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Balancing wind energy expansion and fisheries in the Mediterranean Sea: A trait-based assessment of vulnerability to floating offshore wind farms for commercially important species

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1. Introduction

The urgent global transition towards renewable energy critically requires the expansion of Offshore Wind Farms (OWFs). However, this development intersects with established human activities in the marine environment, often leading to significant conflicts, particularly with fisheries (Gill et al., 2020; Farr et al., 2021; Szostek et al., 2025). Yet, the exclusion of fishing activities within OWF perimeters can sometimes offer positive ecological benefits. Worldwide, OWFs have been shown to affect marine life by disrupting the behavior, reproduction, physiology and survival of exploited species. Such impacts arise through mechanisms including underwater noise and vibration, habitat loss and alteration, electromagnetic fields, and increased collision risk, ultimately affecting the productivity and sustainability of fisheries (Hogan et al., 2023).

While research in regions with established bottom-fixed OWFs, such as the North Sea and the North Atlantic, has documented various ecological impacts that highlight the need for careful planning (White et al., 2012), studies examining the effects of floating OWFs on exploited species and fisheries remain notably scarce. This is particularly true within the unique ecological and socio-economic context of the Mediterranean Sea, where OWF development remains in its early stages (Lloret et al., 2022, 2023; Wawrzynkowski et al., 2025). This knowledge gap is significant given the Mediterranean's unique ecological and economic context, where fisheries are vital for local communities (FAO, 2023). Substantial ambitions for OWF are currently observed in the Mediterranean Sea (Defingou et al., 2019). While large-scale deployment is still in its nascent stages and often faces complex planning and regulatory hurdles, the considerable number of proposed projects and national targets indicate a strong trajectory towards future expansion in this region. This impending development poses significant ocean and coastal management challenges, as the proposed OWF development areas often intersect with fishing grounds. Here, marine resources are ecologically crucial, and fishing activities hold significant economic and cultural importance (Fayram and De Risi, 2007; Lloret et al., 2022, 2023). Therefore, understanding and actively mitigating the potential negative impacts of OWFs on exploited species is crucial for achieving a sustainable coexistence between renewable energy initiatives and the preservation of fishing grounds and coastal communities.

In the Mediterranean, the focus is predominantly on floating technology due to the region's deep waters and challenging seabed conditions (Defingou et al., 2019). The region's vital fishing grounds are concentrated on its generally narrow continental shelves (Papaconstantinou and Farrugio, 2000), holding significant cultural and economic value (Farrugio et al., 1993; Gómez and Maynou, 2020). As floating OWFs are increasingly proposed in these areas, effective maritime spatial planning (MSP) of Offshore Wind Development Areas (OWDAs) and projects becomes critical. This entails optimizing the design and location of these developments to minimize their impact on fishery resources, thereby ensuring sustainable coexistence between renewable energy initiatives and traditional fishing practices (Hogan et al., 2023; Smythe, 2024; Montero et al., 2025). Achieving this necessitates the integration of robust governance frameworks with ecological vulnerability assessments, including consideration of fishers' engagement and cumulative impacts within existing legal and planning instruments.

This paper addresses this critical need by conducting a trait-based vulnerability assessment of commercially important species, examining stressors associated with floating OWFs in the NW Mediterranean.

While there is a growing interest in assessing species vulnerability to a range of stressors using a trait-based approach (Butt et al., 2022), no such methodology has yet been specifically applied to stressors linked to OWFs. The adoption of this methodology in our study, marking its first application in the context of OWF development, is particularly suitable

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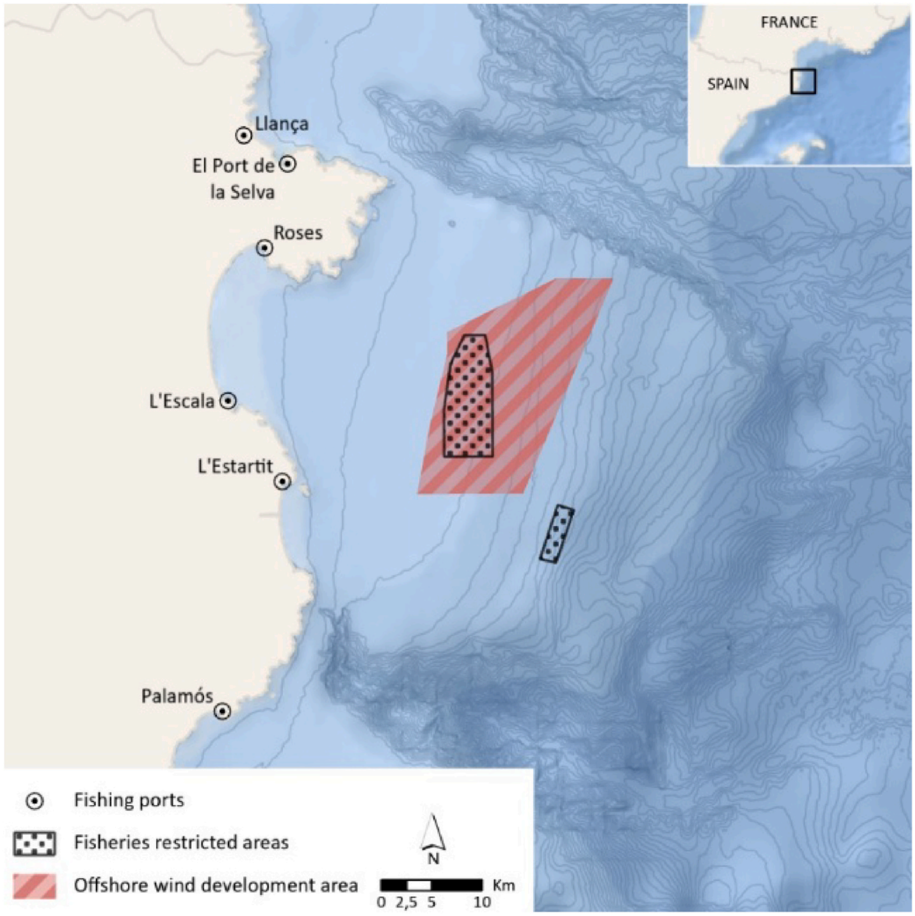

Fig. 1. Map displaying the study area of Cape Creus/Gulf of Roses (Spain, NW Mediterranean) with the location of the Offshore Wind Development Area (OWDA), the main fishing ports and the Fisheries Restricted Areas (FRAs).

because it offers a systematic and predictive evaluation of vulnerability across a broad range of species, even those for which direct impact data are scarce. Crucially, this approach moves beyond simple observation to provide a mechanistic understanding of why certain species are vulnerable to OWF-related stressors. By focusing on inherent ecological and life history characteristics, this method enhances our understanding of how exploited species are likely to respond to various OWF-related pressures. The overarching goal of this study is twofold: first, to provide data-driven insights that aid policymakers in defining OWDAs that avoid or minimize impacts on fishery resources; and second, to offer practical guidance for mitigating the infrastructure's effects on these resources throughout the wind farm lifecycle (survey, construction, operation, and dismantling). Ultimately, this tool strives to provide nuanced, mechanism-based insights that can inform targeted and tailored management strategies for mitigating the potential impacts of OWF-related stressors on commercially important species, while considering the broader context of marine spatial planning and stakeholder interests. Using a case study in the NW Mediterranean, we highlight the importance of understanding and evaluating the vulnerability of commercial species to floating OWF-related stressors within the context of marine spatial planning and marine resource management. This vulnerability assessment tool aims to contribute to informed decision-making for the sustainable co-development of offshore wind energy and commercial fisheries, emphasizing its potential to be operationalized within existing management frameworks.

2. Methodology

2.1. Study area

The Cape Creus/Gulf of Roses region (Spain, NW Mediterranean, Fig. 1) contains LEBA 1, one of Spain's officially designated "Areas of High Potential for Offshore Wind" (MITECO, 2023). Identified as a zone with significant potential for offshore wind energy, LEBA 1 is the focal point of our study. Given the region's deep waters, any OWFs developed here would specifically utilize floating technology. These "Areas of High Potential for Offshore Wind" are defined by Spain's Maritime Spatial Plans (*Planes de Ordenación del Espacio Marítimo* - POEMs) for the Mediterranean demarcation (MITECO, 2023), which aim to organize all maritime activities, including renewable energy development, while prioritizing marine environmental protection. For clarity and broader applicability in this paper, we refer to these officially designated areas, such as LEBA 1, as an Offshore Wind Development Area (OWDA). LEBA 1 additionally overlaps with a zone of High Potential for the conservation of biodiversity.

Critically, this study area is characterized by a significant concentration of Marine Protected Areas (MPAs) within and around the designated LEBA 1. These designations include Natura 2000 sites (Special Protection Areas [SPA], Sites of Community Importance [SCI], and proposed Sites of Community Importance [pSCI]), Specially Protected Areas of Mediterranean Importance (SPAMIs), Particularly Sensitive Sea Areas (PSSAs), Important Bird Areas (IBAs), Important Marine Mammal Areas (IMMAs), Critical Coastal Habitats (CCHs), Key Biodiversity Areas (KBAs), and Important Shark and Ray Areas (ISRAs) (Lloret et al., 2023). The co-location of these MPAs with the proposed OWDA, as highlighted

Table 1
Overview of landings and economic importance of commercially important species in the study area categorized by primary fishing technique. Data sourced from the fish auctions of Llançà, El Port de la Selva, Roses, L'Escala, L'Estartit, and Palamós in 2023.

Primary fishing technique	Species	Landings (kg)	Percentage of total landings (%)	Economic value (euros)	Percentage of Total Economic Value (%)
Purse seining	*Sardina pilchardus*	776,597	22.69	1,916,218	8.46
	Engraulis encrasicolus	576,744	16.85	1,171,170	5.17
	Sardinella aurita	264,360	7.72	216,504	0.95
Small-scale fishing	*Mullus surmuletus*	71,263	2.08	465,292	2.05
	Octopus vulgaris	49,108	1.43	458,049	2.02
	Gymnammodytes spp.	22,963	0.67	492,223	2.17
	Seriola dumerili	18,700	0.55	183,391	0.81
	Paracentrotus lividus	18,638	0.54	92,488	0.41
	Sparus aurata	17,374	0.51	190,445	0.84
	Sarda sarda	9856	0.29	6,6287	0.29
	Thunnus thynnus	8444	0.25	66,595	0.29
Trawling	*Merluccius merluccius*	197,448	5.77	1,550,442	6.84
	Aristeus antennatus	152,291	4.45	6,829,159	30.14
	Micromesistius poutassou	100,765	2.94	357,330	1.58
	Phycis blennoides	90,405	2.64	258,506	1.14
	Lophius spp.	82,385	2.41	828,723	3.66
	Eledone cirrhosa	80,504	2.35	330,243	1.46
	Illex coindetii	76,537	2.24	298,826	1.32
	Parapenaeus longirostris	73,565	2.15	1,329,854	5.87
	Mullus barbatus	71,685	2.09	341,536	1.51
	Nephrops norvegicus	69,902	2.04	1,812,945	8.00
Total		2,829,534	82.7	19,256,226	85.00

by Lloret et al. (2022, 2023), indicates heightened ecological sensitivity.

This complex spatial context emphasizes the critical need for careful spatial planning to mitigate potential conflicts and ensure environmentally responsible deployment. Such planning must align with strategic frameworks like the "Roadmap for the development of offshore wind and marine energy in Spain" (MITECO, 2021), which targets substantial offshore wind capacity by 2030 while emphasizing environmentally sound practices. Furthermore, a fundamental dimension of effectively applying this vulnerability assessment within these MPAs, and a critical consideration for maritime spatial planning, involves understanding how their varied conservation statuses and specific management objectives affect the overall risk perception and management priorities related to OWF development, even if they do not directly alter the intrinsic biological vulnerability of species to OWF stressors. This integrated perspective is crucial for developing effective mitigation strategies and achieving sustainable co-development in such sensitive areas.

The study area includes six fishing ports (Fig. 1), highlighting the region's importance to commercial fisheries. Two Fisheries Restricted Areas (FRAs) designated by the Spanish Government lie within this zone (Fig. 1). One FRA directly overlaps with the proposed OWDA, permanently prohibiting all fishing activities. This closure was notably established by the Roses Fishermen Association (Recasens et al., 2016; MAPA, 2022) to specifically protect a critical nursery habitat for the European hake (*Merluccius merluccius*) (Tuset et al., 2021). The second FRA, located southeast of the OWDA, also enforces a permanent fishing closure (MAPA, 2022).

2.2. Species selection

To identify commercially important species, we analyzed the latest available data from fish landings data for 2023 from ports within our study area (ICATMAR, 2024). These ports included Llançà, El Port de la Selva, Roses, L'Escala, L'Estartit, and Palamós (Fig. 1). Species were then categorized by their primary fishing technique (trawling, purse seining, or artisanal fishery) based on expert judgment. Within each method, we selected species that collectively represented at least 75 % of the total landings. This yielded a diverse selection of 21 species (Table 1). Specifically, three species were primarily caught by purse seining: *Sardina pilchardus*, *Engraulis encrasicolus*, and *Sardinella aurita*. Eight species were primarily caught by artisanal fishing: *Mullus surmuletus*, *Octopus vulgaris*, *Gymnammodytes cicerelus* and *Gymnammodytes semisquamatus*, *Seriola dumerili*, *Paracentrotus lividus*, *Sparus aurata*, *Sarda sarda*, and *Thunnus thynnus*. The 10 species primarily caught by trawling included *Merluccius merluccius*, *Aristeus antennatus*, *Micromesistius poutassou*, *Phycis blennoides*, *Lophius piscatorius* and *Lophius budegassa, Eledone cirrhosa*, *Illex coindetii*, *Parapenaeus longirostris*, *Mullus barbatus*, and *Nephrops norvegicus*. This selection encompasses 14 teleosts, 1 echinoid, 3 decapods, and 3 cephalopods. Collectively, these selected species accounted for 82.7 % (2829.534 metric tons) of the total landings from the study area ports and 85 % (nearly 20 million euros) of the total economic value generated at auctions in 2023 (Table 1).

2.3. Trait-based assessment tool

We adapted a trait-based assessment tool from the framework developed by Butt et al. (2022) to evaluate species vulnerability to floating OWF-related stressors. The original framework was designed to assess marine species' vulnerability to various human impacts.

2.3.1. Identification of stressors

To identify primary stressors affecting economically important species from floating OWFs, we conducted a comprehensive literature review. The identified stressors include: sediment resuspension (Clarke et al., 2000; Utne-Palm, 2002; Au et al., 2004; Hammar et al., 2015), habitat loss (Defingou et al., 2019; Horwath et al., 2020), electromagnetic fields (Tricas and Gill, 2011; Copping et al., 2021), chemical pollution (Bonar et al., 2015; Horwath et al., 2020; Farr et al., 2021), light pollution (Orr et al., 2013), noise and vibration (Wilhelmsson et al., 2010; Mooney et al., 2020), thermal radiation (English et al., 2017; Taormina et al., 2018; Reynaud et al., 2021), entanglement (Maxwell et al., 2022; Svendsen et al., 2022), and oceanographic changes (Van Berkel et al., 2020; Gill et al., 2020; Hogan et al., 2023). Further details on these stressors are provided in Annex 1.

2.3.2. Trait selection

We identified key life history traits influencing species' responses to floating OWF stressors, which either increase sensitivity or limit adaptive capacity (Butt and Gallagher, 2018; Butt et al., 2022). While drawing from Butt et al. (2022), we customized the trait selection for our specific taxa. Traits unrelated to floating OWF stressors or specific to excluded taxa (e.g. seabirds, marine mammals) were excluded.

Conversely, traits specific to floating OWF-related stressors, such as electromagnetic reception for assessing sensitivity to electromagnetic fields (EMFs), were added based on the literature review described in Section 2.3.1 (further details on selected traits are provided in Annex 2).

The selected traits were grouped into five categories, as in Butt et al. (2022): movement, pertaining to dispersal ability to shift distribution in response to stressors; reproduction, indicating population turnover influencing adaptation or recovery; specialization, where species with niche dependence are considered more sensitive; spatial scale metrics, used for defining exposure to stressors; and biophysical traits, serving as indicators of sensitivity to anthropogenic stressors.

2.3.3. Trait-species correlation

Traits were linked to each species, reflecting key biological and ecological characteristics relevant to their vulnerability. These traits were further categorized into the three dimensions of vulnerability: adaptive capacity, which encompasses traits influencing the ability to adapt or recover from stressors; exposure, defined by traits determining the likelihood of encountering stressors based on spatial distribution and habitat use; and sensitivity, comprising traits heightening susceptibility to stressors due to physiological or ecological characteristics (Further details on trait-species correlation are provided in Annex 3).

2.3.4. Trait-stressor combination

Following Butt et al. (2022), we quantitatively assessed each trait-stressor combination by assigning a vulnerability score of "none," "low," "medium," or "high". This provided a graded assessment of how specific traits confer vulnerability to individual stressors. Continuous values were classified into discrete categories to ensure consistency across species.

For spatial scale metrics traits, we specifically tailored the connection between exposure categories and floating OWF-related stressors to our case study. For instance, in assessing the entanglement stressor, we accounted for the absence of coastal anchoring lines, thereby adapting our approach to the unique characteristics of the OWF project.

2.3.5. Vulnerability model

We calculated relative vulnerability scores for each species using the vulnerability model developed by Butt et al. (2022). This comprehensive, species-specific evaluation of vulnerability to floating OWF-related stressors is a function of three main components: sensitivity, adaptive capacity, and exposure.

Sensitivity was determined based on species traits that increase physiological or ecological susceptibility to each stressor. Traits, such as habitat dependence or specialized life-history stages, were assigned scores of high, medium, low, or no sensitivity (weighted as 1.00, 0.67, 0.33, and 0, respectively). The overall sensitivity score for a species i to a specific stressor j was computed as the sum of sensitivity weights for each relevant species trait category k.

$$\text{Sensitivity score } S_{ij} = \sum_{k} s_{jk} t_{ik}$$

Here, s_{jk} represents the sensitivity to stressor j based on trait k, and t_{ik} represents the presence (0 or 1) of trait k in species i.

Adaptive capacity was similarly calculated by assessing traits that enhance a species' ability to recover or adapt to stressors. Traits related to reproduction, population resilience, or mobility were scored using the same weighting system as sensitivity. The model incorporated both specific adaptive capacity (to individual stressors) and general adaptive capacity (broader traits enhancing species' resilience across stressors).

The specific adaptive capacity of a given species i to a given stressor j is the sum of adaptive capacity weights based on the species' traits:

$$\text{Specific adaptive capacity score } A_{ij} = \sum_{k} a_{jk} t_{ik}$$

Where a_{jk} represents specific adaptive capacity to stressor j based on trait k, and t_{ik} represents the presence of trait k in species i.

The general adaptive capacity of a given species i is calculated as the sum of general adaptive capacity weights based on species' traits:

$$\text{General adaptive capacity score } G_i = \sum_{k} g_k t_{ik}$$

Here, g_k represents general adaptive capacity (stressor independent) based on trait k, and t_{ik} represents the presence of trait k in species i.

Exposure represented the likelihood that a species would encounter a given stressor, constrained by the species' spatial distribution and habitat preferences. Exposure potential was binary (0 or 1); species were excluded from vulnerability calculations for stressors outside their habitat range (e.g., deep-water species were not exposed to surface-level stressors like light pollution).

$$\text{Exposure potential modifier } E_{ij} = 1 \text{ when } \sum_{z} e_{jz} p_{iz} > 0, \text{otherwise } E_{ij} = 0$$

Where e_{jz} represents the possible occurrence of stressor j in zone z, and p_{iz} represents the possible occurrence of species i in zone z.

The final vulnerability score of species i to stressor j (V_{ij}) depends on its sensitivity (S_{ij}), is moderated by its specific (A_{ij}) and general (G_i) adaptive capacities, and constrained by its exposure potential (E_{ij}). To account for stressors having varying numbers of associated traits, each component was normalized by the maximum value for that component (for that specific stressor) observed across all species. For example, the sensitivity of species i to stressor j is normalized by $S_j' = \text{max\_}\{i = 1, \ldots, \text{n}\}(S_{ij})$.

$$\text{Vulnerability } V_{ij} = \frac{S_{ij}/S_j'}{1 + G_i/G' + A_{ij}/A_j'} \times E_{ij}$$

The resulting vulnerability score $V_{ij} \in [0, 1]$ increases with sensitivity ($S_{ij}/S_j' \in [0, 1]$), decreases with adaptive capacity (G_i/G' and $A_{ij}/A_j' \in [0, 1]$), and is constrained by exposure potential ($E_{ij} \in \{0, 1\}$). Scores were normalized to enable comparisons across and between taxa and stressors.

Species with high sensitivity and low adaptive capacity, combined with a high likelihood of exposure, received the highest vulnerability scores. This comprehensive framework allowed for a nuanced evaluation of species' relative vulnerabilities to floating OWF stressors, integrating multiple biological and ecological traits.

2.4. Statistical analysis

To enhance the interpretation of species vulnerability scores, we performed additional statistical analyses.

Pearson's correlation coefficients were calculated to assess relationships between the calculated vulnerability scores for different stressors across species. This exploratory analysis aimed to identify patterns of co-occurrence and contrasting effects, highlighting which stressors tended to affect species similarly or differently in terms of their overall vulnerability. The variables used for these correlations, being continuous vulnerability scores (ranging from 0 to 1), met the assumptions of Pearson's r regarding continuity and linearity.

A two-way analysis of variance (ANOVA) was conducted in R software (R Core Team, 2023) to explore the spatial dynamics of vulnerability and assess the influence of ocean zones (littoral, neritic, slope) and ecological zones (benthic, pelagic) on species' vulnerability scores. Post-hoc comparisons examined pairwise differences. Homogeneity of variances, an assumption for ANOVA, was assessed using Levene's Test, and normality of residuals was also checked.

We also analyzed species vulnerability scores in relation to fishing methods. This analysis aimed to both assess the similarity and variability of vulnerability profiles within each method (via Pearson's correlations)

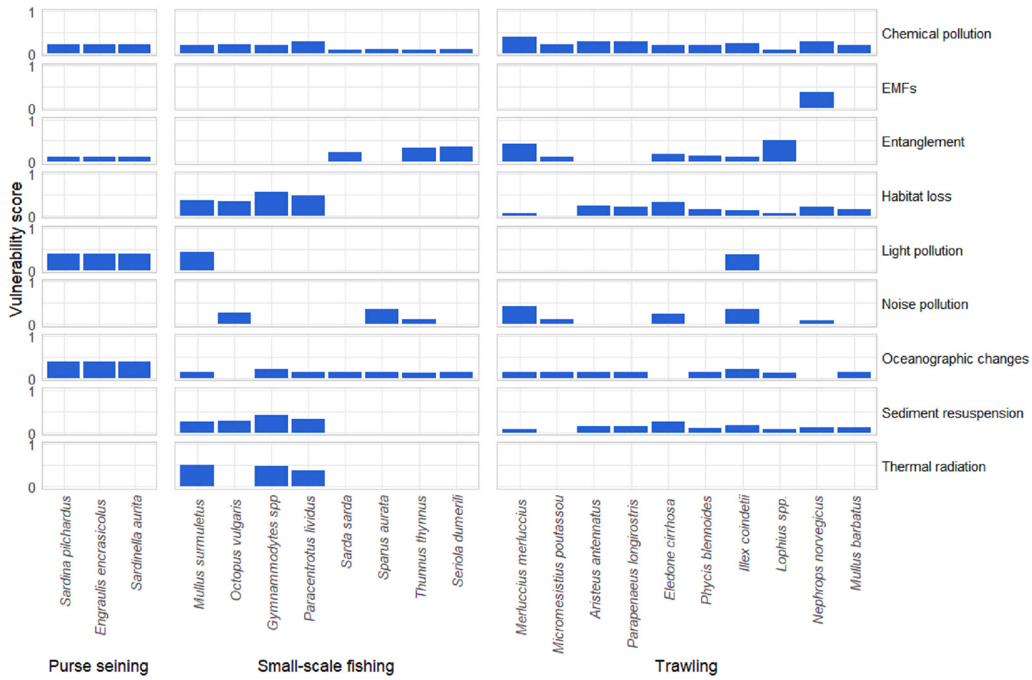

Fig. 2. Vulnerability scores of commercially important species to different Offshore Wind Farm-related stressors. The species evaluated are listed on the x-axis – ordered by fishing method –, the y-axis represents the vulnerability score, with higher values indicating greater vulnerability to the respective stressor.

and to compare the average vulnerability scores between different methods (using t-tests). This grouping by predominant fishing method served as a pragmatic way to categorize species for analysis, allowing us to investigate how their vulnerability to OWF stressors might differ across species assemblages typically targeted by specific fishing practices, rather than implying a direct causal link between fishing gear and OWF stressor characteristics. Pearson's correlation coefficients were used to assess the similarity of vulnerability profiles (i.e., the set of vulnerability scores across all stressors) among species within each fishing method (purse seines, artisanal fishing, and trawling). For this analysis, the variables correlated were the continuous vulnerability scores of different species. To detect potential differences in species-specific vulnerabilities between fishing methods, we employed pairwise t-tests for direct comparisons between fishing methods (e.g., trawling vs. purse seines).

3. Results

OWF-related stressors exerted varying impacts on commercially important marine species, with specific species affected differently by each stressor. Vulnerability scores, ranging from 0 to 1, represent relative potential susceptibility, with higher values indicating greater impact. These numerical values reflect varying degrees of sensitivity, adaptive capacity, and exposure, providing a continuous scale for quantitative comparison and ranking of species' relative vulnerabilities across stressors (Fig. 2). A vulnerability score of 0 for certain species-stressor combinations indicates that, within the model's scope, the species is considered unaffected or not susceptible. This may result from a complete lack of spatial exposure (e.g., no overlap between species distribution and the stressor's footprint) or the absence of relevant sensitive traits, despite potential exposure. Such zero scores highlight species inherently resilient or outside the scope of impact for specific floating OWF pressures based on model assumptions.

Chemical pollution was the only stressor potentially impacting all 21 exploited species, yielding low to moderate vulnerability scores (mean = 0.21, SD = 0.08). *Merluccius merluccius* exhibited the highest score for this stressor (0.399). Oceanographic changes affected 18 species, predominantly small pelagic fishes, with *Sardina pilchardus*, *Engraulis encrasicolus*, and *Sardinella aurita* all scoring 0.387. Sediment resuspension impacted 13 species, including *Gymnammodytes spp*. (0.413) and *Paracentrotus lividus* (0.310). Electromagnetic fields primarily affected the decapod *Nephrops norvegicus*, the only species assessed as vulnerable to this stressor, likely due to its sensitivity to electromagnetic fields (0.375). Entanglement risks affected 12 predominantly larger-bodied species, with *Lophius spp.* (0.500), *Merluccius merluccius* (0.427), *Seriola dumerili* (0.363), and *Thunnus thynnus* (0.343) recording the highest vulnerability scores. Habitat loss affected 13 species;

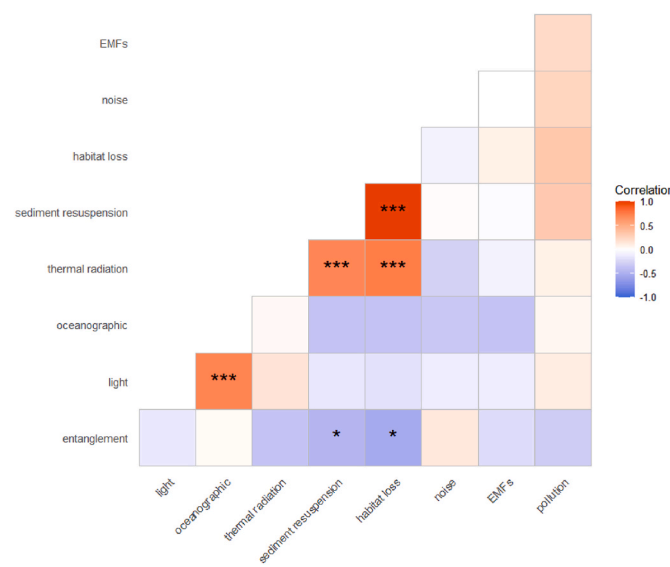

Fig. 3. Correlation plot depicting Pearson's correlations between vulnerability scores of species related to Offshore Wind Farm-associated stressors. Red squares indicate a positive correlation; blue squares indicate a negative correlation; and white squares indicate no correlation. Asterisks denote the significance of the correlations, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Gymnammodytes spp. showed the highest sensitivity score across all stressors (0.571), followed by *Paracentrotus lividus* (0.473), *Mullus surmuletus* (0.375), and *Octopus vulgaris* (0.341). Light pollution impacted 5 species; *Mullus surmuletus* had the highest vulnerability score (0.428), while *Sardina pilchardus*, *Engraulis encrasicolus*, and *Sardinella aurita* all scored 0.387, alongside *Illex coindetii* (0.353). Noise pollution threatened 8 species, including *Merluccius merluccius* (0.427), *Sparus aurata* (0.361), and cephalopods such as *Illex condetii* (0.348), *Octopus vulgaris* (0.265), and *Eledone cirrhosa* (0.258). Finally, thermal radiation affected only 3 species: *Mullus surmuletus* (0.480), *Gymnammodytes spp.* (0.481), and *Paracentrotus lividus* (0.387).

The following results highlight relationships between individual stressors based on species-specific vulnerability scores. Vulnerability scores for sediment resuspension showed a strong positive correlation with those for habitat loss (0.98) and thermal radiation (0.69), indicating that these stressors frequently affect similar species (Fig. 3). For example, *Gymnammodytes spp*. and *Paracentrotus lividus* are highly sensitive to both sediment resuspension and habitat loss due to their strong habitat dependency and limited dispersal ability. In contrast, sediment resuspension vulnerability was negatively correlated with entanglement (−0.45), and similarly, habitat loss was negatively correlated with entanglement (−0.53). This suggests species impacted by habitat loss or sediment resuspension are less likely to be affected by entanglement. These patterns reveal a clear distinction between benthic stressors (e.g., sediment resuspension, habitat loss, thermal radiation) and pelagic stressors (e.g., entanglement), each resulting in different vulnerability profiles. Additionally, vulnerability scores for light pollution and oceanographic changes were highly correlated (0.71), suggesting these stressors may similarly impact certain pelagic species.

For the ANOVA, while no significant main effects were observed for ocean zone or ecological zone individually, a significant interaction occurred between these two factors ($p = 0.0483$). This indicates the effect of one zone depended on the other. However, post-hoc comparisons did not reveal statistically significant differences between most pairwise groupings, suggesting that despite the significant interaction, it did not lead to large disparities in vulnerability scores across specific ocean and ecological zones. Levene's Test confirmed the assumption of homogeneity of variances ($p = 0.5618$).

These findings underscore the complex interplay between ocean zones and ecological zones in shaping species vulnerability and reinforce the clear segregation between benthic and pelagic stressors.

Among small-pelagic species targeted by purse seines (*Sardina pilchardus, Engraulis encrasicolus,* and *Sardinella aurita*), vulnerability scores were highly consistent, exhibiting a Pearson's correlation of 1 (Fig. 2). This high correlation reflects their shared ecological traits and consistent vulnerability to floating OWF-related stressors. Conversely, species predominantly captured through artisanal fishing and trawling displayed a wider range of vulnerability scores, indicating greater species-specific variability in their sensitivity to stressors. Despite this observed variability within fishing methods, no significant differences in vulnerability were found between fishing practices. The distinct vulnerability profiles observed for individual species underscore the importance of trait-based assessments in understanding OWF impacts.

4. Discussion

This study offers critical insights into the vulnerability of commercially exploited marine species to floating OWF development in the Mediterranean. Our findings underscore the urgent need for integrated management strategies that consider both ecological and socio-economic factors to ensure the sustainable coexistence of marine renewable energy and fisheries. To this end, we introduce a trait-based assessment tool designed to guide the planning of OWDAs and the development of floating OWFs. Ultimately, this tool can assist policymakers and developers in minimizing negative impacts of floating OWF on commercially important species.

4.1. Species vulnerabilities to floating OWFs

Our analysis reveals that while chemical pollution, habitat loss, and oceanographic changes are primary stressors in the study area, floating OWF development introduces significant species-specific vulnerabilities. Certain exploited species, particularly those in benthic and coastal environments, show increased susceptibility due to habitat-dependent traits that limit their adaptability to environmental changes. For instance, benthic coastal species such as *Mullus surmuletus*, *Gymnammodytes spp*., and *Paracentrotus lividus* exhibit high vulnerability scores in relation to sediment resuspension, thermal radiation, and habitat loss. Understanding these vulnerabilities can guide OWF design and planning to minimize potential impacts on these species. To reduce risks, maritime spatial planners and OWF developers should prioritize identifying and avoiding key vulnerable habitats early in project design (Sahla et al., 2016). Our findings suggest that targeted measures, such as implementing buffer zones around critical benthic habitats, can help mitigate potential impacts and foster more sustainable OWF development.

Beyond these broad impacts, specific vulnerabilities emerge within benthic exploited species. The effects of electromagnetic fields on the decapod *Nephrops norvegicus* are particularly noteworthy, as it is the only species in our study identified as sensitive to these changes. Additionally, three cephalopod species (*Octopus vulgaris*, *Eledone cirrhosa*, and *Illex coindetii*) are impacted by noise pollution, posing a substantial threat due to the sensitivity of their statocysts (Solé et al., 2013). Chemical pollution affects all benthic species, indicating a broader ecological concern from this stressor.

Demersal exploited fish also exhibit distinct vulnerabilities. The European hake (*Merluccius merluccius*), for example, showed high vulnerability scores for noise pollution, entanglement, and chemical pollution. Crucially, our study area includes a Fishery Restricted Area (FRA) specifically designated to protect and restore a nursery habitat for this species (Tuset et al., 2021) (Fig. 1). This FRA has demonstrated efficacy in safeguarding the habitat and facilitating juvenile European hake recruitment (Recasens et al., 2016; Sala-Coromina et al., 2021). Furthermore, European hake is the most frequently captured species by trawling in the studied area (Table 1). Consequently, potential negative repercussions on this FRA by floating OWF elements such as anchors, mooring lines, and electric cables raise serious concerns regarding impact on *Merluccius merluccius* (Lloret et al., 2022). In such protected and restoration areas, OWF effects on exploited species could be further intensified. Therefore, as Lloret et al. (2023) highlight, OWF development should be excluded from FRAs and other marine protected areas to mitigate these risks.

In contrast, pelagic species (e.g. *Sardina pilchardus*, *Sarda sarda* and *Thunnus thynnus*) are generally less affected by localized disturbances due to their mobility, which allows them to evade immediate impacts. Nevertheless, small pelagic species (*Sardina pilchardus*, *Engraulis encrasicolus*, and *Sardinella aurita*) are strongly influenced by oceanographic processes. These species depend on planktonic food sources, and their population dynamics are highly sensitive to environmental changes due to the importance of egg and larval survival for recruitment (Albo Puigserver, 2019; Sabatés et al., 2024). To mitigate potential OWF impacts on these pelagic species, it is essential to incorporate oceanographic factors into project designs, a consideration often overlooked (Clark et al., 2014). This difference in vulnerability between pelagic species and other taxa necessitates tailored management approaches.

4.2. Interacting stressors and management implications

These nuances in vulnerability scores underscore the need for a comprehensive evaluation approach that considers species' specific ecological dependencies and habitat requirements in each assessment (Lemos, 2023). Implementing this trait-based methodology in different case studies must include such details to ensure accurate and effective assessments. This case-by-case approach is vital for identifying potential impacts, thereby providing a more tailored and precise strategy for balancing renewable energy development with fisheries preservation (Abramic et al., 2022). Ultimately, our findings emphasize considering the life history traits of each species when assessing potential floating OWF impacts and highlight the need for lifecycle-based management plans that incorporate species-specific vulnerabilities to effectively mitigate long-term environmental disruptions. This species-specific variability also highlights the need to move beyond single-stressor assessments and consider the complex interactions between multiple stressors.

The observed correlations between individual stressors, derived from species-specific vulnerability scores, provide valuable insights into the simultaneous vulnerability of certain species to multiple OWF-associated stressors. Strong positive relationships between sediment resuspension, habitat loss, and thermal radiation suggest that these stressors frequently co-occur and can amplify each other's impacts on species with similar biological traits and ecological requirements. For instance, benthic species like *Mullus surmuletus*, *Gymnammodytes spp*., and *Paracentrotus lividus* exhibit high sensitivity to these three stressors, illustrating this trend due to their strong habitat dependency (Boudouresque and Verlaque, 2001; Lombarte et al., 2000). This sensitivity is particularly pronounced for these species as they inhabit the littoral zone, where they are exposed to the combined effects of the export cables associated with OWF (Wawrzynkowski et al., 2025). This pattern aligns with findings from other studies, which indicate that species with high habitat specialization are disproportionately affected by habitat disruptions (Vázquez and Simberloff, 2002; Pratchett et al., 2012). These results underscore the need for management strategies that consider the compounded effects of multiple stressors rather than addressing them in isolation.

Conversely, the negative correlations observed between sediment resuspension, habitat loss, and entanglement suggest a clear separation between benthic and pelagic stressors. This distinction indicates that benthic species—often characterized by limited mobility and reliance on structured habitats—are more vulnerable to physical disruptions like sediment resuspension and habitat loss. In contrast, pelagic species are primarily affected by entanglement and other hazards typical of open-water environments (Wawrzynkowski et al., 2025). This is consistent with ecological theory suggesting that species are more susceptible to stressors that directly interact with their specific ecological zones and physical environments (Solan and Whiteley, 2016). Such differentiation supports the need for targeted management based on species: benthic species may benefit from protective measures against habitat disturbances, while pelagic species might require mitigation strategies aimed at reducing entanglement risks.

The significant interaction between ocean and ecological zones highlights that species' vulnerability to floating OWF stressors depends on both their depth-related habitat and spatial position. This means benthic and pelagic species may experience stressors differently depending on the specific horizontal and vertical characteristics of their habitats. This finding points to the need for conservation strategies that consider these spatial dimensions. Although post-hoc comparisons showed only subtle differences, the interaction underscores the importance of a multidimensional approach when assessing species' vulnerabilities in diverse marine environments. In summary, the complex interplay between ocean and ecological zones significantly influences exploited species vulnerability to floating OWF-related stressors. The observed patterns reflect how species' biological and ecological traits shape their responses to multiple, co-occurring stressors, emphasizing the need for spatially adaptive conservation strategies. Future research should explore how these dynamics may shift with OWF expansion and climate change, enhancing the effectiveness of mitigation strategies that address species vulnerabilities across complex ecological gradients.

4.3. Cumulative impacts and fisheries management

Understanding individual species vulnerabilities is crucial, but it is equally important to consider the cumulative impacts of OWFs in conjunction with other existing stressors in the marine environment. Recognizing that the ecological consequences of OWF development extend beyond immediate site-specific effects, a comprehensive approach incorporating cumulative impact assessments (Willsteed et al., 2018) is essential. This necessitates evaluating the synergistic interactions between OWF-related stressors and pre-existing anthropogenic pressures, including climate change, habitat degradation, and overfishing. Our findings reveal that several exploited species identified as highly vulnerable to potential floating OWF-related stressors are already under significant pressure from existing factors. Notably, many assessed species stocks are currently overexploited in the Mediterranean Sea (STECF et al., 2023), exacerbating their vulnerability to additional disturbances. The cumulative effects of OWF development and these pre-existing stressors could significantly amplify the risk to fisheries (Hogan et al., 2023).

The absence of significant differences in vulnerability values across fishing methods suggests that vulnerability to OWF-related stressors is more strongly linked to the intrinsic biological traits of the targeted fish species rather than the specific fishing gear employed. Indeed, while species captured by purse seines (*Sardina pilchardus*, *Engraulis encrasicolus*, and *Sardinella aurita*) are highly similar in their biological traits and exhibit consistent vulnerability, the species composition across other fishing methods (e.g., trawling and artisanal fishing) is notably diverse. Despite these clear differences in species assemblages between fishing methods, our findings indicate that the collective vulnerability profiles of species associated with each fishing method do not significantly diverge in their susceptibility to OWF-specific stressors. This suggests that the biological traits critical for OWF vulnerability are not systematically or substantially different across these broader fishing categories, even given their distinct species' compositions and targeted fisheries. From this perspective of species vulnerability to OWF-related stressors, our results underscore the need for a holistic approach to fisheries management in OWF planning. This means considering all fishing practices equally in OWF planning and implementation because the OWF-induced vulnerability of the species they target doesn't significantly differ between fishing groups. This approach highlights the importance of broadly addressing OWF impacts on species across all exploited fisheries.

Therefore, management strategies must be tailored to address the specific vulnerabilities of individual species, providing a more accurate understanding of the cumulative ecological burden imposed on these exploited populations. Moreover, adaptive management should be advocated, allowing fisheries policies to be continuously adjusted based on new scientific findings and ongoing monitoring data (Peery and Heyman, 2020). This responsiveness fosters effective management as the impacts of OWFs and other stressors evolve over time. Establishing a collaborative framework that includes stakeholders from the fishing industry and the renewable energy sector can further enhance this integrated management approach, ensuring that all parties' interests and knowledge are appropriately considered in decision-making processes. Additionally, incorporating local ecological knowledge (LEK) from fishers and other stakeholders is vital, as their insights into species behavior and habitat use can significantly inform planning and management strategies (Gómez and Maynou, 2021). Ultimately, this integration can enhance OWF implementation effectiveness while minimizing risks to fishery resources.

4.4. The trait-based assessment tool: A solution for sustainable planning

Despite the clear ecological significance of cumulative impacts, their effective integration into current legal and planning frameworks remains a significant challenge warranting further consideration. In the

Mediterranean, MSP is a key tool for managing marine resources and allocating space for various activities, including OWF development (European Commission, 2025a, b). However, the effective integration of cumulative impact assessments within current MSP frameworks remains challenging and requires critical examination. Specifically, the consistent and comprehensive incorporation of the combined effects of OWFs with existing stressors within MSP decision-making processes remains unclear. Similarly, while Environmental Impact Assessments (EIAs) are typically required for OWF projects, the methodologies for assessing cumulative impacts within these EIAs can vary and may not always fully capture the complex interactions between OWF-related stressors and other anthropogenic pressures. For instance, the spatial and temporal scales of EIAs might be too limited to detect long-term or far-reaching cumulative effects. Furthermore, coordination between fisheries management policies and OWF development planning is often insufficient, leading to a fragmented approach that may underestimate the overall risk to fishery resources.

To effectively address these shortcomings, we advocate for: (i) strengthening legal mandates for cumulative impact assessments within MSP and EIA frameworks; (ii) developing and implementing standardized, robust methodologies for evaluating cumulative impacts; and (iii) fostering enhanced interdisciplinary integration between fisheries management and marine spatial planning authorities. Effective cumulative impact assessments should also integrate local ecological knowledge and stakeholder concerns, particularly from fishers considering the many conflicts arising between them and OWF projects, to ensure comprehensive evaluation and socially acceptable outcomes (Adams et al., 2023). Adaptive management strategies, coupled with improved data collection and monitoring, are also crucial to effectively respond to the evolving nature of cumulative impacts in the face of OWF expansion.

The ecological assessment of OWF is predominantly grounded in evidence accumulated over decades of global OWF development (Szostek et al., 2024). However, relying on literature from various worldwide studies renders this approach somewhat generic and qualitative, lacking precision in capturing unique characteristics of each area, such as species composition and planned technologies. In contrast, implementing a species-trait-based assessment tool, such as the one we advocate, allows for adaptability to a given area's unique species characteristics within a quantitative framework. Furthermore, integrating local knowledge from fishers can significantly enhance the tool's accuracy and relevance by providing invaluable insights into species behavior, habitat use, and ecological sensitivities specific to the region. Moreover, this approach allows for customizing stressors to align with proposed technologies for the study case, ensuring a more accurate depiction of potential OWF impacts. Additionally, the exposure component can be tailored to the specific case study through understanding species' spatial distribution and the placement of OWF infrastructures. This adaptability enables adjusting stressor location and magnitude, enhancing the overall precision of the vulnerability assessment framework. Such a comprehensive and adaptable framework is essential for evaluating potential ecological impacts of OWF on exploited species while considering an area's unique attributes.

Specifically, our trait-based vulnerability assessment can directly inform MSP by clarifying the specific sensitivity of commercially important species to floating offshore wind developments. This information is crucial for minimizing the impacts of OWFs on commercially important species and ensuring the sustainable development of offshore wind energy in the Mediterranean.

4.5. Limitations of the trait-based model

The model used in this study, while offering valuable insights into species-specific vulnerabilities to floating OWF-related stressors, has several limitations. First, the trait-based approach, though effective in identifying general patterns, may oversimplify complex ecological interactions and species' adaptive capacities to stressors, particularly cumulative impacts from multiple sources. Second, the model's reliance on comprehensive data regarding species' biological traits (e.g., life history, physiology, behavior), and known sensitivities to specific stressors means that certain species, especially those with less-studied traits or distributions, may be inaccurately assessed or omitted. While this was generally less of an issue for commercially important species focused on here (Tyler et al., 2012), it remains a general challenge for broader applicability. Although the trait-based framework is generally well supported for commercially important species, its applicability to inherently data-poor taxa warrants consideration. For species with uncertain or incomplete life-history or ecological information, the assessment tool remains operational by using conservative trait categorizations, expert-derived estimates, or proxy traits from phylogenetically or functionally similar species (Butt et al., 2022). While this approach allows inclusion of data-poor species—avoiding systematic omission of potentially vulnerable taxa—it also increases uncertainty in their vulnerability scores and underscores the need for cautious interpretation. Importantly, identifying species for which trait information is sparse can guide future data-collection priorities and help refine subsequent applications of the tool across broader species assemblages. Finally, the model assumes a static relationship between species and their environment, potentially overlooking dynamic factors such as climate-driven shifts in species distribution or changes in habitat conditions over time. These limitations indicate that, while the model provides a solid foundation, further refinement and integration with real-time monitoring data are crucial for more precise and adaptive management strategies.

4.6. Implications for policy and management

By identifying exploited species with high vulnerability to specific floating OWF-related stressors through a trait-based tool, this study provides essential insights for guiding regulatory measures to avoid or mitigate potential adverse effects of OWFs on marine resources. Conducted at the species level, it offers targeted guidance for managing these stressors by addressing the specific needs of the impacted species. Our findings can be instrumental in shaping conservation strategies, planning OWDAs, and implementing protective measures. This tool, focusing specifically on species vulnerability to floating OWF-related stressors, offers valuable input for maritime spatial planners, OWF developers, and fisheries managers. It aids in identifying key floating OWF-related stressors that could impact commercially exploited marine species across the Mediterranean. Our analysis provides a critical ecological layer: the identification of species highly vulnerable to floating OWF stressors. This specific contribution enables policymakers to define OWDAs where the impact on these vulnerable exploited species can be avoided or minimized. Furthermore, it assists OWF developers in avoiding and mitigating impacts on these resources during the different phases of wind farm development (survey, installation, operation, and decommissioning). Such targeted assessments can ensure that the deployment of renewable energy infrastructure, crucial for transitioning to sustainable energy sources, does not compromise the ecological integrity of stocks supporting Mediterranean fisheries.

However, the effective implementation of these targeted assessments and the balancing of offshore wind development with the protection of marine resources requires a robust spatial planning framework that incorporates stakeholder input and minimizes conflicts. MSP provides this crucial framework for coordinating different maritime activities and ensuring the sustainable use of marine space. By integrating vulnerability assessment tools for OWFs into marine resource conservation policies, we can enhance regulatory effectiveness and support a balanced approach to co-developing OWFs and fisheries.

4.7. Socio-economic considerations and stakeholder engagement

The fisheries sector represents a crucial component of the socio-

Fig. 4. Flowchart outlining the proposed trait-based vulnerability assessment tool for evaluating the vulnerability of commercially important species to Offshore Wind Farms (OWFs).

economic system in the Cape Creus/Gulf of Roses region. Beyond its economic value, fishing holds significant cultural importance, shaping the identity and traditions of many coastal communities (Gómez and Maynou, 2020). However, OWF development poses challenges, notably the spatial displacement of fishing activities, forcing fishers to travel greater distances, which increases operational costs and reduces fishing efficiency (European Commission, 2025a, b; Hogan et al., 2023) and disproportionately impacts small-scale fishers (Buchholzer et al., 2022). Furthermore, our findings suggest potential negative impacts on overall fish stocks and their availability to fisheries, stemming from multiple stressors. Collectively, these spatial and ecological changes can increase the economic vulnerability of fishing communities, potentially leading to reduced incomes and the erosion of traditional livelihoods (Buchholzer et al., 2022; Hogan et al., 2023; European Commission, 2025a, b).

Addressing these vulnerabilities and ensuring equitable outcomes necessitates robust stakeholder engagement and participatory governance (Reed et al., 2009). Current OWF planning practices in the region are limited to information dissemination rather than active participation (Fundación Nueva Cultura del Agua, 2023). However, there is a clear need to enhance stakeholder involvement for equitable and sustainable outcomes (Devine-Wright and Wiersma, 2020; Garcia et al., 2026). Therefore, achieving sustainable coexistence of OWFs and fisheries requires a focus on socio-ecological resilience – the capacity of interconnected social and ecological systems to withstand and adapt to disturbances (Folke, 2006). Our study highlights that OWFs can stress marine ecosystems, making them more vulnerable to further disturbances and consequently less able to provide the resources that fishing communities rely on. Similarly, economic dependency on a single activity (fishing) makes communities vulnerable to disruptions in that activity. If OWFs negatively impact fisheries, they may reduce the community's capacity to adapt to change.

4.8. *Conclusion and future directions*

A key contribution of this study is the development of a trait-based vulnerability assessment tool designed to support decision-making in OWF development and marine management, specifically focusing on commercially important species. This tool provides a framework for evaluating the relative vulnerability of these species to various floating OWF-related stressors and offers a proactive approach to managing ecological impacts. By identifying commercially important species particularly sensitive to specific stressors, the tool informs MSP by identifying areas where OWF development poses the greatest risk to fishery species, guiding OWDA placement, and minimizing ecological impacts on fisheries. Understanding these vulnerabilities also guides OWF design and planning to avoid impacts and prioritize habitat avoidance during early project stages. Furthermore, the tool is highly relevant to EIAs, aiding in identifying and predicting key impacts on commercially important species and evaluating mitigation effectiveness. It also contributes to cumulative impact assessments by analyzing species' vulnerability to multiple stressors.

The tool's ability to highlight the greatest threats to the most vulnerable commercially important species allows for a more targeted and efficient allocation of resources for mitigation efforts, such as implementing buffer zones around critical benthic habitats to protect benthic species of commercial importance. This is particularly crucial in sensitive areas like Fisheries Restricted Areas (FRAs), where our tool can inform decisions to exclude OWF development to mitigate risks to commercially important species, as highlighted by the potential negative repercussions of OWF elements on the FRA in our study area. Moreover, the tool's trait-based approach supports targeted management strategies, and its consideration of the interaction between ocean and ecological zones further emphasizes the need for spatially adaptive conservation strategies. Successful operationalization of this vulnerability assessment tool necessitates collaboration between scientists, managers, policymakers, and fisheries stakeholders. By implementing this evidence-based approach, we can move towards a more proactive management of the ecological impacts of offshore wind energy development on commercially important species, ultimately ensuring the sustainable coexistence of renewable energy and marine ecosystems without affecting fishing activities and fisher's livelihoods.

This study presents a vital tool for navigating the complex interactions between floating offshore wind energy development and sustainability of exploited marine species. Specifically, the presented trait-based vulnerability assessment tool (detailed in Fig. 4) offers a robust mechanism for policymakers and floating OWF developers to minimize ecological impacts on exploited species. By proactively identifying and addressing potential floating OWF impacts on exploited species throughout the OWF lifecycle, results facilitate the development of effective strategies to allow collocation of offshore wind farms and fisheries in a sustainable way. Looking forward, adaptive management, continuous monitoring, and inclusive stakeholder engagement—particularly with fishers—are essential to navigate the evolving challenges of offshore wind energy expansion and ensure the resilience of both marine ecosystems and fishing communities.

CRediT authorship contribution statement

Wawrzynkowski Paul: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Sabatés Ana:** Writing – review & editing, Validation. **Lloret Josep:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2025.107770.

Data availability

Data will be made available on request.

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