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Biodiversity baseline assessment for offshore wind projects: Challenges to implement Ecosystem-Based management

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ABSTRACT

Offshore wind energy (OWE) is expected to grow as part of the efforts to transition to a low-carbon economy. Its environmental and social impacts should be comprehensively assessed to identify and mitigate potential adverse effects. For this purpose, developing an appropriate biodiversity baseline that considers the ecological complexity of target areas, a crucial pre-construction phase of environmental impact assessment (EIA), can benefit from Ecosystem-Based Management (EBM) principles. Here, we review international guidance documents containing guidelines for performing biodiversity baseline assessments in OWE projects. We synthesize the guidelines and critically discuss their potentialities and limitations under an EBM perspective for the EIA process, proposing a conceptual approach applicable to OWE development. The reviewed documents recommended stakeholders' involvement in selecting priority biodiversity components and point to the need for assessing cumulative impacts, which agrees with EBM principles. However, we note insufficient guidance to evaluate the synergism between OWE impacts and climate change effects in the baseline phase and scarce recommendations about assessing impacts on ecosystem functions and services. To overcome such limitations, we discuss strategies to perform a retrospective-analytical baseline study prioritizing integrative-paired assessments of ecological processes, rather than species-centered assessments. Designing regional ecosystem models to clarify the causal nexus between OWE projects, biodiversity, and ecosystem-level indicators is also a fundamental need to incorporate EBM principles into baseline studies. Therefore, our contribution can support a holistic baseline assessment for offshore wind projects toward an ecologically responsible energy transition.

1. Introduction

Renewable energy projects, such as offshore wind energy (OWE), are being developed as an essential mitigation strategy against the current climate crisis. The OWE industry is rising fast, and its development is fundamental to achieving the United Nations Sustainable Development Goals (SDGs), especially SDG 7 – "Clean and affordable energy" (Bravo et al., 2023). However, OWE also has great potential to change the marine environment, affecting biodiversity, ecosystem functioning, and services (e.g., Causon & Gill, 2018). Several contributions have compiled ecological impacts from OWE farms, including changes in structure, processes, and functions of marine communities as well as hazards for important avian species and marine mammals (Cook et al., 2018; Galparsoro et al., 2022; Watson et al., 2024). In this regard, OWE must be developed following best practices to avoid amplifying the human pressures on the ocean, providing an opportunity to contribute to SDG 14 – "Life below water" (Bravo et al., 2023). Such assumptions can be the central step to turning OWE into a better tool to simultaneously face the climate and biodiversity crises.

To evaluate the potential changes caused or amplified by OWE

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projects, a comprehensive and well-planned environmental impact assessment (EIA) is needed. The effectiveness of the EIA process depends on pre-construction phases that include scoping the study, defining the spatial coverage, the information requirements, the biodiversity components, and the associated ecosystem functions that must be part of the assessment (e.g., Tamis et al., 2021). All these pre-construction steps are essential to design an appropriate baseline assessment of the biodiversity status, ecosystem structure, and functioning in the area projected for the development of OWE farms (e.g., Lemos et al., 2023; Teschke et al., 2023; Van Parijs et al., 2023). Baseline assessments are indispensable to guarantee an evaluation of the ecological reference conditions that will be used later to predict and identify the post-construction impacts of specific projects (Villnäs & Norkko, 2011; Cooper & Barry, 2017), supporting decisions on the environmental feasibility of the project and the definition and dimensioning of mitigation strategies. Considering the different activities and scales of the pressures regarding distinct project phases is also essential to define baseline data needs that address installation and operation impacts. In this regard, the baseline assessment must be made considering proper spatial and temporal scales to understand the natural dynamic of the ecosystems and associated biodiversity, also identifying the major ecological patterns, processes, habitats, services and species that will be potentially affected by the project, selecting the best metrics to work as indicators (Borja et al., 2016; Robert, 2024). In contrast, an inappropriate baseline assessment will not capture the reference ecological status and, consequently, will compromise future comparisons with post-construction conditions, hampering mitigation, monitoring, and management strategies and, ultimately, compromising the entire effectiveness of the EIA process (Mihoub et al., 2017; Clark et al., 2020; Dias et al., 2022).

Despite the importance of baseline data being recognized among several industries globally, scoping a baseline assessment for an EIA process is not a trivial task. Establishing reference conditions involves understanding the natural dynamics of local biodiversity (Robert, 2024), aiming to recognize future non-natural changes possibly related to a new project installation and operation (Van Parijs et al., 2023). The current context of global changes and intensive industrial offshore development increases the complexity of establishing these reference conditions since the current ecological dynamic of a target area is intensely and cumulatively interacting with past and current pressures (Elliott et al., 2015; Halpern et al., 2015; Declerck et al., 2023; Willsteed et al., 2023). Indeed, the baseline assessment must consider the cumulative impacts on marine biodiversity and ecosystem processes of other human activities (i.e., endogenic pressures) and the climate changes (i.e., exogenic pressures) acting on the area possibly affected by a new project (Elliott et al., 2015; Declerck et al., 2023; Piet et al., 2023). This affected area can encompass varied spatial scales (e.g., Daewel et al., 2022) and needs to consider the cross-scale dependence in the land-sea interface since multiple impacts on the continental shelf originate from onshore pressures that could interact with offshore pressures (Gonçalves et al., 2020; Michels-Brito et al., 2024). Cumulative impact assessments strongly depend on properly conducted baseline assessments since these tools are based on relative comparisons between post-construction status and baseline data (Willsteed et al., 2023; Tamis et al., 2024). Furthermore, the baseline assessment must recognize that biodiversity is directly and indirectly connected to many ecosystem functions, services, and social uses that can also be impacted by a new OWE project and its cumulative effects (Causon & Gill, 2018; Declerck et al., 2023; Watson et al., 2024). Therefore, understanding the ecological nexus and linkages based on ecosystem modeling is needed to clarify baseline conditions of the ecosystem functioning and their vulnerabilities (Baulaz et al., 2023; Trifonova & Scott, 2023).

Under this complexity, the principles of Ecosystem-Based Management (EBM) have great potential to support baseline assessments that can contribute to a holistic and integrated EIA process (Coston-Guarini et al., 2017; Turra et al., 2017; Andrade & Turra, 2021; Hyman et al., 2022; Bravo et al., 2023; Guilhon et al., 2023). Long et al. (2015) synthesized the main EBM principles for marine ecosystems, which include considering ecosystem connections, appropriate spatial and temporal scales, cumulative impacts, accounting for the dynamic nature of ecosystems, and conducting participatory processes that use multiple and interdisciplinary knowledge systems to inform decisions. Advances have been achieved regarding the incorporation of these and other EBM principles in the EIA process for multiple offshore industries (Coston-Guarini et al., 2017; Guilhon et al., 2021; Guilhon et al., 2023; Bravo et al., 2023). From this perspective, an emphasis on an overly descriptive baseline study, commonly adopted worldwide (e.g., Clark et al., 2020; Kruger & Pohlo, 2022), could be replaced by a more integrated-analytical and systemic baseline assessment (Wilding et al., 2017; Hyman et al., 2022). However, many basic and practical questions remain overlooked concerning the biodiversity baseline assessment for OWE projects, including: What biodiversity components must be assessed and which metrics must be measured to support indicators of impacts? How can appropriate scales, such as the study area coverage for the baseline assessment, be defined, considering the different spatial and temporal scales of ecological processes? How can the study design assess reference conditions to support later differentiation of project-specific and cumulative impacts, such as climate change? These questions are challenging for EIA, especially in Global South countries, where biodiversity data deficiency and low-quality baselines for impact assessment are generally a reality (e.g., Dias et al., 2022; Kruger & Pohlo, 2022).

In this paper, we developed a conceptual approach for biodiversity baseline studies that incorporates EBM principles in impact assessment for OWE projects. To this end, we first reviewed the information in guidance documents used as backgrounds to develop a biodiversity baseline study for the impact assessment in OWE projects. Our synthesis included the different requirements, practices, data needs, and indicators suggested by the guidance documents for developing the biodiversity baseline, and an inventory of the significant OWE pressures considered by the reviewed documents (section 3). Next, we discussed the potentialities and limitations of the synthesized guidelines considering how much they fit which is expected to support an EBM perspective for the EIA process in OWE projects (section 4). Therefore, our research aimed to conduct a qualitative analysis focused on practical guidance documents (i.e., guidelines for baseline studies) regarding OWE projects and biodiversity. This issue is fundamental for developing countries where several offshore wind projects are still in the planning phase, and baseline studies are an opportunity to overcome data-deficient scenarios and adequately account for uncertainties. Our results can thus guide the elaboration of robust regional-based protocols for pre-construction biodiversity baseline assessments under Ecosystem-Based Management principles worldwide.

2. Guidance documents survey

We performed a bibliographic search for guidance documents used as background to develop biodiversity baseline assessments. We considered official protocols, good practices guidelines, and guidance reports that present orientations for developing biodiversity baseline studies aiming at impact assessment and monitoring. Although applicable guidelines for baseline assessment are available in documents regarding multiple industrial sectors (especially information regarding cumulative impact assessment), here we were interested in specific records related to offshore wind projects or renewable offshore projects that include wind energy. With this focus, guidance documents for baseline assessments regarding other industrial sectors were not considered. Moreover, we aimed to analyze the contents and quality of such guidelines. Thus, we did not include reports of case studies, scientific articles, and other bibliographic documents that were not intended to guide the practical preparation of baseline studies.

For the document survey, we utilized specific bibliographic databases related to studies on renewable energy and their environmental

impacts. First, we accessed the Knowledge Base of Tethys, a platform developed in 2009 by the Pacific Northwest National Laboratory (PNNL, U.S.A.). This base provides over ten thousand documents, including official reports, governmental and non-governmental guides, and best practice protocols. The Tethys platform presents updated information, with recent documents added frequently, all concerning the environmental effects of wind and marine renewable energy worldwide, supporting the OES-Environmental and WREN (Working Together to Resolve Environmental Effects of Wind Energy) initiatives. We used the filtering system of the Tethys platform to select all documents classified in the technology categories of "Fixed Offshore Wind" and "Floating Offshore Wind", resulting in 2711 documents found. Next, we narrowed the resulting documents by the keyword "baseline", using the text box filter of the Tethys platform, which searches for this keyword in the abstracts and titles of all documents previously selected. The search resulted in 284 final documents that were further screened.

The screening process began by eliminating documents not directly related to biodiversity or the habitats supporting it. The next step in the screening process involved reading the title and abstract (or executive summary, description etc.) of each document, excluding those that did not meet at least one of the following criteria: (1) the document aims to guide readers in performing baseline studies; (2) the document aims to guide readers in performing impact assessments or monitoring and includes baseline assessment in its scope; (3) the document reviewed and compiled guidelines or protocols with strategies, practices, or requirements for conducting baseline studies.

Aiming to complement the survey conducted on the Tethys platform, we assessed the Renewable Energy Research Platform of the Bureau of Ocean Energy Management (BOEM, U.S.A.). We searched for the guidance documents on the website by consulting all available links in the "guidelines" folder. We also accessed two bibliographic repositories from Europe, the Renewables Grid Initiative and the Offshore Coalition for Energy and Nature, searching for documents in all folders of the page "Publications". In all these complementary bibliographic sources, we read the titles and abstracts of each document, selecting only those related to offshore wind projects and biodiversity, following the same criteria previously described for the search in the Tethys platform. Finally, after screening, the documents from all bases were categorized by year, locality (i.e., country or continent), and biodiversity components (i.e., biodiversity groups included in the document scope), and were submitted to a thorough reading analysis. For details regarding the final list of guidance documents analyzed (seventeen documents), see supplementary material (Appendix A).

During this final stage of comprehensive reading analysis, we searched for the key guidelines for biodiversity baseline studies in the analyzed document. We identified various recommended practices and requirements that could serve as a foundation for biodiversity baseline studies related to offshore wind projects. We sought guidelines concerning the scoping phase, specific data needs, and indicators proposed for the baseline assessment, using the following questions to extract information from each document:

- How are biodiversity components (i.e., biological groups/habitats), sub-components (i.e., ecological patterns and processes), and pre-construction indicators (i.e., metrics measured) selected for the study? What are the established requirements and selected criteria?
- Considering the requirements and criteria, which biodiversity components, sub-components, and indicators are typically prioritized and selected for the baseline assessment?
- What are the pressures (i.e., causal factors resulting from OWE that induce changes in the state of the environment) connected to each indicator used and related to essential stressor-receptor relationships?
- Did they consider a baseline assessment for ecosystem services related to biodiversity?
- Did they suggest climate change or cumulative effects when scoping the baseline assessment?
- What requirements were suggested to justify the study area coverage in the baseline assessment?
- Did they recommend measuring any additional environmental data that should be included in the biodiversity baseline assessment?

The reviewed guidelines were organized into four categories that represent the fundamental phases to follow for designing a baseline study aligned with an EBM perspective (adapted from Clark et al. 2020): (1) selecting biodiversity components; (2) assessing data needs and indicators for each impact; (3) defining the study area coverage; (4) considering cumulative effects, including climate change.

3. Synthesized guidelines for biodiversity baseline assessment

This section synthetically describes the content (i.e., guidelines) of the analyzed guidance documents. The present synthesis (including the figures) considered only those requirements, data needs, pressures, and indicators mentioned in the guidance documents. Thus, this section does not evaluate the guidance's content critically but systematizes and presents the major guidelines currently available in guidance documents related to biodiversity and OWE projects. A critical qualitative analysis discussing both the potentialities and limitations of the revised guidelines is presented in section 4.

3.1. Selecting biodiversity components

As it is not practical to assess all biodiversity components of a target area, the requirements for selecting the biodiversity priorities presented in the guidance documents are usually associated with defining components considered sensitive, rare, threatened, unique, and with recognized ecological and/or commercial importance (Walls et al., 2009; Klure et al., 2012; McCann, 2012; NYSERDA, 2015; Petruny-Parker et al., 2015; BOEM, 2019a; 2020a; 2020b; Fernandez et al., 2021; Stephenson, 2021; Zottoli et al., 2021; Kershaw et al., 2023; BOEM, 2023). In this regard, the biodiversity components selected as priorities could be an entire biological group at the broadest level (e.g., benthic community), a group within a more restrictive level (e.g., benthic crustaceans), or specific taxa of interest (e.g., lobster population) (Kershaw et al., 2023).

Priorities are considered region-dependent since different regions have their own set of unique habitats and communities, although some priorities could be similar for multiple areas (Klure et al., 2012; Stephenson, 2021; INSPIRE, 2023; Kershaw et al., 2023). Legislative differences between regions regarding important taxa for local biodiversity conservation can be used to select local priorities for the assessment (Klure et al., 2012; NYSERDA, 2015; Stephenson, 2021). Priorities are also considered project-dependent since each project's different technologies (e.g., fixed or floating structures, number of turbines) can provide different stressors and interactions with the local biodiversity receptors (Klure et al., 2012; INSPIRE, 2023). Such stressors and interactions can be raised by local stakeholders' perceptions, including local fishers, academics, and non-governmental organizations (Klure et al., 2012; NYSERDA, 2015; Petruny-Parker et al., 2015; Stephenson, 2021; Zottoli et al., 2021; INSPIRE, 2023). The guidance documents recommend a desktop survey using existing data to identify these priorities and later define data gaps for field surveys (Klure et al., 2012; NYSERDA, 2015).

Biodiversity components that present measurable metrics (e.g., specific behaviors, mean body size, abundance) that proxy for ecosystem-level changes are also suggested as priorities (Stephenson, 2021; Kershaw et al., 2023). It can include taxa or biological groups that provide recognized ecosystem services for the region, such as invertebrates or fish species considered fishery resources, benthic species that form essential habitats for coastal protection or biodiversity

hotspots (i.e., coral reefs), and top predators that can indicate broader environmental integrity (Stephenson, 2021). The status and trends of the chosen metrics regarding these components are assessed in the baseline phase and are later used as indicators of ecosystem-level impacts during the post-construction monitoring (Stephenson, 2021; Kershaw et al., 2023).

3.2. Assessing data needs and indicators for each impact

According to the guidance documents, the biodiversity components that were general priorities for the baseline data survey are birds, benthos, fish, marine mammals, sea turtles, bats, and plankton. Data needs regarding these seven components can be synthesized in six major sub-components (Fig. 1): (1) distribution and composition of the biological communities; (2) habitat condition and use by biodiversity; (3) movement behavioral patterns, including migratory movements; (4) trophic connections across biodiversity components; (5) status of key populations, mainly for fishery resources; (6) functional patterns and processes directly associated to the biodiversity components. Several indicators are suggested for each of these sub-components (Fig. 1), which should be measured to monitor later and identify the ecological effects of the significant impacts of the projects.

The mainly pressures mentioned by the documents are: (1) the "reef effect", attraction of species changing the community composition; (2) the direct disturbance on the benthic environment by the seafloor scouring; (3) the changes in the wind and water dynamic caused by the foundations presence and turbines operation; (4) the increased underwater noise during the pile driving/drilling, installation of structures and operation of turbines; (5) the "barrier effect", which can displace the fauna from the region or hamper the access to their foraging and breeding areas; (6) the electromagnetic field produced by the cable corridors associated with the wind project, which can promote disorientation in sensitive taxa; (7) the collision risk between the biodiversity and the project structures, especially for birds and bats; (8) the benthic enrichment promoted by the epifaunal community which will occupy the new hard structures and; (9) the colonization of invasive species due the new hard structures available as habitats. Some documents also mentioned the cumulative effects promoted by the synergistic and additive effects between these multiple pressures of the project. The connections between components, sub-components, indicators, and pressures are illustrated in Fig. 1 (for details, see supplementary material – Appendix B).

Some additional data were suggested to be obtained with the biodiversity assessment, aiming to clarify direct and indirect causal pressures of the wind project impacts, reducing uncertainties, and helping the interpretation of biodiversity changes (BOEM, 2019b; 2020a; 2020b; Stephenson, 2021; Kershaw et al., 2023). In this regard, we can synthesize such data in six additional components: (1) local aerodynamic patterns; (2) local hydrodynamic patterns; (3) underwater soundscape; (4) seafloor mapping; (5) local disturbances survey; and (6) behavioral sensitivity, assessed by experimental approaches such as electromagnetic sensitivity experiments, to establish baseline thresholds. The linkages between these additional components, their indicators, and connections with biodiversity components and pressures are illustrated in Fig. 2 (for details, see supplementary material – Appendix B).

3.3. Defining the study area coverage

The primary guideline to establish spatial boundaries for the baseline assessment is to consider the scale level of the project (local or regional), including cable routes and onshore structures (Klure et al., 2012; BOEM, 2019b; Kershaw et al., 2023), and also consider if the goal is an assessment for a single project or multiple projects (Kershaw et al., 2023). In this regard, a suitable buffer zone must be designed, considering a radius around the project that covers the entire area that potentially will be impacted (McCann, 2012; Klure et al., 2012; Gove et al., 2013; Stephenson, 2021; Willmott, 2022). In the North American documents analyzed, this buffer zone is named the Area of Potential Effects (APE), defined based on identifying reasonably foreseeable effects associated with the project structures and activities (Petruny-Parker et al., 2015; BOEM, 2019a; 2019b). Petruny-Parker et al. (2015) recommended that, when uncertainty is high, we must prioritize an overestimation of the APE over an underestimation. Similarly, NYSERDA (2015) recommended prioritizing a larger geographic scale than a single project scale, aiming for a regional baseline assessment. Another frequent recommendation is to expand the baseline study area beyond the project influence zone, aiming at establishing a Before-After-Control-Impact design (BACI), or a Before-after-gradient design (BAG) (Klure et al., 2012; McCann, 2012; Gove et al., 2013; Petruny-Parker et al., 2015; Stephenson, 2021; Zottoli et al., 2021; Willmott, 2022; BOEM, 2023; Kershaw et al., 2023; INSPIRE, 2023). In the case of a BACI design, the study area must include control areas as references, free of the project influence, but with similar features to the APE.

A second requirement for determining the study area coverage is considering the known distribution range of the selected biodiversity components (Stephenson, 2021; Willmott, 2022; INSPIRE, 2023; Kershaw et al., 2023). This issue is essential mainly for wide-ranging mobile megafauna that are transitory occupants of the project area (Stephenson, 2021; INSPIRE, 2023). Preliminary desktop surveys can assist in understanding their capacity to move and how far from the project area they can go (including onshore areas), aiming to establish boundaries for the assessment (Willmott, 2022). It is crucial to consider the stakeholders' opinions, such as recreational and commercial fishers, since they have local knowledge regarding important areas for fish species, for instance, and can support decisions concerning priority areas for the assessment (McCann, 2012; Stephenson, 2021; INSPIRE, 2023). Additionally, the study area must not necessarily be static and, indeed, could be dynamic and change during the baseline assessment development based on the information input (Willmott, 2022; INSPIRE, 2023).

3.4. Considering cumulative effects, including climate change

Cumulative effects are an essential concern to be considered for the baseline assessment. Among the documents here consulted, NYSERDA (2015) proposed the "Develop Approach for Estimating Cumulative Impacts", which detailed instructions that include literature synthesis, expert judgment, and quantitative analysis. Walls et al. (2009) suggested undertaking Cumulative Impact Assessments for birds in line with the "Guidance on Ornithological Cumulative Impact Assessment for Offshore Windfarm Developers", proposed by the Collaborative Offshore Wind Research into the Environment (COWRIE, King et al., 2009). McCann (2012) also developed a conceptual framework and approach for cumulative environmental impact evaluation, including quantitative data indices.

In general, a multi-year baseline data set is needed to identify the natural variation, climate change tendencies, and other threats to biodiversity, aiming to understand the future interactions of these factors with the specific project effects (Willmott, 2022; Kershaw et al., 2023). Collecting historical biodiversity information from local institutions could also help construct models regarding cumulative effects (Zottoli et al., 2021). In this survey, it is vital to consider the scale level of the entire extension of the ecosystems for the assessment, not only a project area independently, aiming to understand the cumulative effects between the new project, other offshore wind projects, and projects from other offshore industries (Petruny-Parker et al., 2015). This analysis must also include the cumulative effects of all project infrastructures, such as multiple wind turbines and cable routes (Kershaw et al., 2023).

Another critical strategy for the cumulative impacts assessment is data standardization and sharing among projects. It includes standardizing the sampling methods and indicators used across the sector, facilitating data sharing and aggregation for a regional assessment

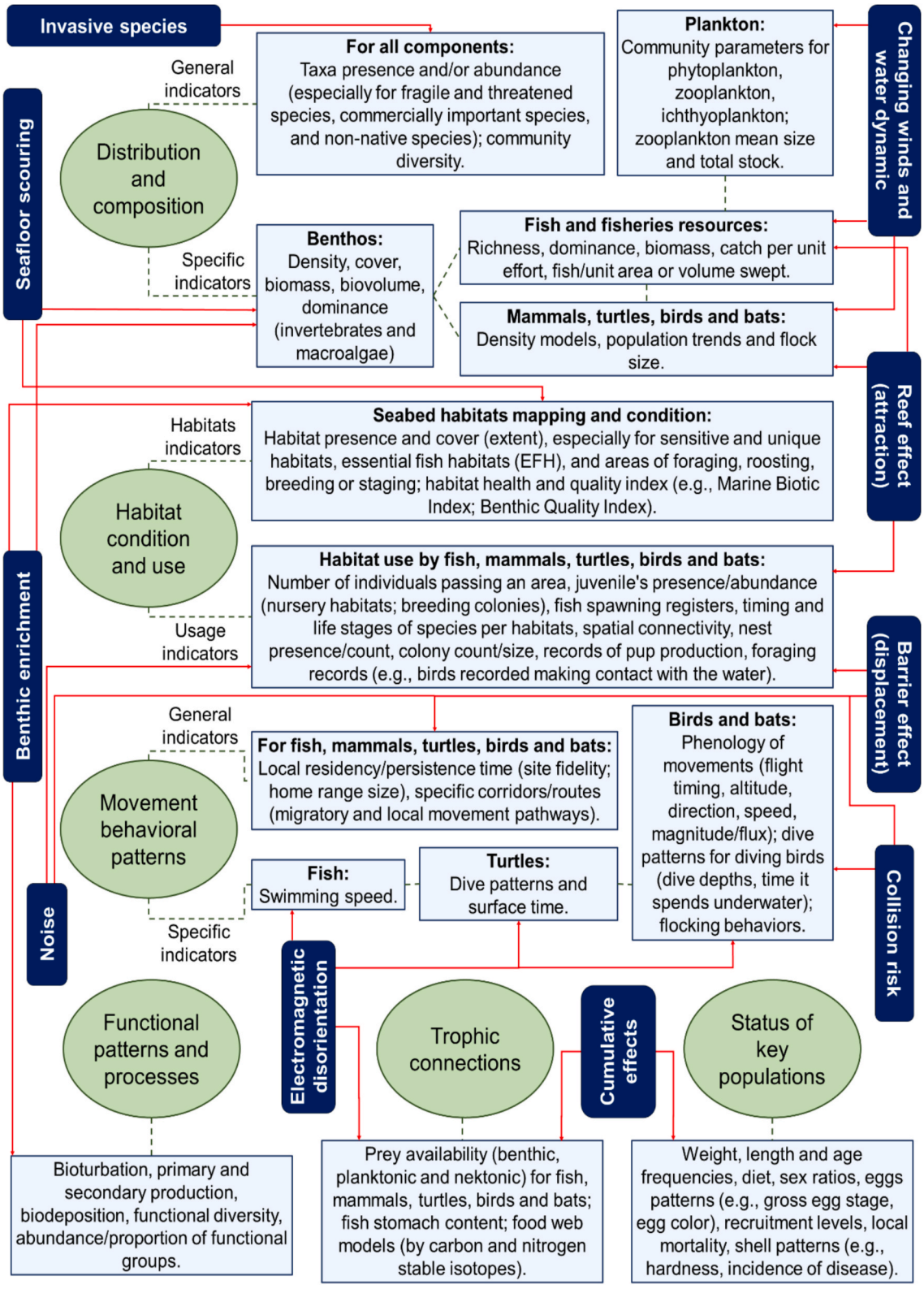

Fig. 1. Biodiversity data needs suggested for the baseline assessment during offshore wind projects (pre-construction phase) extracted from the revised documents. Green circles indicate the data requested (six sub-components). The dashed lines connect each circle to the light blue rectangles, highlighting their respective indicators regarding the different biodiversity components. The central pressures expected for offshore wind projects, mentioned in the revised documents, are represented by the dark blue rectangles. The solid red lines connect each pressure to the light blue rectangles, highlighting their principal related indicators regarding the different biodiversity components.

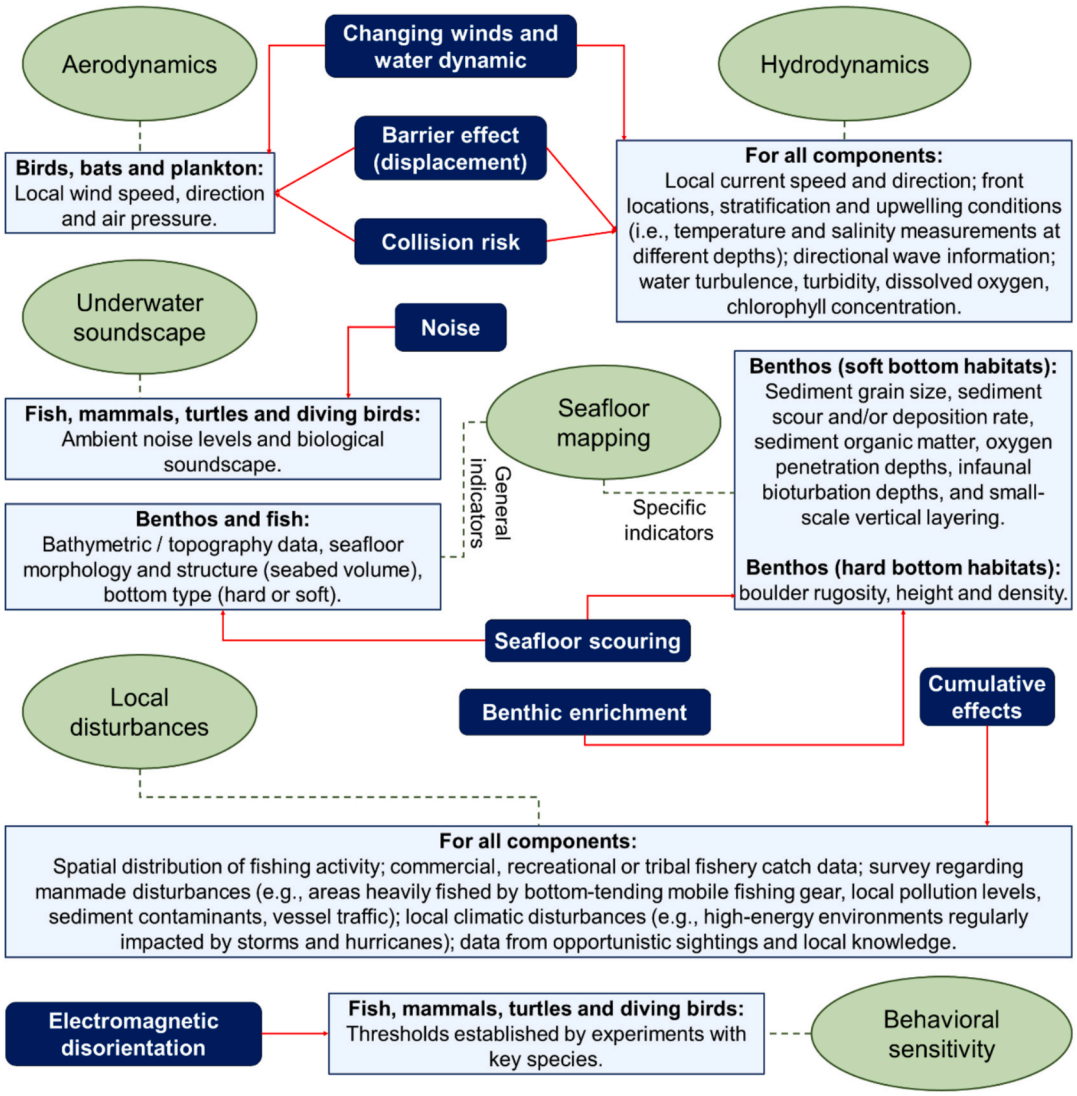

Fig. 2. Additional data needs suggested for the biodiversity baseline assessment during offshore wind projects (pre-construction phase). Circles indicate the data requested (six additional components), connected by the dashed lines to their respective indicators and the different biodiversity components for which indicators are essential (light blue rectangles). Each central pressure (dark blue rectangles), expected for the offshore wind project, is connected by the solid red lines to its related indicators.

(Stephenson, 2021; INSPIRE, 2023). Moreover, it is also essential to identify if the project area is currently affected by extreme climate events (e.g., storms and hurricanes) and characterize artificial disturbances typical for the action area (BOEM et al., 2019a). This survey of anthropogenic and climate disturbances can help the cumulative impact assessments and support the differentiation between the project-specific impacts and other pressures (Stephenson, 2021).

4. How far are we from an ecosystem-based assessment?

The synthesized guidelines presented in the above section showed requirements and practices that could contribute to a biodiversity baseline assessment, but also highlighted limitations to support an EBM perspective for EIAs in OWE projects. In this section, we will perform a critical qualitative analysis discussing both the potentialities and limitations of the guidelines from an EBM perspective, using the EBM principles and the related issues highlighted in Table 1.

4.1. Performing a retrospective-analytical baseline assessment in ecosystemic scales

Among the issues concerning how to scope a biodiversity baseline study, prioritizing biodiversity components that can be a proxy of ecosystem-level changes, such as top predators or structure-forming species, is a recommended practice for an EBM perspective (Crowder & Norse, 2008) since they can provide holistic indicators for impact assessment and monitoring. The premise that the components chosen are sensitive to the predicted project impacts is also fundamental for a focused and precise baseline assessment, which demands a previous place-based understanding of the expected stressors and potential receptors before selecting priority components (Coston-Guarini et al., 2017). Although these issues are addressed by the documents analyzed, the presented inventory of OWE pressures and their relationships with the respective receptors are still limited. The current scientific literature has already evidenced other pressures of OWE projects that were not highlighted by the revised guides. It includes the habitat contamination due to the release of heavy metals from the OWE structures (Wang et al., 2023) and the local changes in nutrient fluxes due to the biofouling community of the turbines (Coolen et al., 2024), also associated to

Table 1
Key principles of Ecosystem-Based Management (EBM). The principles presented were those highlighted by Long et al. (2015) as the most used in the literature (the first 15 principles of the table) and those categorized by the same authors as "potentially emergent key principles" (the last three principles of the table). The principles are also ordered by importance based on the number of mentions in the literature (Long et al., 2015). A brief description of each principle is presented, adapted from Arkema et al. (2006), Boesch (2006), Crowder & Norse (2008), and McLeod & Leslie (2009). The third column shows our suggested issues, related to each EBM principle, which should be considered for performing an ecosystem-based assessment in biodiversity baseline studies associated with offshore wind projects.

EBM principles	Description	Related issues for the biodiversity baseline assessment
1. Consider ecosystem connections	Acknowledge the linkages between ecosystem components, including biotic/abiotic interactions, and socioecological connections.	Baseline data must focus on understanding the ecosystem nexus, including biodiversity-environment connections, trophic linkages, the cascade of predicted impacts, and consequences for ecosystem services.
2. Adaptive management	Continue to improve actions and decisions through systematic evaluation.	Baseline assessment must be flexible and constantly adapted based on the input of new information from the data sampled.
3. Use appropriate spatial & temporal scales	Recognize that ecosystem processes operate over a wide range of spatial and temporal scales.	Baseline assessment must be planned considering spatial and time coverages encompassing the scales of the impacts (wind project scale) and the scales of the biodiversity processes affected (ecological scale).
4. Use of scientific knowledge	Incorporate management decisions based on tested hypotheses with appropriate scientific rigor.	Data sampling, analysis, and assessment conclusions must be based on recognized scientific methods.
5. Stakeholder involvement	Engage interested parties in the management planning.	Local stakeholders must be part of the assessment planning and development, contributing to select data priorities based on traditional, local, and scientific knowledge.
6. Integrated management	Promotes co-management and communication with shared responsibility between multiple stakeholders, including different sectors and administrative levels.	The assessment scoping and development must involve workshops and meetings with stakeholders to share knowledge, responsibilities, and promote social learning.
7. Sustainability	The maintenance of key ecosystem aspects, including ecological processes and services, aiming not compromising future needs.	Baseline indicators must be established with defined thresholds to identify acceptable and unacceptable changes related to the wind project.
8. Account for the dynamic nature of ecosystems	Recognize that ecosystems are naturally dynamic and variable.	Baseline assessment must capture the reference condition of the biodiversity and ecological processes, considering their natural variability, but also their current and past interactions with other pressures, such as climate change.
9. Ecological integrity & biodiversity	The maintenance of ecosystem functioning and biodiversity health.	The assessment must understand the baseline conditions of the ecological functions (supporting services) and must define indicators of ecosystem integrity and health based on biodiversity processes and ecological linkages.
10. Recognize coupled social-ecological systems	Recognize that humans are elements in an ecosystem and use natural resources.	The assessment must understand the connections between biodiversity and society, which includes assessing the baseline conditions of ecosystem services, natural resource uses, and anthropogenic disturbances in a target area.
11. Decisions reflect societal choice	Engage stakeholders to find common solutions given the possibilities.	Baseline assessment must produce ecological models and predictions in different scenarios to communicate the possibilities for decision-making.
12. Distinct boundaries	Recognize that management plans must be spatially defined.	The scoping of the assessment must identify the scale of the ecological processes, the extent of the wind project impacts, and the jurisdictional or geographic barriers to define appropriate spatial boundaries.
13. Interdisciplinarity	Base the decisions on knowledge from several disciplines.	A transdisciplinary team must perform the scoping and development of the baseline assessment.
14. Appropriate monitoring	Track changes in biotic, abiotic, and human ecosystem components.	Baseline ecosystem-level indicators must be properly defined to capture specific changes associated with the wind project during the post-construction monitoring.
15. Acknowledge uncertainty	Characterize and effectively communicate uncertainty.	The assessment must include uncertainty metrics for the baseline indicators proposed.
16. Consider cumulative impacts	Recognize the interactions between the drivers of change.	The assessment must include a survey of existing disturbances in the target area, including climate changes, to understand possible additive and synergistic effects associated with a new wind project, using ecosystem modeling approaches to clarify the interactions.
17. Apply the Precautionary Approach	Manages conservatively when threats to the ecosystem are uncertain.	The metrics and indicators of uncertainty defined in the baseline assessment must be proper and robust to inform precautionary decisions.
18. Explicitly acknowledge trade-offs	Evaluate trade-offs between different ecosystem services and user groups.	Baseline assessment must understand the ecosystem services connected with biodiversity in a target area, creating bases to communicate possible positive and negative effects associated with the new wind project for the user groups associated with each service.

carbon and mineral particle flux to the bottom, with potential accumulation and ecosystem-level consequences (De Borger et al., 2021; Ivanov et al., 2021). The guidelines also associated noise and electromagnetic field impacts mostly with vertebrates (fish, mammals, and turtles), although there are studies evidencing that these pressures also affect invertebrates and their ecosystem functions (e.g., Solan et al., 2016; Scott et al., 2018; Taormina et al., 2020; Scott et al., 2021; Gigot et al., 2023; Cones et al., 2024). From an EBM perspective, it is relevant to consider the potential impacts of OWE projects and their respective receptors with updated information from the scientific literature.

The analyzed documents also addressed appropriate scales and boundaries for the baseline assessment, which are essential EBM principles (Long et al., 2015; Table 1). Considering the project scale level (e.g., stressors extent) and the ecological scale level of biodiversity processes can be a good way to fulfill these principles. In addition to the displacement capacity of the chosen components, mentioned by the documents, the ecological scale should also consider processes that would react to changes in oceanographic settings, such as primary production (Daewel et al., 2022). This process can be affected on large scales, reaching areas far from the projects and triggering cascading effects through the trophic web (Wang et al., 2019; Daewel et al., 2022). For regions with data deficiency that could hamper understanding these ecological boundaries, a regional assessment including their ecosystems with their entire extensions would avoid excluding relevant zones. Characterizing and effectively communicating these uncertainties regarding the ecological boundaries is a crucial EBM principle (Long et al., 2015; Table 1), which can improve transparency and adaptability of the process. The proposal of a flexible assessment, also mentioned by the documents analyzed, can help to address uncertainties and is aligned with the Adaptive Management principle (Long et al., 2015; Table 1), since the survey strategy and scales could be constantly improved based on the information obtained throughout the process. For instance,

defining scales to understand the distribution range of long-distance migratory species is challenging. Still, if necessary, it can be overcome with an adaptive perspective that improves the survey strategy, including amplifying interregional (and international) scientific partnerships for data acquisition during the assessment. The stakeholders' involvement in selecting priority areas, scales, and components also aligns with EBM principles (Long et al., 2015; Table 1) and could be a central strategy in data scarcity. Integrating local, expert, and traditional knowledge on regional scales is a strong tool to support decisions without rich regional datasets (Che & Hickey, 2021; Willsteed et al., 2023).

Considering cumulative impacts is also an EBM principle (Long et al., 2015) and has been rising in importance for the offshore wind industry (e.g., Willsteed et al., 2023; Declerck et al., 2023; Kuempel et al., 2025). Prior considerations about cumulative effects in the baseline assessment are fundamental to understanding tendencies based on retrospective analysis of the interactions between local stressors and receptors (Clark et al., 2020), which could inform predictive models on different scenarios (e.g., Constable et al., 2016; Coston-Guarini et al., 2017). Data standardization and making them publicly available were frequently mentioned in the analyzed documents and are great strategies to support cumulative impact assessments, especially when multiple stakeholders are involved (Che & Hickey, 2021; Declerck et al., 2023). Integrating the baseline assessments for OWE projects in the regional Marine Spatial Planning (MSP) context also has great potential to optimize data collection and cumulative impacts evaluation. MSP usually fosters the stakeholders' integration and needs a desktop survey regarding the multiple uses, vulnerabilities, and possible conflicts/synergisms in a target region, information that is also useful for cumulative impacts assessments (e.g., Tsai et al., 2022; Declerck et al., 2023).

Nevertheless, although the guidance documents analyzed here proposed specific cumulative impact approaches and frequently encouraged a baseline assessment for local stressors, climate change tendencies and interactions with the project impacts were rarely explored. Recent scientific contributions have been developing ecosystem-based frameworks to integrate the climatic component in the impact assessment for renewable energy projects, including defining climate change indicators (Bravo et al., 2023; Declerck et al., 2023). Therefore, these frameworks can also contribute to the future development of specific cumulative impact approaches.

A retrospective baseline assessment can also assist in dealing with the shifting baseline syndrome (SBS), an overall problem of the impact assessment for several sectors (Soga & Gaston, 2018; Willsteed et al., 2023). SBS consists of accepting the current situation of a specific component as its reference condition, without considering that the current situation could be an already changed condition due to historical and cumulative impacts of different human activities (Soga & Gaston, 2018). This problem usually leads decision-makers to overestimate impact thresholds and underestimate conservation goals (Mihoub et al., 2017; Robert, 2024). In this regard, the concept of the Cross-scale Ecosystem-Based Assessment (DIET, Gonçalves et al., 2020) and the Source-to-sea Landscape Approach (Michels-Brito et al., 2024) are interesting tools since they incorporate the interactions between onshore and offshore pressures in a target area, contributing to a holistic cumulative impact assessment. Therefore, aligned with EBM principles (Long et al., 2015), the baseline assessment must consider an appropriate temporal scale to understand the natural dynamic of the components and also the contribution of other pressures to this dynamic, including climate change and local stressors (Elliott et al., 2015; Mihoub et al., 2017; Willsteed et al., 2023). For example, a baseline assessment with at least two years of temporal scale is usually requested for offshore projects in Oceania countries (Clark et al., 2020) and was also suggested by most of the guidance documents consulted here. However, this period is considered insufficient for some components, such as fishery resources (Methratta et al., 2024). In South American countries, as in Brazil, several projects do not consider biodiversity seasonality for EIA baselines, and pre-construction fieldwork sampling usually lasts for a few days (see Dias et al., 2022 for an example with terrestrial mammals). Indeed, there is no consensus concerning what period is enough (Willsteed et al., 2023), since this time would depend on the variable scales of the different processes under analysis. This fact reinforces the need for a place-based, exhaustive desktop survey to determine what is known and the data gaps before planning scales for the field survey.

4.2. *Incorporating ecosystem services and ecological nexus in a focused baseline assessment*

Concerning the data needs and indicators of our synthesis, assessing biodiversity distribution and composition is a classical data need in any impact assessment (Underwood et al., 2018). This sub-component has basal importance in understanding what taxa are in the study area, how many of them are threatened, fragile, or with ecological/commercial significance (i.e., target species), and their spatial distribution (e.g., Lemos et al., 2023; Teschke et al., 2023; Van Parijs et al., 2023). Despite that, assessing biodiversity composition and distribution of several components for a target area is challenging and involves a large amount of data. From an EBM perspective, the survey efforts must be focused on avoiding a scenario of "data-rich, information-poor" (DRIP), a situation in which much data is collected but such data is not appropriate to identify and monitor ecosystem impacts related to the wind project (Wilding et al., 2017) (Fig. 3). Several documents analyzed here (BOEM, 2019b; 2020a; 2020b; Stephenson, 2021; Kershaw et al., 2023) suggested a paired assessment, which means integrating data on biodiversity composition and distribution with additional data regarding the physical environment and local disturbances in a paired sampling design. With well-planned goals, this paired assessment could be a promising step in converting a baseline descriptive list of species into an analytical baseline exploring ecosystem interactions between environment, biodiversity, and disturbances, highlighting the drivers and processes behind biodiversity conditions (Mihoub et al., 2017; Wilding et al., 2017; Clark et al., 2020; Kruger & Pohlo, 2022; Chapman et al., 2024). Past experiences can greatly support scoping this analytical baseline assessment, which includes considering the existing knowledge of cause-effect relationships linking the physical and biotic dimensions (e.g., Dannheim et al., 2020) and defining the most meaningful metrics for detecting accurate responses, based on existing long-term monitoring programs of the OWE effects (e.g., Coolen et al., 2022; Jammar et al., 2025). An excellent approximation between the baseline assessment and EBM could be reached in this paired approach, including the principles "consider ecosystem connections" and "account for the dynamic nature of ecosystems" (Long et al., 2015). This perspective must be central for an ecosystem-based assessment, prioritizing a holistic and deductive focus on environmental connections and processes rather than a reductionist, inductive, centered-species focus.

From an EBM perspective, the major limitation in synthesizing existing guidance was the lack of incorporating specific approaches for evaluating ecosystem services associated with ecological functions in the baseline assessment. Fishery resources are primarily addressed since, as a provisioning service, the impacts on fishery resources are easily related to monetary values (Costanza et al., 2014) and economic and social losses. However, biodiversity is connected to other ecosystem services beyond the fishery provision, such as regulating and cultural services (Le et al., 2017). For instance, coral reefs and rhodolith beds are associated with cultural services such as underwater seascapes with attractive aesthetics for recreational diving, which has an economic value in itself and can also be a driver of the development of a more encompassing touristic sector (Niz et al., 2023). Understanding how to include this and other ecosystem services and material and immaterial benefits of nature to people associated with biodiversity and ecosystem functions in the impact assessment is a central challenge to support EBM (Guilhon et al., 2021). Developing an ecosystem services approach for the impact assessment is a discussion present in the deep-sea mining

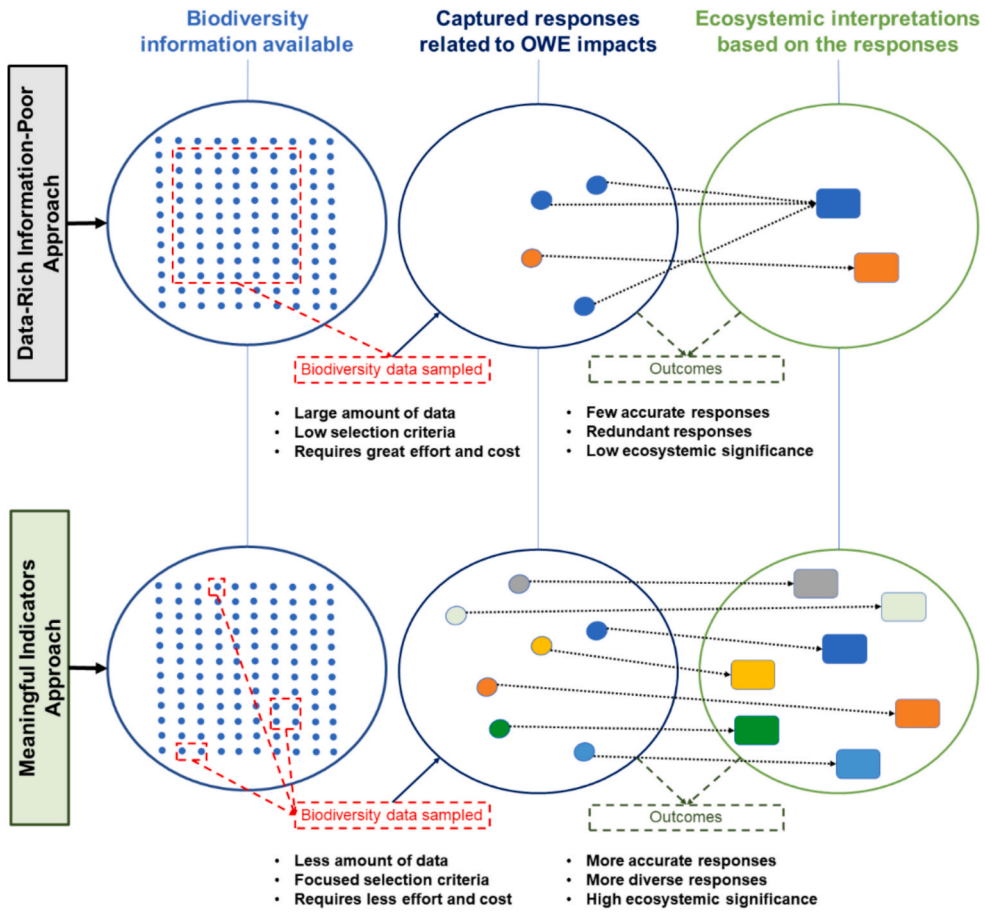

Fig. 3. Schematic diagram illustrating the main differences between a baseline assessment in a "data-rich, information-poor" approach (DRIP – Wilding et al., 2017) and a approach using a paired assessment with meaningful indicators based on the ecosystem causality nexus, in the context of offshore wind energy (OWE) development.

sector (Le et al., 2017; Clark et al., 2020; Guilhon et al., 2021; Hyman et al., 2022), and has been rising in the offshore wind energy sector (Causon & Gill, 2018; Baulaz et al., 2023; Bravo et al., 2023; Watson et al., 2024). Besides fishery resources, some analyzed documents also addressed ecosystem functions, including biodeposition, bioturbation, and primary and secondary production. The assessment of ecosystem functions is a significant advance toward an EBM perspective, but it seems to be still restricted to benthos, plankton, and fish (Fig. 1). Therefore, this functional assessment must be amplified to address connections between all biodiversity components and the abiotic environment, as understanding ecosystem function is usually highlighted as one of the crucial gaps in baseline assessments (Clark et al., 2020; Kruger & Pohlo, 2022; Bravo et al., 2023).

Including trophic connections in the baseline assessment is fundamental to understanding the components' interactions within the ecosystem and their natural dynamic (Crowder & Norse, 2008; Constable et al., 2016). Habitat condition and use, as well as movement behavioral patterns, are also interesting sub-components that contribute to an analytical baseline assessment since these patterns are directly related to critical ecological processes such as feeding, reproduction, and migration (Crowder & Norse, 2008; Bravo et al., 2023). Our synthesis showed that numerous indicators could be associated with each sub-component mentioned (Figs. 1 and 2). Nevertheless, the measurement of all these metrics and variables without key criteria and goals/direction to interpret data in the EIA context could lead the baseline assessment again to the DRIP situation (Wilding et al., 2017), pointing out a need to select priority processes and variables as meaningful indicators (Constable et al., 2016; Bravo et al., 2023; Methratta et al., 2024) (Fig. 3). In this regard, a clear understanding of the causal chain that addresses the nexus of the project impacts with the ecosystem attributes and ecological linkages is needed to clarify the most appropriate indicators. With this goal in mind, the incorporation of ecosystem services in the baseline assessment, exploring their connection with biodiversity and the physical environment, is a central and indispensable step (Wilding et al., 2017; Causon & Gill, 2018; Clark et al., 2020; Guilhon et al., 2021; Baulaz et al., 2023; Bravo et al., 2023). When the baseline assessment includes ecosystem services, the metrics of change selected as indicators can signal how specific project impacts will affect the ecosystem services provision (see recent examples in Baulaz et al., 2023; Piet et al., 2024; Olano-Arbulu et al., 2025).

4.3. Promoting nature-positive outcomes based on conceptual ecosystem models

Understanding the baseline conditions of ecosystem services and associated processes can support approaches to amplifying nature-positive outcomes related to OWE development. Positive outcomes are understood here as those changes associated with OWE projects that can promote biodiversity net gains, improve environmental resilience, enhance ecological functioning, and/or ecosystem services (Pardo et al., 2025). In the context of improving ecosystem services provision, such approaches can include supporting multi-use coexistence strategies by identifying potential synergies between the OWE positive impacts when sharing space with other activities, such as food production and biodiversity conservation, aiming for mutual benefits (Turschwell et al., 2022; Pardo et al., 2025). Undoubtedly, the coexistence of multiple

activities still generates negative impacts, which demand some precaution. For instance, OWE areas are usually closed to fishing activities, creating a refuge for species vulnerable to bottom trawling (Reubens et al., 2014; Coates et al., 2016). This effect synergizes significantly with the goals of marine protected areas (Pardo et al., 2025). Thus, the coexistence strategy for sharing space between these two uses can improve biodiversity conservation and fishery stocks. If such a closed area allows some level of sustainable fishing within its borders, the positive outcomes could expand to improving food provision and nutrition for coastal communities (Viana et al., 2024), potentially reducing conflicts between OWE projects and local fishers. Nevertheless, OWE remains an anthropogenic activity with multiple negative effects that will impact this marine protected area, demanding a complete understanding of these potential cascade effects to evaluate if such coexistence is truly positive for local biodiversity and ecosystem functioning.

As another example, OWE farms can change the local hydrodynamic favoring nutrient fluxes and improving biomass production of suspension feeders (Wang et al., 2019; Borger et al., 2025), a change that creates a favorable environment for offshore bivalve aquaculture. This activity can coexist with OWE to improve food production and reduce the spatial footprint (by sharing infrastructures) regarding the multiple uses of the continental shelf (Griffin et al., 2015). OWE farms can also promote a productive environment for seaweed cultivation, which, besides improving food production, can facilitate an increased capture of CO_2, enhancing a regulatory service against climate change (Moreira & Pires, 2016). Besides improving ecosystem services supply, multi-use strategies that allow OWE to coexist with other impactful projects are useful to reduce the ecological footprint by decreasing the cumulative impact risk (Tamis et al., 2024). For example, the offshore renewables (including wind and solar energy) can share the power transmission infrastructure (i.e., cables), which can significantly reduce the potential cumulative impacts on seafloor, compared to the additive effects that these structures can cause when multiple projects are operating isolated (Tamis et al., 2024). However, offshore renewables or aquaculture are anthropogenic activities that still generate negative changes compared to the baseline condition, despite the reduction in the spatial and ecological footprint associated with the coexistence. Even though some specific ecosystem services are enhanced by these multi-use strategies (e.g., food production, climate regulation), the coexistence of such impactful activities may not necessarily provide positive outcomes for improving environmental resilience, ecological functioning, biodiversity net gains, and other associated ecosystem services that the environment would provide without the projects. Therefore, numerous coexisting projects must also share the impact assessment process, including the baseline phase, to properly assess risks, legal feasibility, responsibilities, and potential indicators to evaluate if this synergism truly generates net environmental benefits (Tamis et al., 2024).

Fish aggregation related to the OWE reef effect is also usually associated with positive outcomes. This process dependent on the structural complexity of OWE installations (Bicknell et al., 2025), and can be strengthened by nature-inclusive designs, benefiting resilience, functional diversity, and ecosystem services provision (Kingma et al., 2024; Pardo et al., 2025). However, a point of attention regarding the reef effect is that attraction does not always create a positive outcome for fishery production. Based on the "attraction-production hypothesis" developed for artificial reefs, habitat creation tends to increase food availability for fishery resources, consequently increasing fish production, as was already noted for different species that usually aggregate in OWE areas (Reubens et al., 2014; Mavraki et al., 2021). In other cases, artificial reefs can function as an "attraction ecological trap-production", creating a low-quality habitat compared to natural reefs, which can result in no production or even negatively impact fish stocks (Reubens et al., 2014). The reef effect is also species-dependent, and some organisms can be displaced from the OWE area after construction, especially those adapted to live in soft-bottom substrates, habitats that tend to be partially replaced by the introduced hard-bottom structures (e.g., Van Hal et al., 2017).

All the above explored examples highlight that determining positive and negative outcomes is not trivial, reinforcing the need for a participatory approach that considers societal choices in trade-off analysis and for a comprehensive understanding of the causal chain of impacts. These issues are the basis to assess why a change could be considered positive (or negative), for which components (entire biodiversity or specific groups), from what perspective (ecological, economic or social benefits/losses), and the extent to which supposed positive outcomes are sustained over time. The construction of a conceptual ecosystem model is the first step to identifying this causal chain, clarifying the nexus between project activities, expected impacts, environmental and biodiversity receptors, ecological connections, ecosystem services, and the appropriate indicators of change (Causon & Gill, 2018; Clark et al., 2020; Baulaz et al., 2023; Bravo et al., 2023). Once the nexus is clear, biodiversity indicators such as abundance, density, or biomass no longer represent isolated species-centered information. Instead, they will inform changes in ecosystem processes, function, and services, ultimately related to human well-being (Baulaz et al., 2023; Bravo et al., 2023). Establishing integrated ecosystem-level indicators, considering the combinations of metrics from different biodiversity components (Borja et al., 2016), is also facilitated when the ecosystem nexus is clear. Naturally, developing this robust strategy requires proper financial support and professional dedication from scientists and governments, which also demands a political interest in an efficient, sustainable pathway, exposing significant challenges for practical implementation.

Despite that, the use of ecosystem modeling to understand the ecological nexus and the cascade chain for renewable energy projects has been rising with practical examples to be applied worldwide (e.g., Heath et al., 2020; Trifonova et al., 2021; Baulaz et al., 2023; Trifonova & Scott, 2023). Additionally, several existing approaches already use an EBM perspective aiming for a holistic and cost-effective understanding of human effects (from several industrial sectors) on marine ecosystems, especially in Europe. These approaches are explored in Borja et al. (2016) and are strong practical examples to base other approaches

Table 2
Synthesis of the major potentialities and limitations found in the guidelines (extracted from the revised guidance documents) to perform biodiversity baseline assessment for offshore wind projects in alignment with Ecosystem-based Management (EBM) principles.

Potentialities to incorporate EBM	Limitations to incorporating EBM
Proposal to:	**Lack of:**
• Involve stakeholders in selecting priority areas and biodiversity components. • Perform a paired assessment integrating data on biodiversity with additional data regarding the physical environment and local disturbances. • Assess the ecological functions connected to benthos, fish, and plankton. • Consider the wind project scale in integration with the biodiversity-ecological scale to define the study area coverage and spatial boundaries. • Perform specific cumulative impact approaches and baseline assessments for local stressors. • Foster data standardization and sharing among different projects to support integrated cumulative impact assessments. • Use indicators sensitive to the predicted project impacts, including ecosystem-level indicators associated with the biodiversity components.	• Incorporating specific approaches for evaluating ecosystem services associated with biodiversity. • A formal proposal for constructing a conceptual ecosystem model to identify the causal chain and ecological nexus as the first step. • Incorporating ecological functions associated with marine mammals, turtles, birds, and bats. • Understanding of the ecological causal nexus to define the scale of the biodiversity processes affected before establishing spatial boundaries. • Incorporating climate change tendencies on cumulative impact approaches. • A formal proposal for a retrospective baseline assessment, with proper temporal scales, to deal with the "shifting baseline syndrome". • A focused selection of indicators, based on the ecological causal nexus, to avoid the situation of "data-rich, information-poor".

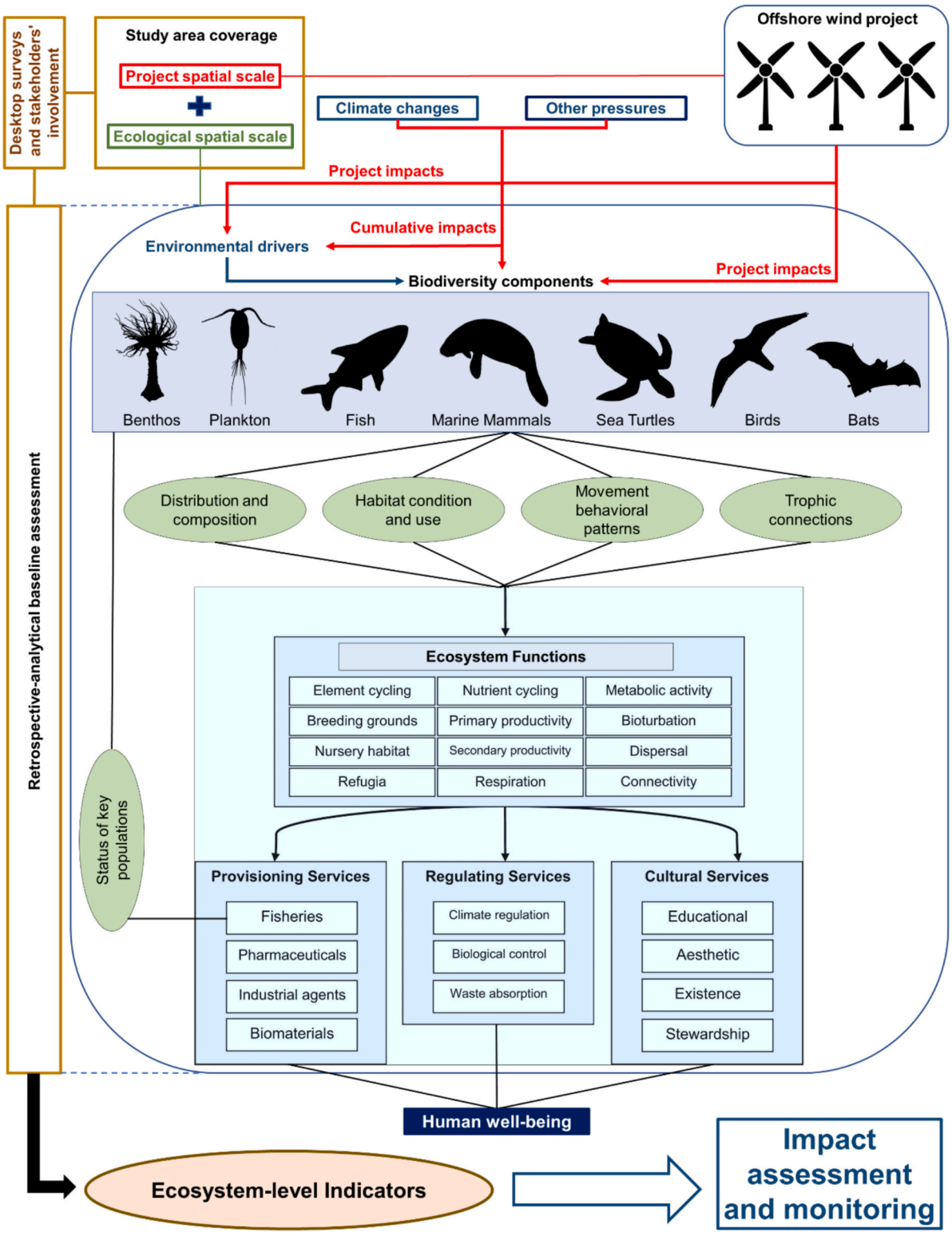

Fig. 4. Summarized outputs concerning the synthesized recommendations for biodiversity baseline assessments, provided by our guidelines survey, in integration with the insights from the literature of Ecosystem-Based Management. The illustration includes the significant elements to be considered for a retrospective-analytical baseline assessment, including a desktop survey, the stakeholders' involvement, and the determination of study area coverage to establish ecosystem-level indicators for impact assessment and monitoring. Arrows indicate the direction of the impacts, including the direct, indirect, and cumulative impacts on biodiversity components, sub-components, and ecosystem services. The rectangles with the primary ecosystem functions and services were extracted and adapted from Le et al. (2017).

worldwide. They include the Ecosystem Health Assessment Tool (applied for the Marine Strategy Framework Directive in the Bay of Biscay), the Marine Biodiversity Assessment Tool, and the Nested Environmental Status Assessment Tool. In areas where the wind energy industry is beginning, such as South America, the previous construction of these conceptual models and holistic approaches for each region is an excellent opportunity to start an ecosystem-based impact assessment.

5. Concluding remarks: Toward regional ecosystem-based assessments

The studied guides presented essential issues that must be considered for new offshore wind projects, but lack important principles of Ecosystem-Based Management. A summary of the main potentialities and limitations discussed here is presented in Table 2. It is worth noting that the guides evaluated here are predominantly from North America. Thus, our summary of potentialities and limitations more accurately represents the projects under development in this region, but also can help design improved protocols, especially for South America, which still lacks particular OWE guidelines. In contrast, the baseline requirements enhanced by the insights from the EBM literature discussed, summarized in Fig. 4, can be a strong approach to support EIA and guide future biodiversity baseline studies in multiple regional contexts worldwide. However, it is also important to mention that we did not include scientific articles, technical reports from case studies, or guidance documents not related to offshore wind energy in our guidelines survey. Thus, to expand our results, we recommend that future research explore guidelines and tools to foster the relationship between impact assessment and EBM in a more general context, including other industrial sectors beyond wind energy. Such studies can adopt standardized methods for the bibliography search to also consider the state-of-the-art knowledge regarding the guidelines present in the scientific literature, which was not the focus of the present study. As another future step, we suggest that studies focus on providing regional precise/specific recommendations based on the causal chain and ecosystem functioning models, which are being produced for use with offshore renewables (e.g., Heath et al., 2020; Trifonova et al., 2021; Trifonova & Scott, 2023) and can be adapted to different realities where OWE projects will be developed.

In this context, the Global South has great potential for developing offshore wind energy, where several projects are planned to be constructed in the next few years. For instance, in Brazil, a total of 103 open licensing processes for offshore wind energy were already planned and were under government analysis as of December 2024. However, no one project has begun construction yet (IBAMA, 2025). These emerging markets of the Global South also harbor large macrometropolitan areas, with large-scale ports, offshore oil and gas exploration, and several marine protected areas (MPAs) with unique habitats, biodiversity hotspots, and fundamental ecosystem services (e.g., Gonçalves et al., 2020; Niz et al., 2023; Laurino et al., 2024; Lino et al., 2024). These features signal the high complexity of understanding reference conditions for the biodiversity in these developing countries (especially in data-deficient conditions), highlighting an urgent need to establish robust regional-based protocols for pre-construction baseline assessments under the EBM principles discussed here. EIA development is currently a costly process that demands extensive efforts, but the cost-effectiveness of EIA baselines is often questioned. Our proposal for incorporating EBM principles in EIA does not aim to increase costs and unnecessary complexity, but, on the contrary, it seeks to optimize the current efforts for a more focused and efficient baseline assessment. It includes increasing the efforts in the rational use of previous data and stakeholders' knowledge to concentrate field sampling efforts on indicators with holistic meaning for the EIA process (reducing efforts and costs on sampling non-informative data). Based on that, incorporating an EBM perspective, such as an ecosystem services approach, instead of increasing complexity and costs, can improve and optimize the EIA process. The practical viability of this proposal increases in countries that are currently developing their own Marine Spatial Plans (MSP), including regions with OWE interest. The unification of the efforts regarding the MSP and the incorporation of EBM in EIA is a key opportunity to optimize costs and professional dedication for an efficient baseline assessment.

In conclusion, we suggest the following key recommendations to be applied to baseline studies, aiming to perform EIA processes under the EBM principles:

(1) First, design a conceptual regional-based ecosystem model to clarify the linkages between predicted wind projects, biodiversity and environmental connections, ecosystem services, and indicators of ecosystem-level changes;
(2) Based on the ecosystem model, conduct a regional baseline study that combines desktop research and stakeholder engagement to define the priority biodiversity components, sub-components, and data gaps for impact assessment and monitoring;
(3) Incorporate climate change effects and other pressures into a retrospective baseline study to better understand the ecosystem dynamics and support cumulative impacts predictions;
(4) Prioritize integrative-paired assessments considering the cause-effect relationships among biodiversity components, the physical environment, and human disturbances, aiming to understand baseline conditions of ecological processes, ecosystem connection, key drivers, and potential direct and indirect impacts;
(5) Include targeted approaches for assessing ecosystem services and functions as a part of the biodiversity baseline assessment.

These recommendations are the primary actions to establish a robust baseline assessment for offshore wind projects. Thus, they constitute the "step zero" of an ecologically responsible energy transition and expanding ocean sustainability strategies worldwide.

CRediT authorship contribution statement

Ivan Rodrigo Abrão Laurino: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luciana Yokoyama Xavier:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Allan Yu Iwama:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Monique Fogaça Fernandes:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Lucas Bernardinelli de Souza:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Marcia Regina Denadai:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration. **Luis Enrique Sánchez:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Alexander Turra:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, 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.jnc.2025.126983.

Data availability

Data will be made available on request.

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