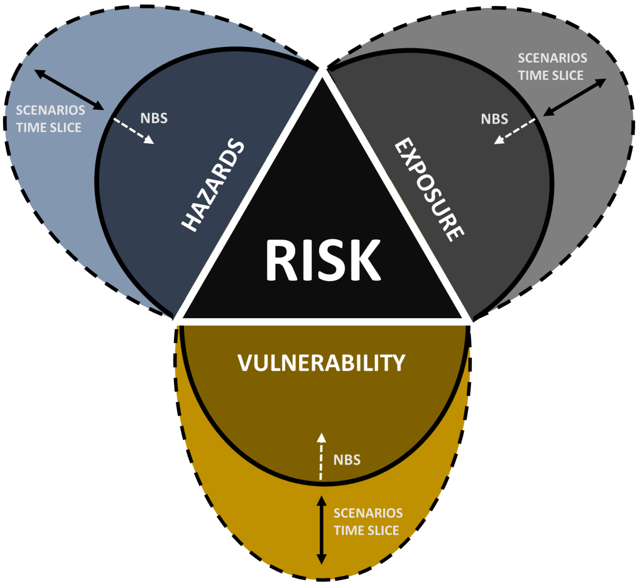

FIGURE 2 Conceptual framework of the risk dimensions and the potential influence of NBS on them. The effect of socio-political scenarios or periods of time ("time slices") are also represented.

2.2 | Units of analysis

The effectiveness of the NBS is measured from the perspective of each unit of analysis. The application of the method starts at the species level, given that the risk of the species in a habitat or in a socioecological system is introduced as a hazard indicator for the higher levels of organization (Figure 3). The way in which the different risk assessments of the species are combined to provide the input for the CRA of a given habitat (or any other higher-level unit of analysis) follows the works of Cinner et al. (2013) and Thiault et al. (2019), where ecological and social CRAs are ensembled to obtain a general social-ecological perspective risk assessment. The link is established with a system of three species categories, established according to the following criteria:

- *First-level species*: habitat-forming or habitat engineers that establish some sort of physical basis for the establishment of the entire ecosystem.
- *Second-level species*: high importance in terms of biomass or trophic relationships with the first-level group.
- *Third-level species*: lower relevance in terms of biomass and that are not pivotal for the functioning of the ecosystem.

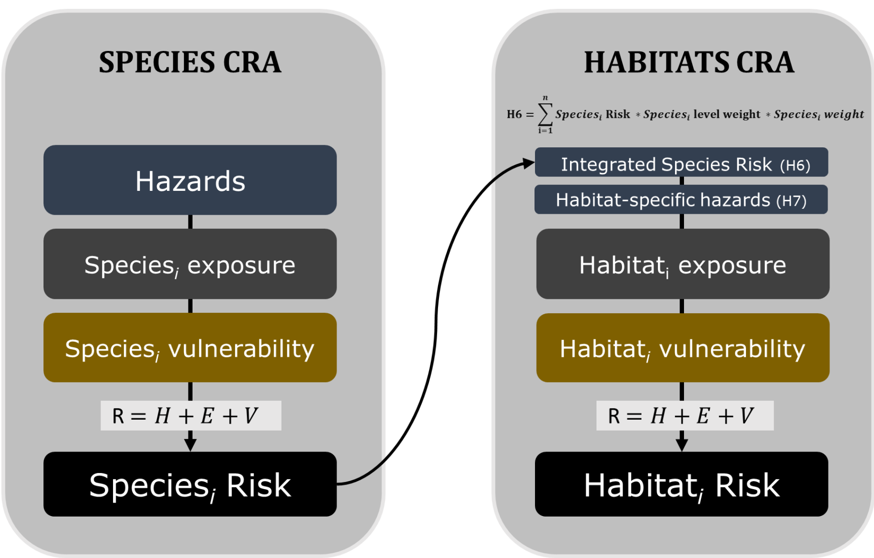

FIGURE 3 Relationship between the CRAs for species and the CRA for habitats. The estimated risks of each species (species$_i$ risk) are integrated as a function of the weight of each species on the habitat (weight$_i$) to obtain their "integrated species risk." This combined risk is one of the hazard indicators in the habitats CRA.

The first group receives 60% of the weight, the second level 30%, and the third level 10%. Within each group, the weight of each species is assigned according to the proportions/weights of the species biomass in the habitat considered.

2.3 | Scenarios

Climate risk assessments are typically carried out considering predefined future climate change scenarios. These scenarios can be purely ecological, based on future scenarios of emissions such as the representative concentration pathways scenarios of the IPCC (IPCC, 2014), or a mix between ecological and socio-political scenarios, such as the "shared socioeconomic pathways" (SSP scenarios; Kreiss et al., 2020). In the analysis carried out here, we consider two future periods of time (2040–2060 and 2080–2100) and three SSP scenarios: (1) "global sustainability," where the world shifts gradually to a more sustainable path, emphasizing inclusive development that respects perceived environmental boundaries; (2) "world markets," characterized by the push of economic and social development coupled with exploiting abundant fossil fuel resources and adopting resource and energy intensive lifestyles around the world, and (3) "national enterprise" where countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development, with a low international priority for addressing environmental concerns leads to strong environmental degradation in some regions (FutureMARES, 2021).

2.4 | Design of the CRA methodology

Since CRA are indicator-based approach, having a common structure and list of indicators is key to developing transferable and universal approaches. Indicators are structured in two levels: dimensions, and subdimensions of risk (Tables 1 and 2). In our approach, the hazard dimension incorporates the effects of climate change and other human impacts into the CRA through five indicators. These hazard indicators form the core of the assessment because the remaining dimensions (exposure, sensitivity, and adaptive capacity) will also be assessed in relation to them. The selection of the hazards relies on the CRA coordinator, who should take into account the opinion of and information collected by representative stakeholders from the area of study. For illustrative purposes here we consider three climate signals and two human-driven impacts as hazards. The weight of these two subdimensions within the hazard dimension can also be adapted. Here we consider 60% and 40%, respectively, for climate signals and human impacts as the CRA focus is on climate risk. The weights of these subdimensions should be considered when computing the value of the exposure, sensitivity, and adaptive capacity as well. The indicators weight can also be adjusted to capture expected intensities of climate change (see percentages in Tables 1 and 2). By default, to ensure comparability between the different CRAs implemented within the FutureMARES project, two of these hazards were predefined (H1 and H2 in Table 1) while the rest were left to the criteria of the different practitioners.

2.5 | Expert elicitation using an aspects-based assessment

The CRA methodology proposed here relies on expert elicitation for the dimensions of Exposure and Vulnerability (Tables 1 and 2; Data S1 and S2 for a detailed description of indicators for species and habitats respectively). Additionally, expert elicitation may be needed for hazards for which no time series or projections are available.

Since this method intends to work for any type of species or habitat, the use of the indicators based on life history or other biotic factors has been substituted by universal aspects capturing very general characteristics of the relationship between the hazard and the organism's fitness or the habitat integrity. These *aspects* are used for the assessment of exposure and sensitivity (see Tables 3 and 4 for exposure aspects) and are designed to capture the idea of exposure intensity being represented by the number of aspects (*how many*) that are affected by the hazard evaluated (e.g., the growth rate of a given species is affected by temperature increase, but not by poaching). In the case of sensitivity, the same set of aspects of exposure is considered although, this time, the level of sensitivity of a species to a given hazard is represented by an intensity scale (*how much*) related to the natural range of variation known for the species (see expert templates in Data S3 and S4 for species and habitats respectively, with a description of the aspects and a guide for their interpretation by experts in tab "Aspects info" of the same template).

2.6 | The variation index

Similar to the use of *aspects* to evaluate exposure and sensitivity, the analysis of hazards in our approach intends to allow the comparison of different climatic or human-driven signals across case studies. To do that, we propose the use of a variation index (VI; Bueno-Pardo et al., 2021), which allows us to consider the future degree of variation of the variables considered as hazards rather than raw projected values. By definition, the variation index is unitless (Equation 2), making it possible to compare variables of a very different nature. Ideally, the VI can be calculated when time series exist for a given signal corresponding either to measurements or model hindcasts or forecasts. The VI compares the expected average change of the variable to the current degree of variability (standard deviation), making that a minimal increase of a highly stable variable gives high VI values, and high increases of highly variable variables give low VI values. The rationale of the VI is to compare the future environmental values to the current

TABLE 1 Structure of the species CRA approach. The table shows the risk dimensions, subdimensions, and indicators. The type of indicator (numerical or categorical) is also shown. Note that the five hazards are also considered in the dimensions of exposure, sensitivity, and adaptive capacity. All weights (in brackets) can be adjusted by convenience to each case study. VI stands for "variation index" (see Section 2.6).

Risk dimension	Subdimension (weight)	Indicator (weight)	Type of indicator (way of evaluation)
Hazard	Climate signals (60%)	H1. Temperature (50%)	Numerical (VI indicator)
		H2. Extreme events (30%)	Numerical (VI indicator)
		H3. Climate signal (20%)	Numerical (VI indicator)
	Human threats (40%)	H4. Human threat 1 (60%)	Numerical (VI indicator)
		H5. Human threat 2 (40%)	Numerical (expert elicitation)
Exposure	Exposure to climate signals (60%)	E1. Exposure to H1 (50%)	Categorical (expert elicitation)
		E2. Exposure to H2 (30%)	Categorical (expert elicitation)
		E3. Exposure to H3 (20%)	Categorical (expert elicitation)
	Exposure to human threats (40%)	E4. Exposure to H4 (60%)	Categorical (expert elicitation)
		E5. Exposure to H5 (40%)	Categorical (expert elicitation)
Vulnerability	Sensitivity to climate signals (60%)	S1. Sensitivity to H1 (50%)	Categorical (expert elicitation)
		S2. Sensitivity to H2 (30%)	Categorical (expert elicitation)
		S3. Sensitivity to H3 (20%)	Categorical (expert elicitation)
	Sensitivity to human threats (60%)	S4. Sensitivity to H4 (60%)	Categorical (expert elicitation)
		S5. Sensitivity to H5 (40%)	Categorical (expert elicitation)
	Adaptive capacity to climate signals (−60%)	A1. Adaptability to H1 (50%)	Categorical (expert elicitation)
		A2. Adaptability to H2 (30%)	Categorical (expert elicitation)
		A3. Adaptability to H3 (20%)	Categorical (expert elicitation)
	Adaptive capacity to human threats (−40%)	A4. Adaptability to H4 (60%)	Categorical (expert elicitation)
		A5. Adaptability to H5 (40%)	Categorical (expert elicitation)

variability of the hazard, considering that the system could potentially have adaptive capacities to natural variation of the hazard. This index is calculated as the difference between the future and present values of the variable divided by the standard deviation of the variable in the present (Equation 2):

$$\mathrm{VI} = \frac{\mu_{\mathrm{fut}} - \mu_{\mathrm{ref}}}{\sigma_{\mathrm{ref}}} \quad (2)$$

where μ_{fut} represents the average of the variable in the future, μ_{ref} is the mean of the variable in the reference period, and σ_{ref} is the standard deviation of the variable during the reference period.

The limits of Equation (2) are $-\infty$ and $+\infty$, which is a challenge for indicator standardization. To circumvent this problem, we establish the thresholds of the VI values as: $|\mathrm{VI}| = 0$ ("null"); $|\mathrm{VI}| \leq 0.1$ ("low"); $0.1 < |\mathrm{VI}| \leq 0.3$ ("moderate"); $0.3 < |\mathrm{VI}| \leq 0.5$ ("high"); $0.5 < |\mathrm{VI}| \leq 0.7$ ("very high"); and $|\mathrm{VI}| > 0.7$ ("extreme").

2.7 | Overall risk calculation

Once the categorical value of each indicator of the CRA has been obtained, the value of the next level (subdimensions) can be calculated

TABLE 2 Structure of the habitats CRA approach. The table shows the risk dimensions, subdimensions, and indicators, together with the type of indicator (numerical or categorical). Note that the five hazards are also considered in the dimensions of exposure, sensitivity, and adaptive capacity. All weights (in brackets) can be adjusted by convenience. VI stands for "variation index" (see Section 2.6).

Risk dimension	Subdimension (weight)	Indicator (weight)	Type of indicator (way of evaluation)
Hazard	Species risk (60%)	H6. Species risk (100%)	Categorical
	Habitat hazard (60%)	H7. Habitat hazard (100%)	Numerical (VI indicator)
Exposure	Exposure to climate signals (60%)	E6. Exposure to H1 (50%)	Categorical (expert judgment)
		E7. Exposure to H2 (30%)	Categorical (expert judgment)
		E8. Exposure to H3 (20%)	Categorical (expert judgment)
	Exposure to human threats (40%)	E9. Exposure to H4 (60%)	Categorical (expert judgment)
		E10. Exposure to H5 (40%)	Categorical (expert judgment)
Vulnerability	Sensitivity to climate signals (60%)	S6. Sensitivity to H1 (50%)	Categorical (expert judgment)
		S7. Sensitivity to H2 (30%)	Categorical (expert judgment)
		S8. Sensitivity to H3 (20%)	Categorical (expert judgment)
	Sensitivity to human threats (60%)	S9. Sensitivity to H4 (60%)	Categorical (expert judgment)
		S10. Sensitivity to H5 (40%)	Categorical (expert judgment)
	Adaptive capacity to climate signals (−60%)	A6. Adaptability to H1 (50%)	Categorical (expert judgment)
		A7. Adaptability to H2 (30%)	Categorical (expert judgment)
		A8. Adaptability to H3 (20%)	Categorical (expert judgment)
	Adaptive capacity to human threats (−40%)	A9. Adaptability to H4 (60%)	Categorical (expert judgment)
		A10. Adaptability to H5 (40%)	Categorical (expert judgment)

by transforming the categories into numbers: Low = 1, Moderate = 2, High = 3, Very high = 4, Extreme = 5 and aggregating them according to their weight (see Tables 1 and 2). The numerical value of the subdimensions should be finally normalized between 0 and 1. To obtain the value of vulnerability, the subdimensions sensitivity and adaptive capacity should be subtracted. Finally, to get the overall risk value, the normalized hazard, exposure, and vulnerability scores are summed. To facilitate interpretation, the final risk score (whose theoretical minimum is 0 and theoretical maximum is 3) is also normalized between 0 and 1.

TABLE 3 List of aspects considered to evaluate the exposure of species to a given hazard.

Category	Aspects of the exposure	
Growth and development	1	Is the growth rate of the species directly affected by the Hazard?
	2	Is the development rate of the species directly affected by the Hazard?
Energy intake	3	Is the amount of food/prey encounter rate of the species directly affected by the hazard?
	4	Is the quality of food available directly affected by the hazard?
Reproduction	5	Is the sex ratio of the population affected by the hazard?
	6	Are the reproductive outputs (size of propagules/eggs; number of propagules/eggs) directly affected by the hazard?
	7	Is the hazard likely to affect the fecundation process/mechanisms?
	8	Is the hazard likely to affect the timing of the fecundation (phenology)?
Mortality	9	Is the mortality rate by physiological stress (at any pre-adult stage) directly affected by the hazard?
	10	Is the mortality rate by physiological stress (at adult stress) directly affected by the hazard?
	11	Is the number of predators (of any life stage) likely to be affected by the hazard?
	12	Is the availability (size, number) of shelters (for any life stage) affected by the hazard?
	13	Is the mortality rate by mechanical accidents (at any pre-adult stage) directly affected by the hazard?
	14	Is the mortality rate by mechanical accidents (at adult stage) directly affected by the hazard?

2.8 | Confidence

Each indicator of the CRA has an associated estimate of confidence level (C) following the approach of the IPCC 6th Assessment Report (IPCC, 2022a). Confidence is calculated as a function of the type of evidence (Ev) used in the assessment of the indicator and the level of agreement between experts (A) when the indicator is estimated by expert elicitation. In the case of the indicators where no expert elicitation is used (e.g., some hazard indicators) the level of confidence equals Ev, which is calculated following a five-degrees categorical classification (Table 5). On the other hand, the level of agreement across the experts was calculated as the ratio between the standard deviation of their answers (in numerical values, σE) and the number of experts (n; Equation 3):

$$A = \sigma E / n \quad (3)$$

To convert the answers of the experts to numerical values (σE) different approaches were followed according to the dimension they estimated. For exposure, the number of aspects marked by each expert was considered; for the sensitivity, the number of tallies allocated to each intensity was multiplied by its value ("low" = 1, "intermediate" = 2, "high" = 3, "very high" = 4, "extreme" = 5), and the sum of intensities estimated for each aspect was considered as the numeric answer reported by each expert; for the adaptive capacity the same conversion considering the value of each intensity was done, but in this case, as no aspects are considered, the numerical value provided by expert was directly obtained. The agreement value was finally transformed into a category considering the criteria in Table 5. A final categorical value indicating the degree of C on the value of each indicator is obtained by averaging scores of Ev and A (Table 5).

3 | RESULTS AND DISCUSSION

3.1 | A transferable methodology

We provide a replicable method for the assessment of the effectiveness of marine NBS, based on the application of two CRAs. Since each CRA is conducted considering a specific unit of analysis (species or habitats), the effectiveness of the NBS is also estimated from the perspective of the unit of analysis, meaning that the method should be able to detect differences in the effect that the NBS has on each of them separately. This methodology seeks to serve as a rapid assessment tool and hence a set of self-explained semi-automated templates is provided in the Data S3–S7 (see Table 6 for a summary of the templates and their use).

TABLE 4 List of aspects considered to evaluate the exposure of habitats to a given hazard.

Category	Aspects of the exposure	
Physical structure	1	Is the habitat geographical extension affected by the hazard?
	2	Is the habitat structure (besides extension) affected by the hazard?
	3	Is the habitat geochemical structure affected by the hazard?
Biological structure	4	Is the habitat taxonomic diversity (net number of taxa) affected by the hazard?
	5	Is the hazard likely to cause taxa substitution in the habitat?
	6	Is the habitat functional diversity affected by the hazard?
Biological processes	7	Is the biomass size-spectra affected by the hazard?
	8	Is the hazard likely to affect the reproductive dynamics through habitat change?

3.2 | Application of the method

Here we apply the method with illustrative purposes to two simplified case studies (case study 1 and case study 2), of shellfisheries harvesting the clams *Cerastoderma edule*, *Ruditapes philippinarum*, and *Venerupis decussatus* in Galicia (NW Spain). In addition, the group of species Phytoplankton spp. (one of the main food resources of clams) is considered to show how the method provides different hints on the effectiveness of the NBS when very different kinds of organisms are considered. Table 7 summarizes the main characteristics (species composition, and hazard weights) of the two case studies. In case study 1, the analysis is split between two habitats: habitat 1 (intertidal) and habitat 2 (subtidal). The two fishing guilds apply an NBS of the type "nature-inclusive harvesting" system, consisting of a set of ecosystem-based management measures where native species (*C. edule* and *R. decussatus*) seeds are provided by public administration entities, fishing periods are regulated, license numbers are restricted, and poaching is actively controlled. Here, the NBS effectiveness has been measured for the five species in both case studies, while for habitats only case study 1 was considered.

The assessment considered five hazards: temperature increase (H1), heatwaves (H2), salinity decrease (H3), pollution by pig farms (H4), and poaching (H5). In case study 1, the importance of pig farm pollution is much higher than in case study 2 due to the proximity of the farm. In case study 2, the impact of poaching is much higher due to accessibility conditions. Within case study 1, habitat 1 and habitat 2 differ in the level of poaching mainly because habitat 2 is subtidal.

The results of the risk assessments show differences in the dimensions of risk and in the overall estimated risk when scenarios are considered, both for species (Figure 4) and habitats (Figure 5). The

TABLE 5 Confidence estimation. Transformation of the categorical values of evidence to numeric (left columns), of the agreement (A) to a numerical scale between 0 and 1 (central columns), and of the numerical values of confidence to categories (right columns).

Evidence (Ev)		Agreement (A)		Confidence (C)	
Criteria	Score	Criteria	Score	C = mean (Ev, A)	Categorical value
Expert's experience or observations	1	A > 0.4	1	C ≤ 1.667	Very low
Scientific literature or reports where contradictory results are often found	2	0.3 < A ≤ 0.4	2	1.667 < C ≤ 2.5	Low
Scientific literature suggests a potential direction, from other regions or slightly different contexts than the Storyline	3	0.2 < A ≤ 0.3	3	2.5 < C ≤ 3.33	Intermediate
Scientific literature suggests a potential direction, from the same region or context as the Storyline	4	0.1 < A ≤ 0.2	4	3.33 < C ≤ 4.167	High
Scientific literature points to an unequivocal direction, from the same region or context as the Storyline	5	A ≤ 0.1	5	4.167 < C ≤ 5	Very high

TABLE 6 List of templates. The template names, corresponding supplementary files and descriptions provided for the assessment of the effectiveness of the NBS using CRA.

Template name	Supplementary file	Description
ExpertData	Data S3 (species) Data S4 (habitats)	It gathers the opinion of experts. Each copy of the template should be used to evaluate a unique unit of analysis (e.g., a single species and a single habitat), its relationship to a single hazard (H1, H2, H3, H4, or H5), and one NBS
IndicatorCalculator	Data S5 (species) Data S6 (habitats)	It integrates the answers from different experts to calculate the final value of a given indicator. As for the *ExpertData* templates, separate versions are provided for species and habitats. The template is designed to be used with a single combination of species, hazard, and NBS
CRAtemplate	Data S7	It is a compilation tool to gather the categorical values of all the indicators and their respective confidence estimates that showcase the results of the assessment. If more than one NBS is considered, a separate copy of the *CRAtemplate* should be used

TABLE 7 Summary of the species and hazard composition of the three analyses of NBS effectiveness carried out.

	Case study 1		Case study 2
	Habitat 1 (intertidal)	**Habitat 2 (subtidal)**	**Intertidal**
Species composition	*Cerastoderma edule* (Species level 1, 60%) *Ruditapes decussatus* (Species level 1, 40%) *R. philippinarum* (Species level 2, 100%) Phytoplankton spp. (Species level 3, 100%)	*C. edule* (Species level 1, 60%) *R. decussatus* (Species level 1, 40%) *R. philippinarum* (Species level 2, 100%) Phytoplankton spp. (Species level 3, 100%)	*R. philippinarum* (Species level 1, 80%) *R. decussatus* (Species level 1, 20%) *C. edule* (Species level 2, 100%) *Phytoplankton* spp. (Species level 3, 100%)
Hazard composition	**H1:** temperature increase (50% of climate signals) **H2:** extreme temperature events (30% of climate signals) **H3:** salinity decrease (20% of climate signals) **H4:** pollution by pig farms (70% of human hazards) **H5:** poaching (30% of human hazards)	**H1:** temperature increase (50% of climate signals) **H2:** extreme temperature events (30% of climate signals) **H3:** salinity decrease (20% of climate signals) **H4:** pollution by pig farms (100% of human hazards) **H5:** poaching (0% of human hazards)	**H1:** temperature increase (50% of climate signals) **H2:** extreme temperature events (30% of climate signals) **H3:** salinity decrease (20% of climate signals) **H4:** pollution by pig farms (30% of human hazards) **H5:** poaching (70% of human hazards)

differences between both case studies are noticeable only at the hazard level for bivalves (only *C. edule* results are shown for simplification), as the NBS seems to be effective in lowering hazard intensity only at case study 2 (different NBS ON column height between Figure 4a,b). The NBS is also effective in lowering the sensitivity of the species (very slightly) and increasing its adaptive capacity. This effect seems to be the same in both case studies.

Exploring the reasons why the NBS only lowers the hazard dimension in case study 2 can be informative in identifying effective risk mitigation measures. The higher level of poaching registered in case study 2 is probably the reason why the surveillance measures encompassing the application of the NBS help lower the hazard dimension, while, on the other hand, it also indicates that in their current form, the NBS has no effect on lowering the hazard due to pig

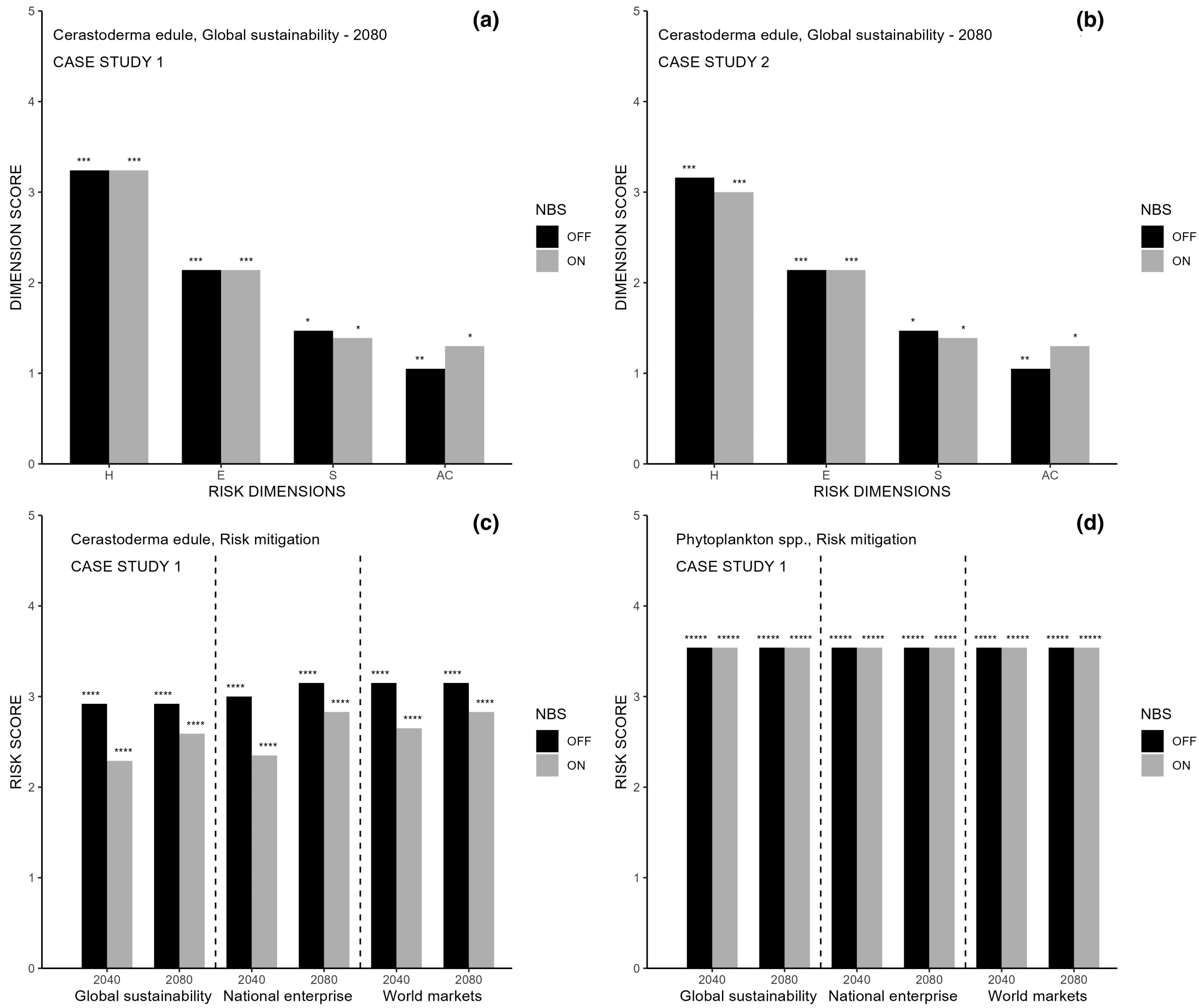

FIGURE 4 Outputs from the method for the assessment of the NBS effectiveness for *Cerastoderma edule* and Phytoplankton spp. Panels (a) and (b) show the estimates of the dimensions of risk (AC, adaptive capacity; E, exposure; H, hazard; S, sensitivity) on a 0–5 scale for *C. edule* in case study 1 (habitat 1) and case study 2 respectively. Panels (c) and (d) show the different overall risk estimates in case study 1 under different scenarios of climate change and time slices, for *C. edule* and Phytoplankton spp. respectively. All the values shown, for the dimensions and overall risk, have two versions: NBS OFF (dark gray) and NBS ON (light gray). The difference in risk estimated between NBS OFF and NBS ON represents the potential effectiveness of the NBS. The asterisks over the bars represent the confidence estimate of each risk assessment (*: very low; **: low; ***: intermediate; ****: high; *****: very high).

farms runoff in case study 1. The increase of the adaptive capacity in both case studies is identical, probably because high-quality seeds are provided from the same source and this is considered one of the effects of the NBS.

Considering the overall risk score of the species and how it is expected to evolve under different future socio-political scenarios, we found that for *C. edule* (Figure 4c,d), the differences in risk between NBS ON and NBS OFF conditions are lower for the 2080 scenarios than for the 2040s, suggesting a potential loss of effectiveness of the NBS in reducing the species risk in the long-term future. Also, the risk estimated for *C. edule* under the World Markets scenario is higher both for NBS ON and NBS OFF, pointing to specific difficulties for the species in the near future under these scenario conditions. Comparing the effect of the NBS on different species can also reveal interesting management strategies to lower the climate risk. In this case, our methodology did not reveal any potential effect of the NBS to lower the climate risk of Phytoplankton spp. at any scenario measured (Figure 4d). This is probably due to the type of measures applied within the NBS implementation (mainly poaching surveillance, provision of autochthonous clam seeds, and establishment of extraction quotas) having a null effect on phytoplankton abundance or performance.

Regarding the effect of the NBS at the habitat level (Figure 5), the CRA carried out under the Global Sustainability scenario reveals that the hazard intensity is expected to increase by 2080 (Figure 5a,b). Interestingly, the adaptive capacity due to the application of the

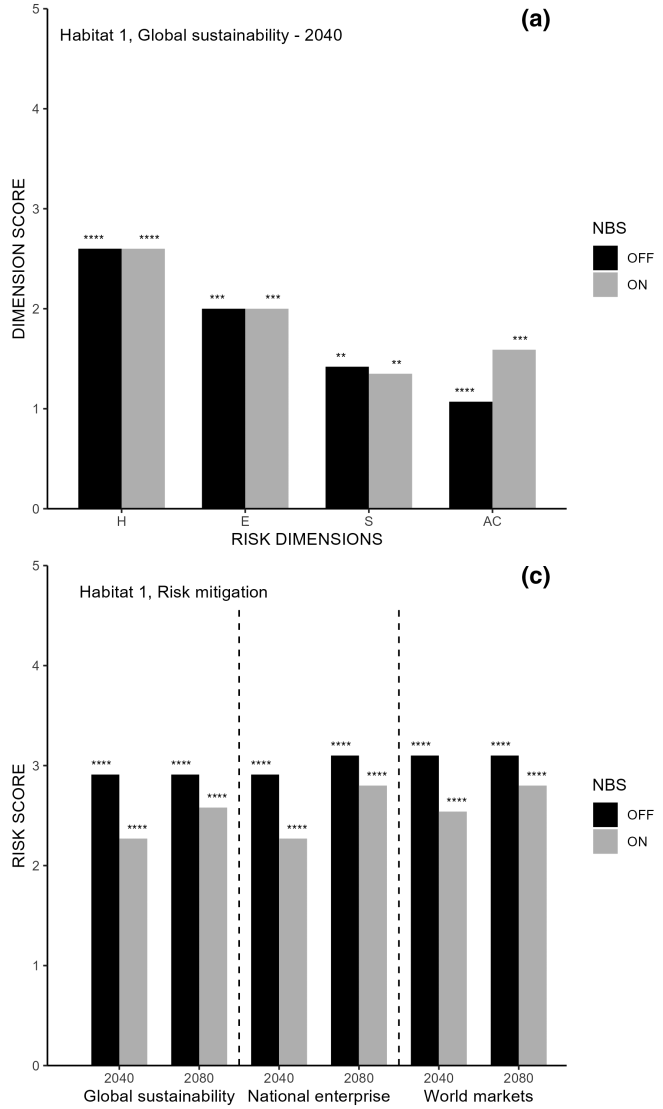

FIGURE 5 Outputs from the method for the assessment of the NBS effectiveness regarding habitat 1 and habitat 2 from case study 1. Panels (a) and (b) show the estimates of the dimensions of risk (abbreviations as in Figure 4) on a 0–5 scale for habitat 1. Panels (c) and (d) show the different overall risk estimates at habitat 1 and habitat 2, respectively, under different scenarios of climate change and time slices. All the values shown, for the dimensions and overall risk, have two versions: NBS OFF (dark gray) and NBS ON (light gray). The difference of risk estimated between NBS OFF and NBS ON represents the potential effectiveness of the NBS. For asterisks' meaning see Figure 4 caption.

NBS is also predicted to drop in 2080, pointing to a potential loss of effectiveness of the NBS in the long-term future. Nevertheless, even though the adaptive capacity will be higher in 2080 when the NBS is applied (NBS ON), the effectiveness of the NBS is not expected to be completely lost by 2080. On the other hand, considering the overall risk estimate of the habitats (Figure 5c,d) it is apparent that habitat 1 has a higher risk score than habitat 2 in all the scenarios. Also, the risk increases across scenarios, with Global sustainability being the one with (slightly) lower risk estimates. The method also captures that habitat 1, under the National enterprise scenario, gets a higher risk score in 2080 than in 2040. In regards to the NBS effectiveness at the habitat level, interestingly, both habitats have lower risk scores when NBS ON, demonstrating that the NBS is effective in lowering their climate risk. Nevertheless, the amount of climate risk mitigated when NBS ON is lower in the 2080 scenarios, indicating a decrease in the effectiveness of the NBS in the long term. Another outcome from the analysis is that the differences of risk estimated between NBS ON and NBS OFF are in general larger for habitat 1 (the one where poaching exists), indicating a higher effectiveness of the NBS in this habitat (intertidal) than in habitat 2 (subtidal).

3.3 | Universality of the method

The approach presented here relies on the conceptual framework of the risk assessments proposed by the IPCC 5th Assessment Report (IPCC, 2014), and depends on the difference of risk estimated when an NBS is applied ("NBS ON") and when it is not

("NBS OFF") to infer the potential effectiveness of the NBS. Many examples of CRA exist in the literature, each of them with specific methodological characteristics making it difficult to compare the results. The methodology proposed here intends to be applied in a comparable way to very different marine species (from invertebrates to large mammals or birds), geographic scales, sociopolitical scenarios, and NBS, to limit the subjectivity of the assessment and allow comparison at different scales. The classical use of indicators from the vulnerability and risk literature (e.g., Bueno-Pardo et al., 2021; Ruiz-Díaz et al., 2020) has been replaced by a series of aspects capturing the relationship between the hazard and: (1) the fitness of the species and (2) the integrity of the habitat. The definition of exposure by the IPCC (2014) makes explicit reference to the physical coincidence between the unit of analysis and the hazard. Similarly, in this work, to express the intensity of the exposure, we consider the number of aspects (i.e., *how many*; Tables 3 and 4) impacted by the hazard in its relationship with the unit of analysis. Evaluating the exposure in this way prevents using specific life history traits with arguable meaning in terms of exposure to environmental conditions (e.g., Hare et al., 2016) and allows us to compare the response of very different types of organisms to specific hazards. Similarly, the assessment of sensitivity has been carried out in very different ways throughout the literature (e.g., Hare et al., 2016; Morrison et al., 2015) so, aiming to provide a more universal approach, the exposure aspects are measured considering *how much* (in relation to current natural degree of variation) each aspect is impacted by the hazard. Finally, the assessment of the adaptive capacity is performed considering external aspects of the system and relates to management, level of knowledge, infrastructures, and technological measures available to adapt to the impacts of climate change. This approach for measuring adaptive capacity intends to isolate the specific effects of the NBS compared to other management measures, while making explicit distinction between the sensitivity (internal characteristics of the system) and the adaptive capacity (external).

The present method partly relies on expert elicitation for its implementation. Such an approach has the advantage of allowing assessments in data-poor contexts and in general in shorter periods of time, which are often needed for policymaking. However, counting with the right experts is pivotal for the correct evaluation of the risks of the species or habitats under analysis. Ideally, the experts should know the idiosyncrasies of the unit of analysis in the area of study as well as be familiar with cultural, social, environmental, or management-relevant local characteristics. In addition, providing an opinion on the state of social-ecological systems under future conditions can be extremely speculative, and hence, adequate previous training on the meaning of the evaluated scenarios is fundamental, together with terminology or other aspects relative to the CRA and NBS effectiveness. Similarly, the meaning of the NBS ON and NBS OFF versions of the indicators should be clearly stated to avoid different interpretations across experts. In this regard, a joint workshop with the different experts, led by the case study responsible prior to evaluation is highly advisable. On the other hand, good planning of the assessment needs to be carried out by practitioners prior to experts' consultation. This planning should ensure a good representation of the species to be evaluated (also including new species to the system that might enter due to climate change) and an appropriate choice of the hazards forming the core of the CRA. To do this, consultation with stakeholders from the area of study is advised. In fact, the limitations of the method are related mostly to the subjectivity inherent to any participatory approach considering the opinion of different experts on a given theme. The different background of the experts, or even their personal political opinion might influence the way they see sociopolitical scenarios, or the measures involved with the application of the different NBSs. Finally, the number of hazards considered in the CRA is limited for practical reasons. Increasing the number of hazards would capture different climate impacts on the system, which is pivotal for a good representation of the reality of the case study, but this increases the time taken by experts to complete the assessment. These hazards, and their impacts, are often additive in their consequences on the system, which is not considered in this framework. Because of this, the construction of well-structured implementation plans prior to the CRA assessment is advisable (Zebisch et al., 2021).

3.4 | Relevance of the method in a policy context

There is an increasing demand from decision-makers for adaptive solutions based on local approaches promoting local employment and avoiding hard engineering investments to adapt and mitigate the impacts of climate change (Nordgren et al., 2016). As such, the methodology developed here expands the pool of DRR to marine NBS, to cover the need to measure the effectiveness of marine NBS with a rapid assessment tool. The application of NBS as DRR is not new (Tyllianakis et al., 2022), albeit the focus has been mostly given to the interface between meteorological hazards and human infrastructures (e.g., Arce-Mojica et al., 2019; Mashiyi et al., 2023; Shah et al., 2020). The applications of this method connect with the European Green Deal (Fetting, 2020), and other European (e.g., Marine Strategy Framework Directive) and international policy initiatives explicitly encouraging the use of NBSs to mitigate biodiversity and ecosystem services degradation or loss locally and in sustainable ways, and to support a circular economy and local communities. In this context, evaluating the effectiveness of NBS is fundamental for (1) policy evaluation, (2) social accountability of citizens' concerns, and (3) supporting investment in NBS, by comparing NBS benefits with those from other approaches (European Commission, 2021a).

The methodology presented here can also be used to explore potential limits, pitfalls, or tipping points of the NBS itself. Situations where the effectiveness of the NBS lowers or gets nullified for a given species can arise both over time or geographically when the magnitude of climate impacts or certain environmental or social thresholds are exceeded (European Commission, 2021b). In this regard, the application of the present methodology over an extensive geographic area could throw some light on exploring the mechanisms by which NBS effectiveness varies (decreases) with respect to specific environmental or socio-political conditions. This type of information is pivotal for the development of adaptation pathways (Hanger-Kopp et al., 2022) directed to lower the climate risk and enhance the adaptability of species or ecosystems. The underlying idea is that, by identifying the social, political, or environmental scenarios where the effectiveness of the NBS is lower, managers should be able to identify the causes of the drop in effectiveness and use this information to provide more effective adaptation pathways (Magnan et al., 2020).

4 | CONCLUSIONS

This work provides a methodology to measure the effectiveness of NBS based on the framework of climate risk assessments developed by the IPCC (2014). The method relies on a combination of data and experts' opinion to infer the state of the evaluated system under certain environmental and socio-political scenarios that are not always exempt from subjectivity, and for this, previous preparation by the CRA coordinators is needed. The method is useful in the context of decision-making by offering the possibility to understand potential losses of the effectiveness of the NBS at lowering overall risk or specific risk dimensions, considering future environmental and socio-political contexts. In this way, our approach is complementary to current monitoring and indicator-based approaches to infer the effectiveness of NBS. Further developments of this approach, including an extensive comparison of results from its application, will be of utmost interest to understand the effectiveness of NBS in a wider context and extend its use to other units of analysis such as social groups or ecosystem services.

AUTHOR CONTRIBUTIONS

Juan Bueno-Pardo: Conceptualization; formal analysis; investigation; methodology; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Ana Ruiz-Frau:** Formal analysis; investigation; methodology; visualization; writing – review and editing. **Clement Garcia:** Conceptualization; formal analysis; investigation; methodology; visualization; writing – review and editing. **Elena Ojea:** Conceptualization; formal analysis; investigation; methodology; supervision; validation; visualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in Zenodo at https://doi.org/10.5281/zenodo.10974377.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors did not use any generative AI or AI-assisted technologies for the writing of this work.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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