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A flexible framework for species-based regional cumulative effects assessments to support offshore wind energy planning and management

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ABSTRACT

Offshore wind energy development (OWED) is pivotal for renewable energy transition and climate resiliency. However, OWED activities may negatively affect wildlife, contributing to cumulative effects (CE) from human activities and natural processes. Cumulative effects assessments (CEAs) are vital for informed planning and management of OWED activities during regional assessment, site selection, and site evaluation phases. To reduce impacts on wildlife, OWEDs should be sited in areas that avoid or minimize CE. We present a flexible, species-based framework to assess CE from OWED activities and other pressures, supporting decision-making in early planning phases. The framework uses a species-based approach, applicable to various wildlife receptors (i.e., species or populations), and adapts to available information on ecology, socioeconomics, and pressures. The analytical strategy uses a CE metric to indicate the presence or magnitude of effects from all pressures on receptors. Spatially explicit optimization methods identify OWED site configurations that minimize a CE metric. The framework accommodates alternative pressure scenarios that include foreseeable future human activities and natural processes and can explore the sensitivity of the results to uncertain parameters. Given sufficient spatial information on receptor density, pressure magnitude, and cause-effect pathways, the spatial optimization algorithm can find solutions that minimize species- or population-level impacts from CE. If this ideal standard cannot be achieved due to information gaps, alternative metrics may be used to inform the immediate decision-making process. This framework offers a practical approach for balancing renewable energy goals with wildlife conservation, even when information is incomplete.

1. Background

The pace at which offshore wind energy developments (OWEDs) are being built is increasing rapidly, fueled by increasing energy demands and recognition that transitioning to clean, renewable energy is critical to meeting climate targets (Bilgili and Alphan, 2022). However, OWED activities also pose risks for wildlife, including birds and bats (Williams et al., 2024). Mitigation of these impacts follows a near-universal hierarchy for the priority in which mitigation measures are to be considered and applied: avoidance, minimization, restoration, and compensation (Council on Environmental Quality, 2020). Avoidance, achieved through careful siting of OWEDs away from high-risk areas, remains the best available option for mitigating impacts on wildlife (Gulka et al., 2024).

Decisions regarding the future of the OWED industry will differentially impact people, wildlife populations, and ecosystems. The effects of OWED on wildlife should be considered in the context of other anthropogenic and environmental pressures. We define “cumulative effects” as the combined effects of human activities and natural processes on wildlife across space and time (i.e., past, present, and reasonably foreseeable future)(Canadian Council of Ministers of the Environment [CCME], 2014). Cumulative effects may be individually minor, but collectively significant (Clarke Murray et al., 2020; Goodale and Milman, 2016). “Natural processes” are phenomena inherent to the ecosystem, such as predator-prey dynamics, seasonal warming and cooling trends, and interannual or interdecadal met-ocean cycles that

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may have rippling effects throughout ecosystems, such as the North Atlantic Oscillation, El Niño Southern Oscillation, and Arctic Oscillation. The term "reasonably foreseeable" refers to something that is likely or expected to occur (Duinker and Greig, 2007). A cumulative effects assessment (CEA) is a systematic process of identifying, analyzing, and evaluating CE on a receptor, for the purpose of informing planning and management (Canadian Council of Ministers of the Environment [CCME], 2014). Ideally, a CEA should be conducted at the regional scale early in the planning process so that information is available to guide planning decisions, including where to site OWED licencing areas. We define a "region" to be a broad geographic area, typically spanning hundreds of thousands of square kilometers, such as the extent of a large marine ecosystem (e.g., Alexander, 1993; Sherman, 1995). The amount and types of information available to include in a CEA varies by receptor, location, and time.

In Canada, the OWED industry is emerging. Federal and provincial governments are designing regional strategies for managing future activities related to OWED in Newfoundland and Labrador, and Nova Scotia (i.e., Regional Assessments; Committee for the Regional Assessment of Offshore Wind Development in Newfoundland and Labrador, 2024; Committee for the Regional Assessment of Offshore Wind Development in Nova Scotia, 2024). In particular, under the authority of the Impact Assessment Act of 2019 (IAA), Regional Assessment Committees are tasked with identifying and considering the potential positive and adverse effects of future OWED activities in the two regional study areas, as well as "potential interactions between the effects of future offshore wind development activities and those of other existing and future physical activities, including the potential for resulting cumulative effects". Currently, Canada does not have a cohesive framework for conducting regional CEAs, which presents an opportunity to develop one.

To support the sustainability of the emerging OWED industry in Canada and worldwide, this paper presents a framework for assessing the CE of OWED activities, other human activities, and natural processes on wildlife at a regional scale, with birds as the focal example. First, we synthesize best practices, including fundamental CEA concepts and basic steps for a species-based CEA that could be applied to a variety of wildlife receptors (i.e., populations or species). Then we present the analytical strategy, providing both a mathematical and a verbal description of the CE metrics, and a verbal description of the spatial optimization algorithm. While conceptually similar to Halpern et al. (2008), our approach extends its utility by allowing the variables related to receptors and pressures that are required to compute the CE metric to vary depending on available information, enhancing the flexibility and applicability across different receptors and pressures. We clearly show how a number of superficially different approaches to conducting a CEA fit under a single umbrella, and we explain how analyses based on different information types can complement each other in a single analysis. This framework is suitable for delineating areas where OWEDs are most likely to minimize CE. A glossary is provided to facilitate a common understanding of terminology (Appendix A).

2. Phases of OWED planning

A CEA may be used to inform decision-making during three distinct phases of OWED planning: (1) regional assessment and OWED area delineation (i.e., defining boundaries within regions where one or more offshore wind sites may occur); (2) site selection for OWED activities; and (3) OWED site evaluation (Fig. 1). We use the term "site" to be synonymous with the terms "licencing area", "lease area", or "wind farm". Ideally, these planning phases should be considered hierarchically, with the outputs from early-phase CEAs supporting decisions at finer spatial scales, such as site evaluation. Phases 1 and 2 often encompass large geographic areas, such as large marine ecosystems (e.g., Alexander, 1993; Sherman, 1995).

Phase 1, **regional assessment and OWED area delineation**, describe the processes used to analyze and evaluate OWED scenarios, with the goal of informing and improving future planning, licencing, and impact assessment processes. The identification of "Recommended Offshore Wind Licencing Areas" and "Potential Development Areas" by the Committees for the Regional Assessments of offshore wind development in Newfoundland and Labrador, and Nova Scotia (respectively) are examples of this phase (Fig. 2; Committee for the Regional Assessment of Offshore Wind Development in Newfoundland and Labrador, 2024; Committee for the Regional Assessment of Offshore Wind Development in Nova Scotia, 2024).

Phase 2, **site selection**, occurs within pre-defined OWED area boundaries. This is the process of identifying specific boundaries for project areas that developers may bid on to create offshore wind farms.

Phase 3, **site evaluation**, contrasts with phases 1 and 2 because it involves assessing the potential CE or impacts from one specific OWED project at a particular location, considered alongside a range of other OWED projects in the region or other types of activities influencing the same wildlife receptors (i.e., species or populations).

Our framework was designed to identify the best strategies for delineating boundaries of future potential OWEDs within a larger geographic area, with the aim of minimizing CE of human activities and natural processes on wildlife. Therefore, the framework can support the identification of future development area(s) within a larger region during the **regional assessment and OWED area delineation** phase, and the delineation of licencing or lease areas during the **site selection** phase. Following the regional assessment process and leasing of offshore areas for wind energy development, site-specific CE evaluations (i.e., phase 3 **site evaluations**) should be conducted. The products developed during phases 1 and 2 may inform the site evaluation phase. For example, information about receptors and pressures that is compiled during the first two phases may be incorporated into future site evaluations. Additionally, the results of regional assessment, OWED area delineation, and site selection could provide regional context to inform the design and interpretation of site evaluations.

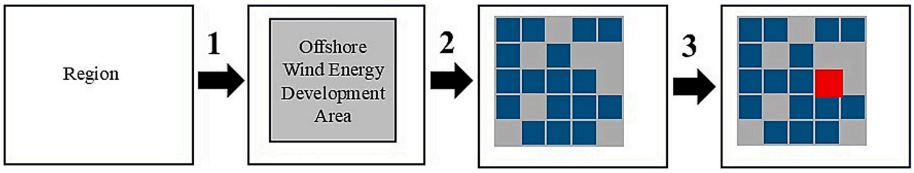

Fig. 1. Schematic representation of three phases of offshore wind planning: 1) regional assessment and OWED area delineation; 2) site selection; and 3) site evaluation. The white Region is the largest geographic area considered for future offshore wind energy development activities; it may coincide with large marine ecosystems (e.g., Alexander, 1993; Sherman, 1995) or federal or provincial jurisdictional boundaries. The gray Offshore Wind Energy Development (OWED) Area represents the result of the first level of refinement in the spatial planning process at the conclusion of the regional assessment and OWED area delineation phase. The small blue squares represent licencing or lease areas (sites) that developers may bid on, which are delineated within the OWED areas during the site selection phase. During site evaluation, products generated from regional and site selection phases may support analyses assessing the cumulative effects of a specific licencing / lease area, highlighted in red in the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

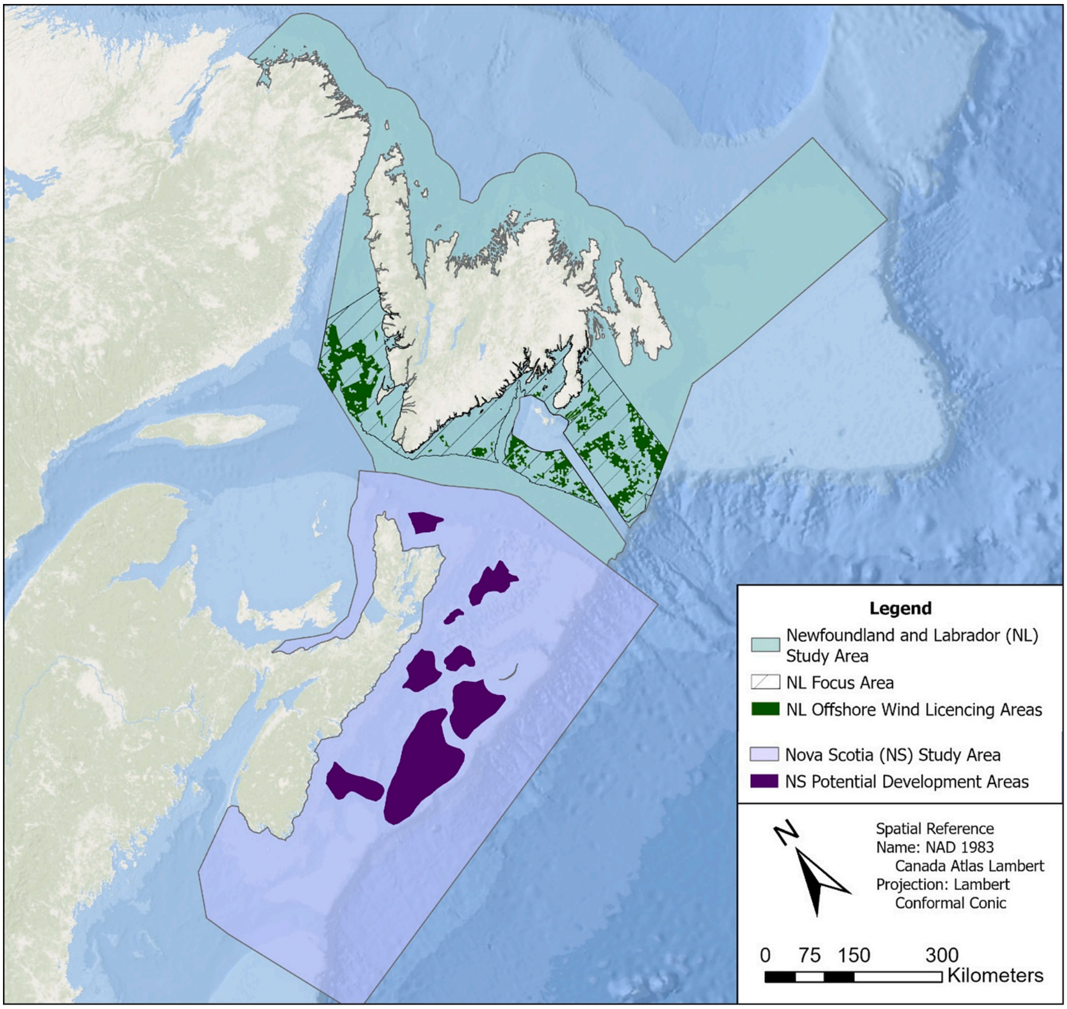

Fig. 2. Offshore wind development areas were delineated during the Regional Assessments of Offshore Wind Energy in Newfoundland and Labrador and in Nova Scotia. Respectively, these were called Recommended Offshore Wind Licencing Areas in Newfoundland and Labrador (Committee for the Regional Assessment of Offshore Wind Development in Newfoundland and Labrador, 2024) and Potential Development Areas Nova Scotia (Committee for the Regional Assessment of Offshore Wind Development in Nova Scotia, 2024).

3. Fundamental CEA concepts

In this section we address four fundamental concepts related to CEAs. Because a clear statement of the management objectives is essential for guiding the remaining steps in the CEA, we begin in *Section 3.1* by providing examples of the range of management objectives that CEAs have addressed. In *Section 3.2* we define the scope of a CEA, which comprises several variables that delimit the extent of the CEA. Defining the scope is critical for constructing a problem that can be solved reasonably and for communicating the utility of the CEA results. In *Section 3.3* on typology, we identify four general types of CEA frameworks and provide our definition for a "species-based approach". Lastly, we list and describe the fourteen basic steps involved in conducting a species-based CEA (*Section 3.4*).

3.1. Management objectives

The management objectives of a CEA are set by decision-makers and will predominantly guide the definition of the CEA's scope variables and selection of analytical methods. Decision-makers may include those departments and agencies that are responsible for regulating the development of the offshore environment and energy resources, and for the conservation and management of natural resources and wildlife. They collaborate in making decisions to balance energy transition goals, social and economic priorities, and environmental considerations at national, regional, and project-level scales. A non-comprehensive list of the types of management objectives that CEAs in Europe, the United States, and Canada have addressed, either alone or in combination, include:

1. identifying areas within which OWED can occur (i.e., product of phase 1 defined in *Section 2: Phases of OWED Planning*);
2. identifying licencing areas (i.e., product of phase 2 defined in *Section 2: Phases of OWED Planning*);
3. assessing and evaluating the risks to receptors from different anthropogenic sources;
4. identifying actionable measures to avoid, minimize, or compensate for cumulative adverse effects to wildlife from human activities; and
5. evaluating estimated CE metrics with respect to pre-established decision-making criteria and thresholds.

Our CEA framework can assist with each of these objectives, given appropriate specification of the scope variables (*Section 3.2: Scope)* and alternative scenarios (*Section 4.7: Scenario-building and Sensitivity Testing*).

3.2. Scope

Conceptually, an environmental CEA is all-encompassing: it includes all effects from all anthropogenic activities and natural processes on all environmental components, with no spatial or temporal constraints. However, in practice, every pressure, interaction, and effect cannot be understood and analyzed. Without narrowing the scope of a CEA down from "all-encompassing" to a justifiable and manageable subset of possibilities, the CEA is intractable (Adams et al., 2023; Brignon et al., 2022; Goodale and Milman, 2016; Masden et al., 2010).

In a CEA, the term "scope" refers to the envelope or boundaries defining: the (i) spatial and temporal constraints of the analysis; (ii) receptors (e.g., species or populations) included in the analysis; (iii) specific sources (i.e., anthropogenic activities and natural processes) and pressures that are assessed; and (iv) future development scenarios that are assessed (e.g., total area occupied by OWED or total energy produced). While natural processes are generally not subject to management, it is best practice to include them in the CEA scope because of their effects on receptors and potential interactions with anthropogenic pressures.

3.3. Typology

Clarke Murray et al. (2020) categorize CEAs into four typologies: activity-based, stressor-based, species- or habitat-based, and area-based frameworks. Although a truly comprehensive CEA would consider all activities, stressors, and species in a given area, practical constraints often limit assessments to a narrower scope (Clarke Murray et al., 2014). For example, species- or area-based CEAs are commonly used because they are the focus of regulatory frameworks and, given data limitations and time constraints, are typically more feasible than fully comprehensive assessments.

Our CEA framework applies a species-based approach (which could also be considered a receptor- or population-based approach), wherein the ecology of the species is the primary factor used to constrain the spatial, temporal, and activity/pressure scope variables (Clarke Murray et al., 2020; Willsteed et al., 2017). In the text that follows, we use the term "species" for simplicity. For cases in which population structure is known or can be inferred, it is best from an ecological perspective to base the analysis on the population rather than the entire species. A population comprises individuals that can potentially interbreed, which is important for effective conservation and management. However, for cases in which relevant laws or regulations apply to species, it may be more appropriate to base the analysis on the species.

3.4. Basic steps for a species-based CEA

Regardless of the OWED planning phase for which a CEA is prepared (regional assessment and OWED area delineation; site selection; or site evaluation), we propose a species-based CEA that includes the following steps:

1. Explicitly define the objectives of the CEA (Stelzenmüller et al., 2018; Willsteed et al., 2018). The CEA objectives should align with the designated management objectives.
2. Identify the specific geographic boundaries of the area(s) of interest. This will depend on the phase of OWED planning (*Section 2 Phases of OWED Planning*).
3. Inventory the species that occur within the geographic boundaries for the area of interest that were specified in Step 2. This should include species that occur in the area only occasionally (e.g., migratory or other species with spatiotemporal variability in their distribution) and seasonal and permanent residents. The initial species inventory should be comprehensive, including species that rarely occur in the area or whose distribution is uncertain but may overlap the area at some point in time (Brignon et al., 2022). The inventory should be based on the best available information and may be supported by expert judgment where information is scarce.
4. Identify all known potential cause-effect pathways that link the species to known OWED pressures (e.g., barriers to movement) and effects (e.g., collision, displacement). This step can be based on expert knowledge and a review of the available literature. It is important to define which development stages (i.e., construction, operation, or decommissioning) and type of OWED technology (e.g., fixed foundation or floating platform) will be included in the scope. At this step, the list of pathways should be comprehensive; the particular pressures included in the analysis will be refined in Step 8.
5. Select the receptor species that will be included in the CEA from the inventory of species identified in Step 3. *Section 4.1: Selection of Receptor Species* provides a list of nine criteria that can be used to prioritize species, ensuring that focal species selection is transparent and aligned with conservation, cultural, and management objectives.
6. Inventory the other primary sources (i.e., non-OWED activities and natural processes) and associated pressures occurring anywhere in the ranges of the selected receptor species. This step can be informed by expert knowledge and a review of the available literature. See *Section 4.2: Identifying Cause-effect Pathways* and *Section 4.8: Role of Expert Knowledge* for more details.
7. Identify all known potential cause-effect pathways that link the receptor species and the non-OWED pressures listed in Step 6. This step can be informed by expert knowledge and a review of the available literature. See *Section 4.2: Identifying Cause-effect Pathways* and *Section 4.8: Role of Expert Knowledge* for more details.
8. Select the OWED and non-OWED pressures that will be included in the CEA. Factors to consider include, inter alia, understanding of the cause-effect pathway linking the pressure to the receptor species, sensitivity of the receptor species to the pressure, and availability of information needed to incorporate the pathway into the CEA. To guide future assessments, high-risk pathways that lack sufficient information to include in the CEA can be documented as future research priorities.
9. Refine the spatial scope. The spatial extent of the geographic area(s) of interest for OWED activities that prompted the CEA (identified in Step 2) is likely to be smaller than that of a given receptor species' range. For the consideration of non-OWED cumulative effects, the spatial scope can be extended beyond the spatial scope defined in Step 2. Hierarchical analytical strategies exist to allow for differences in the types and resolution of information that are used to assess effects within the OWED activity area compared to other parts of the species' range. See *Section 5.3 Spatial Optimization Algorithm*.
10. Define the temporal scope of analysis. This requires specifying baselines (i.e., reference states) for the receptor species, the start date and end date for the analysis (i.e., the period over which the CE metric will be calculated for the baseline scenario and each alternative scenario), and the temporal resolution of the assessment (e.g., Will the CE metric be seasonal?). Determining the temporal scope is essential for capturing how the species ecology and the pressures may vary over time, as pressures impacting a receptor species might differ depending on the timeframe considered (e.g., historical baselines, operational lifespan, and decommissioning stages). Factors to consider in determining baselines for species and scenarios are discussed below (*Section 4.3: Species' Baselines* and *Section 4.7: Scenario-building and Sensitivity Testing*).
11. Define the metric(s) (i.e., variable(s) or parameter(s)) that will be used to measure CE and the decision-making criteria and thresholds that will be used to evaluate the significance of the

resulting effects. The CE metric(s) should provide the information required to apply the decision-making criteria. Standardizing CE metric(s), criteria, and thresholds across assessments should allow the results of different assessments to be compared and facilitate consistency in the decision-making process (Stelzenmüller et al., 2020). See *Section 5.2: CE Metrics* and *Section 4.9: Decision-making Criteria and Thresholds* for more details.

12. Define a set of scenarios with reasonably foreseeable changes in OWED pressures, non-OWED anthropogenic pressures, or natural processes. This step will benefit from diverse input (i.e., from energy and environmental regulators, developers, scientists, Indigenous peoples, and stakeholders; Duinker and Greig, 2021, Duinker and Greig, 2007). For OWED, scenarios may involve different types of technology or different buildout goals that are defined in terms of total energy produced or total area covered by OWED activities. Multiple types of human activities and natural processes can be included in scenarios. See *Section 4.7: Scenario-building and Sensitivity Testing* for more details.
13. Estimate the values of the CE metric(s) and associated uncertainty for each baseline scenario and alternative scenario, recognizing that uncertainties may vary significantly depending on the availability, precision, and accuracy of data, our understanding of linkages among species, activities, and natural processes, and our ability to model complex interactions (e.g., Searle et al., 2023; Stelzenmüller et al., 2020). For more details see *Section 4: Critical Considerations for CEA Implementation*, and *Section 6: Discussion.*
14. Apply the estimated CE metric(s) to the evaluation criteria and thresholds to inform spatial planning and CE management decisions by decision-makers.

4. Critical considerations for CEA implementation

In this section, we expand on the following nine considerations that refine and expand on the four fundamental CEA concepts described above: selection of receptor species (*Section 4.1*); identifying cause-effect pathways (*Section 4.2*); definition of baselines for species (*Section 4.3*); species-specific spatial responses and spatial variability in marine habitats (*Section 4.4*); sources of uncertainty and methods for estimating uncertainty in CEA results (*Section 4.5*); data availability, representativeness, and quality (*Section 4.6*); scenario uncertainty (*Section 4.7*); the role of expert knowledge (*Section 4.8*); and decision-making criteria and thresholds (*Section 4.9*).

4.1. Selection of receptor species

The receptor species selected for inclusion in a CEA may depend on the OWED stage (i.e., construction, operation, maintenance, decommissioning) due to interspecific differences in vulnerability to stage-specific pressures and the likely effects of those pressures on each species. They also depend on the spatial extent of the OWED activities for which the CEA is conducted, because the prioritization of a species or activity may vary with the geographic location or size of the analysis area. There are many factors to consider when selecting receptor species (Lerner, 2018; Masden et al., 2010; Popper et al., 2022; Regional Synthesis Workgroup of the Environmental Technical Working Group, 2023; Tulloch et al., 2024), including:

- conservation status, based on either official designation (provincial, national, international) or inferred vulnerability to predicted future ecological or anthropogenic changes;
- number of individuals or proportion of the population that uses the area;
- age, age class, or sex of individuals that use the area;
- activity/activities undertaken in the area (e.g., feeding, migrating, breeding, molting, nesting, or rearing young);
- known or suspected vulnerability to OWED activities in the area;
- life history parameters, such as long lifespan and low reproductive output, that would make the species particularly sensitive to disturbance;
- importance to Indigenous peoples or stakeholders;
- ecosystem functioning and trophic interactions, because the presence, absence, or abundance of certain species may have considerable influence on the ecosystem, or the species may represent a broader collection of taxa, such as a guild, community, or ecosystem; and
- availability of information needed to conduct the CEA.

If a species ranks high in priority based on these factors, but insufficient information exists to estimate any of the CE metrics described in *Section 5 Analytical Strategy*, the species can be added to a list to help prioritize future research.

4.2. Identifying cause-effect pathways

Pathways of effects modeling (PoE) is a useful tool to systematically identify cause-effect pathways between human activities, the associated stressors to ecological components, and the expected effects (Government of Canada, 2012; Knights et al., 2013). PoE development involves defining measurable endpoints (e.g., habitat distribution, availability) that vary based on management objectives (Government of Canada, 2012). Mapping PoE includes reviewing and synthesizing existing knowledge on pressures, mechanisms, and potential effects. PoE models provide simplified visual representations of complex interactions (which may include additive, synergistic, or countervailing interactions), allowing opportunities to further identify more complex CE and possible mitigations (Clarke Murray et al., 2014; Isaacman and Daborn, 2011; Knights et al., 2013). Comprehensive PoEs may include all known potential effects or impacts of pressures on receptors that can be considered and addressed, ultimately contributing to more complete and accurate CEAs. We provide an example of a PoE for a hypothetical seabird species in Appendix B.

4.3. Species' baselines

In a CEA, the species' baseline represents the reference state of a species, against which changes from pressures associated with OWED and other sources are assessed. A species' baseline is typically defined by two factors: 1) a temporal range or specific period; and 2) population abundance or effective population size. Factors to consider when setting baselines for species may include the following:

- formally designated conservation targets for individual populations or species;
- best available information on abundance immediately prior to development (but see "shifting baseline syndrome," below);
- estimated trends in population abundance over time;
- maximum historical abundance estimate;
- Indigenous knowledge;
- uncertainty in existing abundance estimates;
- spatiotemporal variability in the distribution of the species relative to the distribution of effort used to estimate abundance, because it is typically more difficult to estimate abundance for species whose distributions are highly variable;
- history of known mortality, such as from directed harvest, bycatch, diseases, oil spills;
- estimates of critical parameters, such as carrying capacity or maximum net productivity level, from population models; and
- changes in environmental conditions within the area over time.

The aforementioned list of factors includes information compiled from Masden et al. (2010), Adams et al. (2023), Committee for the

Regional Assessment of Offshore Oil and Gas Exploratory Drilling East of Newfoundland and Labrador (2020), Goodale and Milman (2016), Warwick-Evans et al. (2018), Kelsey et al. (2018), Bureau of Ocean Energy Management, O. of R.E.P [BOEM] (2020), Bureau of Ocean Energy Management [BOEM] (2024), Jongbloed et al. (2023), Peschko et al. (2024), Halpern et al. (2008), Goodale et al. (2019), Rijkswaterstaat (2022), Potiek et al. (2022), Tulloch et al. (2024), Robinson Willmott et al. (2013), and Layton-Matthews et al. (2023).

Sources of this type of information for wildlife in Canada include Committee on the Status of Endangered Wildlife in Canada (COSEWIC) status reports, *Species at Risk Act* recovery strategies, and conservation strategy reports for Bird Conservation Regions and Marine Biogeographic Units (Environment Canada, 2013).

Care must be taken to avoid the "shifting baseline syndrome" (Pauly, 1995), which occurs when abundance decreases over time, yet the time series of abundance is ignored when setting the species' baseline. As a result, the species' baseline reflects only the most recent abundance estimate, leading to a gradual decline in the baseline and, hence, management targets that are insufficient for conservation or management purposes. For information on baseline scenarios see *Section 4.7 Scenario-building and Sensitivity Testing.*

4.4. *Species-specific spatial responses to pressures and spatial variability in marine habitats*

Depending on how a species uses the marine environment and the species' response to pressures, CE may be compounded or mitigated by clustering activities in a confined subarea, or, alternatively, by broadly dispersing activities across a vast area (Goodale et al., 2019; Masden et al., 2010). For example, if a species exhibits macro-avoidance to OWED, dispersing wind farms across a large area could increase CE by limiting access to habitat. Masden et al. (2010) illustrate how species with different migratory strategies may experience varying levels of impact depending on the spatial distribution of wind farms: *"a widespread species such as the chaffinch Fringilla coelebs migrates in a broad front rather than on a specific route. A single wind farm will therefore only affect a restricted portion of the population, and multiple wind farms will affect a different set of birds in turn."* This contrasts with species that migrate along narrow corridors, where multiple wind farms located within that corridor could concentrate impacts on the same individuals, potentially affecting a larger proportion of the population.

The most effective way to avoid negative effects of OWED activities on a receptor species is to locate the activities outside of the species' range. If that option is not feasible, CE may be minimized by siting OWED activities outside areas of high ecological productivity or important habitat for the species, such as migratory corridors, breeding grounds, and feeding zones. Features that are physical (seamounts, shelf breaks, canyons, estuaries, points, elevated land), atmospheric (wind patterns, air currents), or oceanographic (currents, fronts, eddies, upwelling) can create zones of high biological productivity where food resources aggregate. Siting in areas with enhanced food availability may coincide with increased species density and thus exposure to overlapping OWED and non- OWED pressures.

4.5. *Uncertainty*

When considering the results of a CEA and comparing the estimated CE metric(s) to the evaluation criteria (*Section 4.9: Decision-making Criteria and Thresholds*), decision-makers need to know how much confidence to put in the results. Confidence and uncertainty are inversely related: we are less confident in things that are highly uncertain, and more confident in things that have low uncertainty.

In the field of CE, "uncertainty" can be defined in relatively broad terms as "the state of deficiency of information related to understanding or knowledge of an event, its consequences or likelihood" (Stelzenmüller et al., 2018). Uncertainty in a CEA may be classified into four categories:

- **Observation uncertainty** could be due to random errors (i.e., precision) or systematic discrepancies in magnitude or direction between data and reality (i.e., bias) (Stelzenmüller et al., 2020; Section 4.6 Data Availability, Representativeness, Quality).
- **Process uncertainty** in ecology refers to incomplete knowledge of relationships among natural phenomena, such as interactions among species, how species relate to their environment, and spatiotemporal variability inherent in ecosystems (Cressie et al., 2009). Ecological process uncertainty also includes incomplete knowledge of the relationships between natural phenomena and human activities (e.g., cause-effect pathways, *Section 4.2 Identifying Cause-effect Pathways2*).
- **Statistical uncertainty** refers to uncertainty in the assumptions used in statistical models; examples include model structure or parameter estimates (Stelzenmüller et al., 2020).
- **Pressure scenario uncertainty** arises due to imperfect knowledge about the range and intensity of future human activities and natural processes (*Section 4.7: Scenario-building and sensitivity testing*).

For further details on uncertainty in CEAs, see Stelzenmüller et al. (2020).

The sources and magnitudes of uncertainty, and the methods used to account for uncertainty, will affect the results of a CEA. Some CEAs ignore uncertainty; others use qualitative (e.g., ranks) (Kelsey et al., 2018; Potiek et al., 2022; Robinson Willmott et al., 2013) or quantitative methods (e.g., Monte Carlo simulations, Potiek et al. (2022) and Soudijn et al. (2022); Bayesian networks, Tulloch et al. (2024)) to try to estimate and propagate uncertainty from the input variables to the final CE metric(s). When unable to explicitly account for uncertainty in an analysis used to estimate seabird mortality due to collisions with wind turbines in the North Sea, Potiek et al. (2022) relied on the precautionary principle and assumed the "worst case scenario", which they defined as the scenario that would result in the highest mortality. The degree to which a CE metric responds to uncertainty may be investigated using statistical methods such as sensitivity testing, which is discussed further in *Section 4.7: Scenario-building and Sensitivity Testing.*

4.6. *Data availability, representativeness, and quality*

Observation uncertainty is a function of the amount of data available (often referred to as sample size) and how well the data (the sample) represents the underlying truth. Observation uncertainty can be quantified using precision and bias.

Precision is known by several terms, including random error, variability, random variation, and noise. Precision has no preferred direction, and increasing sample size should effectively increase precision. Quantifying the size of a sample of biological data is not always straightforward. The following are guidelines on metrics that may be used to evaluate sample sizes for a variety of types of ecological data, modified from Harrison et al. (2023):

- **Bio-logging**: number and type of tags deployed in different age and sex classes or populations at particular locations and times; tag longevity (i.e., the length of the time series from each tag); and the number of years across which the tags were deployed on a particular population or species;
- **Opportunistic visual observations**: number of observations and the temporal and spatial extent and resolution of the observation effort;
- **Photo-ID**: number of individuals identified; study duration (in years); spatial and temporal extent of sampling; representativeness of the sample (e.g., age class, sex, proportion of the population with identifiable markings); number of resightings of individuals; and the maximum number of years a single individual has been identified in an area;
- **Line- or strip-transect survey**: number of surveys in the time series; number of observations; number and length of the transects;

effective strip width; time lag between surveys; and the temporal and spatial extent and resolution (i.e., spacing between transects) of each survey; and
- **Passive acoustic monitoring (PAM)**: number and location of acoustic recorders; spatial and temporal extent of recordings; sample frequency; and number of signals (i.e., calls, whistles, clicks, songs, etc.) of the specific species detected.

Bias has a net direction and magnitude regardless of sample size and is therefore a measure of inaccuracy. In general, bias can arise during the sample design, data collection, or analytical steps when the underlying assumptions are not valid for the case study. A biased dataset may result from systematically preferring (or avoiding) objects with particular characteristics during sampling, resulting in a skewed or unrepresentative sample of reality. Bias may inadvertently arise during data collection when inclement weather precludes sampling the entire survey design. Other examples of data that may be considered biased for a particular case study include data that were collected in the following ways: on species other than the receptor species in the CEA; in a different place than the area of interest to the CEA; during a different period (e.g., month, season, or year) than the period of interest to the CEA. Bias may result from collecting data using a tool that is poorly calibrated so that the measurements are all either too low or too high. Bias can also arise during analysis due to the estimator chosen or the methods used to analyze the data. When sampling bias is known to exist and methods are implemented to estimate and correct the bias during analysis, the bias does not propagate to the results of the analysis.

Data quality is a qualitative assessment of observation uncertainty that is related to precision and bias, and is case specific. For example, to help represent uncertainty in models of the demographics of seabirds in Dutch waters of the North Sea, Potiek et al. (2022) incorporated ordinal (0, 1, or 2) scores based on the quality and representativeness of the data sources used to derive input parameters. They scored data quality based on the number of years in the data, the number of individuals in the data, and whether uncertainty was reported. They scored representativeness based on data recency, how representative the data were to their geographic area of interest, and how representative the data were to the current trends in seabird populations in their geographic area of interest.

4.7. *Scenario-building and sensitivity testing*

One method of examining the sensitivity of CEA results to changes in parameters or model structure that are not known with certainty is to implement the CEA independently in multiple scenarios (i.e., sensitivity testing). In the context of CEAs, a scenario is defined by a set of parameter values and assumptions about the relationships among species, human activities, and natural processes. A baseline scenario represents the state of the ecosystem and human activities without OWED and can be used to estimate a CE metric for the receptor species that serves as a reference point for comparison with alternative scenarios. In mathematical terms, the baseline scenario is defined by specific parameter values and assumptions about relationships among interacting components in a reference state.

Each alternative scenario uses scenario-specific parameters to address one or more unknowns, such as: total OWED buildout (e.g., measured in terms of total energy produced or area covered by OWED projects); effects of other anthropogenic activities on the receptor species, taking into consideration existing and hypothesized future management decisions; climate change effects; spatiotemporal variability in natural processes, and the resultant effects on the receptor species; current receptor species abundance; life history parameters; and the presence, direction, or strength of cause-effect pathways.

Comparing CEA results from multiple scenarios can help to distinguish between parameters that heavily influence CEA results (i.e., a small change in the parameter value generates a large change in the CE metric) and parameters that have only weak influence on the results (i.e., a large change in the parameter value generates a negligible or small change in the CE metric). Understanding the sensitivity of the CEA results to different parameters can help prioritize future research, with the ultimate goal of enhancing the certainty of future CEAs and the effectiveness of future management decisions.

The conclusions that can be drawn from the analysis of multiple scenarios are only as good as the suite of investigated scenarios. The future is unpredictable. It is acceptable if the actual progression of events does not align with any of the scenarios analyzed because sensitivities can still be investigated using a well-designed collection of scenarios. Input from Indigenous peoples, developers, scientists, stakeholders, and decision-makers (*Section 3.2: Management Objectives*) may be used to define the set of scenarios to analyze. We present general guidelines for scenario-building, and then provide an example of how those general guidelines may be applied specifically to designing pressure scenarios for CEAs focused on OWED activities. The general guidelines, which were based on those provided in Duinker and Greig (2007), are as follows:

- The set of scenarios should include sharp contrasts in the unknown parameter(s);
- The set of scenarios should comprehensively span the range of likely values of the unknown parameter(s);
- Each scenario should be rooted in the present (e.g., climate change forecasts should be empirically grounded in the present to provide confidence that they begin in the right place), plausible (not impossible), and internally consistent;
- Our collective ability to judge probabilities of outcomes is poor. Therefore, avoid trying to create a “most likely” scenario. This also applies to creating three scenario clusters with some notion of “high”, “medium” and “low”, and to classifying the likelihood of future events into “almost certain,” “reasonably foreseeable,” and “hypothetical”; and
- The total number of scenarios that are evaluated should represent a balance between parsimony (i.e., few scenarios) to make the analytical task tractable, and comprehensiveness (i.e., many scenarios) to disentangle interactions among parameters for realism.

The first two general guidelines can be adapted to the specific task of designing alternative scenarios for a CEA focused on OWED activities as follows:

- To test the potential for significant effects, the set of scenarios should include sharp contrasts (e.g., extreme values) in alternative futures that are defined by factors with substantial uncertainty. These factors could include: OWED buildout and technology; climate change; or management decisions that affect the receptor species (e.g., management actions that mitigate the effects of pressures for the receptor species such as bycatch, light pollution, contaminants, noise, competition for prey, disease);
- To enhance the ability to identify nonlinear or threshold effects, the set of scenarios should comprehensively span the range of values (including intermediate values at which threshold effects may occur) of potential future OWED buildout and technologies, and all key pressures with the potential to measurably affect the receptor species (either individually or cumulatively).

4.8. *Role of expert knowledge*

Expert knowledge plays a crucial role in CEAs, particularly in building inventories of primary sources (e.g., OWED, non-OWED activities and natural processes) and understanding associated pressures and pathways of effects impacting receptor species. These insights help to recognize interactions among species and pressures, estimate the likelihood of a receptor species’ exposure to a pressure, assess potential effect severity, and gauge uncertainty, all of which are essential to identifying high-risk pathways. Expertise can come from diverse sources, including Indigenous Knowledge Holders, scientists, stakeholders, industry, and decision-makers (*Section 3.2: Management Objectives*). Eliciting this knowledge should be scientifically rigorous, inclusive, and respectful of different ways of knowing (Adams et al., 2023). Structured and transparent methods should gather insights across these groups, ensuring all contributions are valued and meaningfully integrated (e.g., Tulloch et al., 2024).

Despite its value, expert judgment alone has limitations. Above, we stress the importance of ensuring the management objectives guide the CEA's objectives, scope, and analytical methods (*Section 3.2: Management Objectives*). Here, "analytical methods" implicitly includes the choice of the CE metric. One cannot use expert judgment alone to derive estimates of spatially explicit and quantitative species or pressure variables that are needed to address certain management objectives. Thus, while expert elicitation can bridge knowledge gaps in certain data-poor contexts, it may be insufficient in others. If insufficient information exists to allow the development of a complicated model, then the model structure should be simplified until it can be built using the available information and still meet the CEA objectives. It is possible that the CEA objectives will need to be revised due to knowledge gaps that preclude achieving the stated objectives.

4.9. Decision-making criteria and thresholds

Although absent from many CEAs (e.g., Stelzenmüller et al., 2020), decision-making criteria and thresholds are highly recommended tools that allow transparency in the determination of whether the results are significant.

Criteria may be defined as the "terms of reference against which the significance of a risk is evaluated" (Ross et al., 2022). The decision-making criteria are technical rules. Criteria should be chosen with objective input from the decision-makers (*Section 3.2: Management Objectives*) and experts in the different types of criteria that have been used in other cases.

Criteria often contain thresholds, which are the specific "values used to establish concrete decision points and operational control limits to trigger management action and response escalation" (Stouffer et al., 2017). Designating thresholds is a policy decision that requires stakeholder engagement on acceptable levels of risk.

Ideally, candidate criteria and thresholds should undergo simulation testing to evaluate whether they will likely provide the necessary information to support decisions and trigger timely action. The CE metric (s) should provide the information required to apply the decision-making criteria.

5. Analytical strategy

5.1. Overview

Briefly, our analytical strategy uses spatial optimization methods that aim to minimize the value of a CE metric via the spatial allocation of individual polygons within a larger geographic area. Thus, it can be used both when the CEA is intended to inform phase 1 (i.e., regional assessment and OWED area delineation) or phase 2 (site selection). The combination of possible polygons that may be selected to form a valid solution to the optimization problem may be constrained by factors such as minimum or maximum OWED site size, total area of all OWED sites within the region, total energy produced in the region, or avoidance of areas of concern (e.g., based on pre-defined ecological, social, economic, or logistical factors).

Given sufficient spatially explicit information about the density of the selected receptor species, magnitude of the selected pressures, and cause-effect pathways linking the receptor species and pressures, we can program the spatial optimization algorithm to find solutions that minimize population-level impacts to a receptor species or a community from the CE of all pressures. If this ideal standard cannot be achieved due to information gaps, alternative metrics presented below may be used to inform the immediate decision-making process. The list of information gaps may help guide future research efforts.

The CE metric is defined as the product of a spatiotemporally explicit species variable and a spatiotemporally explicit pressure variable, summed across all species and pressure combinations. Although our approach is conceptually similar to that of Halpern et al. (2008), we extend its utility by allowing the specific variables used to compute the CE metric to vary depending on available information. This type of flexible yet cohesive approach allows for standardization of metrics and criteria across all assessments, enabling the results from different assessments to be compared and facilitating consistency in the decision-making process.

5.2. CE metrics

Five structurally similar CE metrics can be produced from the species and pressure variables, dependent upon data availability. Fig. 3 shows a schematic representation of how different combinations of species and pressure data can be incorporated into CE metrics that are structurally similar, but that represent diverse types of information about the CE across species, pressures, space, and time.

The variable for receptor species *s* at location *h* and time *t* may be one of three types: binary presence/presumed absence or presence/absence, $I_{s,h,t}$; relative density, a potentially biased estimate of the number of animals per unit area, $\widehat{D}^{rel}_{s,h,t}$; or absolute density, an unbiased estimate of the number of animals per unit area, $\widehat{D}_{s,h,t}$.

The variable for pressure *p* at location *h* and time *t* may also be one of three types: binary presence/presumed absence or presence/absence, $I_{p,h,t}$; estimated pressure magnitude, $\widehat{M}_{p,h,t}$; or estimated pressure effect on an individual of a given species, $\widehat{E}_{p,s,h,t}$. The effect (i.e., proximate response of an individual, such as a change in behavior or diet) that a pressure has on an individual likely depends on the species' sensitivity to the pressure and on the magnitude of the pressure.

Broadly, the information captured in these five CE metrics increases from the **Boolean exposure** ($\widehat{X}_1$) metric to the **total effect** ($\widehat{X}_5$) metric, resulting in a concurrent increase in the utility of metrics.

$$\text{Boolean exposure } \widehat{X}_1 = \sum_t \sum_h \sum_p \sum_s I_{s,h,t} I_{p,h,t} \tag{1}$$

$$\text{Relative exposure I } \widehat{X}_2 = \sum_t \sum_h \sum_p \sum_s \widehat{D}^{rel}_{s,h,t} I_{p,h,t} \tag{2}$$

$$\text{Relative exposure II } \widehat{X}_3 = \sum_t \sum_h \sum_p \sum_s \widehat{D}^{rel}_{s,h,t} \widehat{M}_{p,h,t} \tag{3}$$

$$\text{Relative effect } \widehat{X}_4 = \sum_t \sum_h \sum_p \sum_s \widehat{D}^{rel}_{s,h,t} \widehat{E}_{p,s,h,t} \tag{4}$$

$$\text{Total effect } \widehat{X}_5 = \sum_t \sum_h \sum_p \sum_s \widehat{D}_{s,h,t} \widehat{E}_{p,s,h,t} \tag{5}$$

First, we define each of the metrics. In *Section 5.3: Spatial Optimization Algorithm*, we discuss how more than one metric could be combined within a single CEA.

1. The **Boolean exposure** ($\widehat{X}_1$) metric represents the sum across all receptor species, pressures, and locations of a spatially explicit presence/absence metric. The $\widehat{X}_1$ metric can be used only to account for spatial overlap between species and pressures.
2. The **relative exposure I** ($\widehat{X}_2$) metric provides information about spatial heterogeneity in species' relative density across the region, but it considers only the overlap of the species and pressures - not the magnitude of the pressures or the pressures' effects on the species. Furthermore, because $\widehat{D}^{rel}_{s,h}$ represents only relative density, metric $\widehat{X}_2$

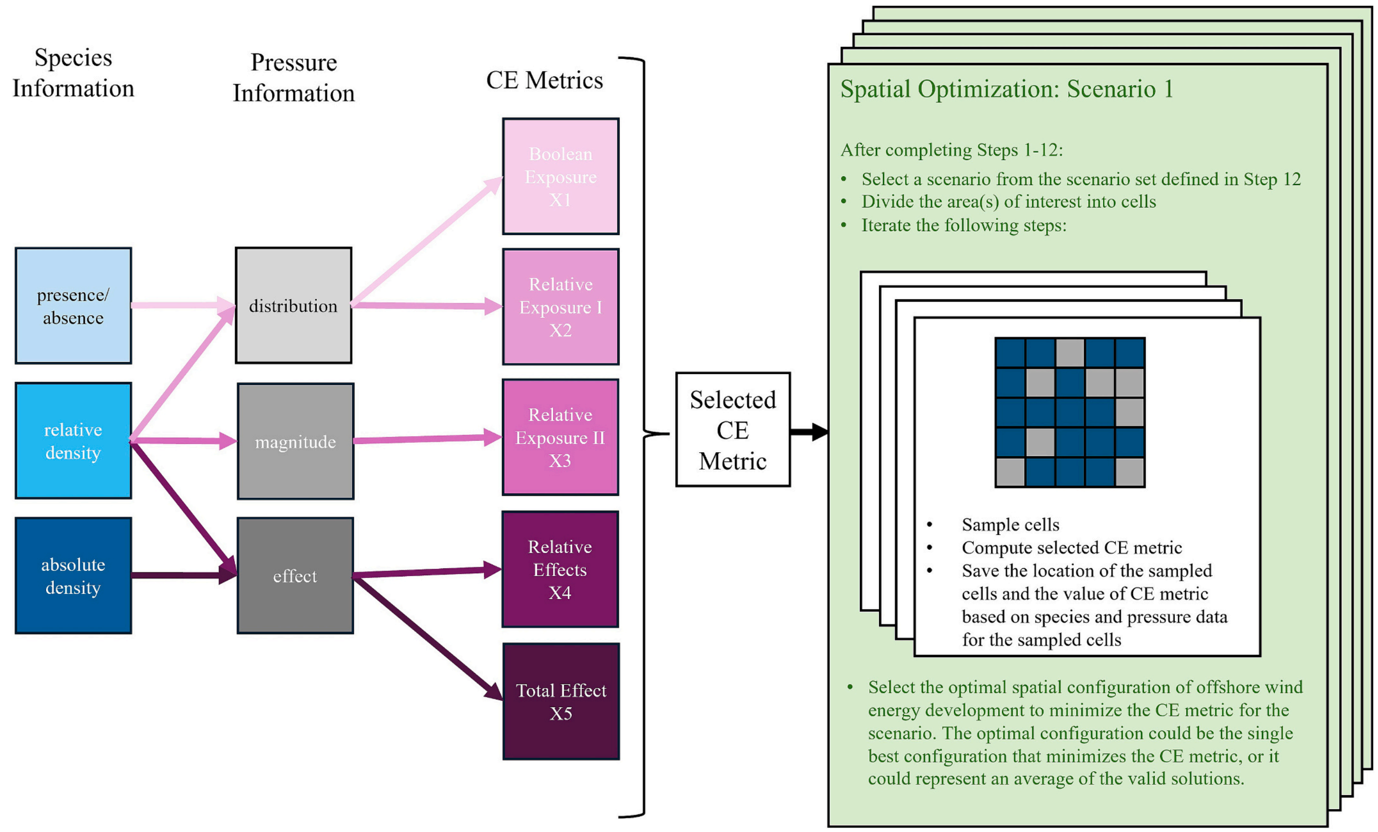

Fig. 3. Schematic representation of the species-centric cumulative effects assessment (CEA) framework. Selection of the cumulative effects (CE) metric is influenced by the types and quality of spatial information available on the species and pressures that are included in the pressure scope. In the figure, higher quality information is indicated with darker shading. If spatial information does not exist on species or pressures, cumulative effects assessments using this framework are not possible. Following the selection of the CE metric, the spatial optimization process is run iteratively for each of the defined scenarios. The output for each scenario is the optimal spatial configuration of OWED sites that will minimize the CE metric, or an average of valid solutions.

should be applied and interpreted with caution due to the potentially unequal and unknown weighting of each species.

3. The **relative exposure II** ($\widehat{X}_3$) metric also relies on relative species density, but it incorporates information about the spatial heterogeneity across the region in the magnitude of each pressure. Metric $\widehat{X}_3$ should be interpreted with caution because it is based on a relative species variable that may have biases that are not consistent across all species and on a pressure variable (magnitude) that might not relate consistently across all species to the pressure's effect on an individual (e.g., if species differ in their sensitivities or proximate responses to the pressure).

Metrics $\widehat{X}_1$, $\widehat{X}_2$, and $\widehat{X}_3$ could be converted to vulnerability metrics if information about sensitivity is known for each combination of species and pressure. For example, any one of these three CE metrics could be multiplied by a species-specific sensitivity metric. The resulting spatially explicit vulnerability metric could be used to evaluate the risks from alternative management scenarios, or it could be used in the spatial optimization algorithm defined below to identify strategies for minimizing effects to vulnerable species.

4. The **relative effect** ($\widehat{X}_4$) metric provides information on vulnerability or relative effects by weighting the relative density of each species according to each pressure's effect on the species. However, $\widehat{X}_4$ cannot address the absolute number of individuals of each species that are affected because it incorporates species-specific estimates of relative density, which may be biased, and the biases may not be consistent across all species.

5. The metric with the most utility is the **total effect** ($\widehat{X}_5$) metric because it is an unbiased estimate of the total effect of each pressure on each species. In the case of only a single species, if the effect of a pressure on an individual is death, then $\widehat{X}_5$ represents the total number of individuals that die from the pressures included in the scope of the analysis. Alternatively, if the effect of a pressure is reduced reproductive success, then $\widehat{X}_5$ could represent a reduction in the size of the breeding population, number of offspring produced, or number of offspring surviving to reproductive age.

Metric $\widehat{X}_5$ could be used in a population viability analysis (PVA) to infer population-level impacts, such as the magnitude of the change in abundance over time, variation in population growth rates, or the probability that abundance will change within certain parameters over a specified period. Additionally, $\widehat{X}_5$ could be multiplied by an estimate of population vulnerability (e.g., conservation status) to inform risk-based management decisions.

Note that it is possible to multiply absolute species density by either a binary pressure variable ($I_{p,h,t}$) or the magnitude of the pressure ($\widehat{M}_{p,h,t}$). However, we do not include either of those metrics as distinct options because the result of either operation would be essentially another relative exposure metric. Although the number of individuals being exposed would be assumed to be known without bias ($\widehat{D}_{s,h,t}$), there would be insufficient information about the pathway of the pressure's effect on individuals ($\widehat{E}_{p,s,h,t}$) to estimate the total effect of the pressure to the species.

5.3. Spatial optimization algorithm

The generalized spatial optimization algorithm proceeds as follows (Fig. 3):

1. Specify the parameter values that define the scenario (see Step 12 in *Section 3.4: Basic Steps for a Species-based CEA* and *Section 4.7: Scenario-building and Sensitivity Testing*). Assuming the scenario under investigation is specific to OWED, specify the buildout goal (e.g., in terms of total GW of energy generated or total OWED area) for the region(s). It is possible to include multiple regions with region-specific buildout goals in a single analysis by specifying additional constraints. Scenarios may have scenario-specific values for unknown parameters related to driving factors such as the effects of other anthropogenic activities on the receptor species, climate change, current receptor species abundance, life history parameters, or cause-effect pathways.
2. Specify the (likely) minimum size (area) of any single management area (for a regional assessment / OWED area delineation CEA), licencing area (for a site selection CEA) or project (for a site evaluation CEA), a_{min}.
3. Divide the area within the geographic area(s) of interest for OWED defined in Step 2 into cells (h) that are smaller than a_{min}. The algorithm can be constrained to select neighboring cells until the size of a given spatial cluster is at least a_{min} (e.g., Ferguson et al., 2023). Allowing the algorithm to construct cells from smaller building blocks will result in the most effective use of space, assuming the species or pressure variables exhibit detectable spatial heterogeneity within a_{min} and data with sufficient resolution are available. If the granularity of both the species and the pressure variables is larger than a_{min}, then it is possible to obtain multiple solutions with different spatial configurations (i.e., different cells selected) but identical values of the CE metric.
4. Repeat the following steps for each iteration i until an optimal solution or a set of valid solutions is found:
   a. Select a subset of cells, $\boldsymbol{h}_i = \{h_1, \dots h_n\}$ according to the prespecified analytical constraints (including scenario parameter values).
   b. Compute and save the CE metric $\widehat{X}_{\bullet,i}$ that is best suited to the information about the selected species and pressures. In the nomenclature for $\widehat{X}_{\bullet,i}$, the dot specifies only one of the five CE metrics defined above. Below we address the more complicated scenario in which the available information varies across species or pressures, requiring computation of multiple types of CE metrics.
   c. If the analytical objective is to find a single optimal solution, then:

If $\widehat{X}_{\bullet,i}$ is the lowest value of the of the metric among all previous iterations, then save $\widehat{X}_{\bullet,i}$ and $\boldsymbol{h}_i$ as the new minimum value and associated solution, $\widehat{X}_{\bullet,min}$ and $\boldsymbol{h}_{min}$, respectively.

d. If the analytical objective is to find a collection of valid solutions (i.e., collection of cells that meet all of the designated analytical constraints), then save $\boldsymbol{h}_i$ and $\widehat{X}_{\bullet,i}$ as a valid solution and its associated CE metric, respectively.

The spatial optimization analysis may be run using different values of scenario-specific parameters (*Section 4.7: Scenario-building and Sensitivity Testing*), a_{min}, and cell size to examine the sensitivity of the results to these factors. Existing software such as Marxan (Ball et al., 2009) or Marxan with Zones (Watts et al., 2009) are publicly available and free. Alternatively, customized computer code that applies linear integer programming (e.g., Ferguson et al., 2023) could be used and would provide the greatest flexibility for incorporating constraints specific to case studies; however, this approach would require additional time to create and debug the code.

For cases in which the available information varies across species or pressures, the spatial optimization analysis may be implemented independently for subsets of species or pressures using the relevant CE metrics. Recall from above that, for cases in which a given metric applies to multiple species, the contributions from each species are added together to compute the metric. Each implementation of the optimization algorithm would produce an optimal subset of sites, which would be solutions to the problem of minimizing potential CE of pressures on species based on the specific metric. In a subsequent step, the selected sites from each independent optimization analysis could be compared to identify where they do and do not overlap. Protocols should be specified in advance to weight the information from the different solutions in the following situations: cell h is present in all solutions; cell h is present only in the case for which a lot of information about the species or pressures was available; cell h is present only in the case for which relatively little information about the species or pressures was available; cell h contains individuals from a particularly vulnerable population (e.g., based on conservation status). A similar type of post hoc analysis could be used to combine results from species-focused CEAs with spatially explicit results from investigations focused on other aspects of the spatial planning issue, such as minimizing effects of OWED on socioeconomic factors or on maximizing profit for the offshore wind energy industry. However, the results from this type of post hoc overlay analysis likely would differ from a comprehensive analysis that considers *all* constraints simultaneously.

The hierarchical spatial structure mentioned in Step 6 of *Section 3.4: Basic Steps for a Species-based CEA* is one way to incorporate the cumulative impacts of pressures that a species encounters outside of the OWED activity area. Based on knowledge or assumptions about the method in which multiple effects interact to impact a species (i.e., additive, synergistic, or countervailing), an additional step could be used to incorporate the effects of pressures encountered outside of the OWED activity area into the CE metric estimated using the spatial optimization algorithm. For example, if the species experiences heavy mortality due to bycatch in another portion of its range, then the estimated bycatch mortality could be added to an estimate of mortality produced using the total effect metric $\widehat{X}_5$. The total mortality could be used as input into a PVA.

6. Discussion

As the offshore wind industry continues to expand, understanding and mitigating its impacts on wildlife is essential for sustainable development. This paper provides a comprehensive framework for conducting CEAs tailored to the early phases of planning and management of the OWED sector. Specifically, the framework can be used when the CEA is intended to inform regional assessment / OWED area delineation or allocation of individual OWED project (licencing or leasing) areas inside predefined OWED boundaries. The products developed using this framework may inform the site evaluation phase. For example, information about species and pressures that is compiled during the regional assessment / OWED area delineation or site selection phases may be incorporated into future impact assessments.

Building on best practices, we introduce a species-centric approach to CEAs that can be used to guide the strategic siting of OWEDs to ensure they contribute to climate goals while protecting vulnerable wildlife populations. Our analytical strategy enhances the flexibility and applicability of CEAs across various wildlife receptor species or populations. The CE metric is defined as the product of a spatiotemporally explicit species variable and a spatiotemporally explicit pressure variable. We extended the utility of Halpern et al.'s (2008) approach by allowing the specific variables about receptor species and pressures that are required to compute the CE metric to vary depending on the types of information that are available for the analysis. We explained how a number of superficially different approaches to conducting a CEA may be unified into a single overarching analytical framework that may be applied to different information types, and we explain how analyses based on different information types can complement each other in a single analysis. We described spatial optimization methods that aim to minimize the value of the CE metric via the spatial allocation of individual polygons within a larger geographic area.

We highlighted that siting OWED activities to avoid effects on wildlife is the most effective mitigation technique (Croll et al., 2022; Gulka et al., 2024). This technique can be easily incorporated into our CEA framework using exclusion zones in the spatial optimization analysis. Considerable uncertainty exists around the effectiveness of alternative mitigation strategies (Gulka et al., 2024). The sensitivity of a CEA to mitigation strategies can be evaluated using alternative scenarios that modify the pathways of effects between pressures and receptor species (*Section 4.7: Scenario-building and Sensitivity Testing*). This could be implemented by changing the linkages among sources, pressures, effects, or impacts, or by changing the strength or direction of effects or impacts.

In the interest of producing a resource with practical guidelines and presenting a flexible analytical strategy for regional CEAs, it is beyond the scope of this framework to include a complete quantitative demonstration of the methods. However, to improve comprehension we present a conceptual model of potential cause-effect pathways that could form the basis of a CEA for hypothetical seabird species in Appendix B. The conceptual PoE model therein depicts complex interactions (arrows) among three sources (fisheries, climate change, and OWED), eight pressures (three types of fishing gear, prey availability, increased sea surface temperature and storm intensity, thermal stress to chicks, and wind turbines), four effects (entanglement, changes in an individual's energy budget, habitat displacement, and collisions), two impacts to individuals (mortality and reproductive success), and, ultimately, population-level impacts manifest as changes in population size and structure. The existing CEA framework can incorporate nonlinear relationships, temporal lags, or random effects to estimate the additive effects or impacts of each pressure on the receptor species using the relative effect ($\widehat{X}_4$) or total effect metrics ($\widehat{X}_5$).

This CEA framework does have limitations, including inability to explicitly account for interactions among pressures (e.g., cyclic and reciprocal relationships), latent variables, and random effects. These limitations are illustrated with the example presented in Appendix B. For example, there is a cyclic relationship among fisheries, OWED, and prey availability: the distribution of priority fishing areas influences OWED siting decisions; OWED activities affect prey availability (possibly as a temporally lagged effect); and prey availability affects fisheries. Fisheries also affect prey availability, an example of a reciprocal relationship. Climate change affects prey availability indirectly by increasing sea surface temperature, which causes prey distributions to shift to greater depths that some diving seabirds cannot reach. Climate change can be incorporated into the existing CEA framework as an "observable" variable, but not as a latent ("hidden") variable. If there are OWED site-specific effects, then adding random effects to the model structure could account for this source of variability, but the current framework cannot incorporate random effects. The existing CEA framework also cannot accommodate interactions among receptors.

A variety of different analytical techniques allow for different combinations of the model complexities discussed above. Causal modeling strategies such as structural equation models (SEMs; Thorson and Kristensen, 2024), piecewise SEMs (Lefcheck, 2016), dynamic SEMs (Thorson et al., 2024), qualitative network models (Levins, 1974), Bayesian belief networks (Marcot et al., 2006; Tulloch et al., 2024), and simulation models (Tulloch et al., 2022) should be considered to determine if they can create the desired model.

The ultimate advantages of this framework are that it can: (i) incorporate a broad range of spatiotemporally explicit information about species and pressures; (ii) allow for standardization of metrics, criteria, and thresholds across all assessments; and (iii) enable the results from different assessments to be compared, facilitating consistency in the decision-making process across space and time. While the framework was developed to support CEAs in Atlantic Canada, it is broadly applicable globally. Future research should focus on refining these methods through application to regional case studies.

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CRediT authorship contribution statement

Megan C. Ferguson: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Kathryn A. Williams:** Conceptualization, Writing – review & editing, Supervision, Project administration. **M. Wing Goodale:** Writing – review & editing. **Evan M. Adams:** Writing – review & editing. **Paul Knaga:** Writing – review & editing. **Katrien Kingdon:** Writing – review & editing. **Stephanie Avery-Gomm:** Conceptualization, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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. Supplementary data

Supplementary material (1: Glossary, 2: Demonstration of CEA Framework) to this article can be found online at https://doi.org/10.1016/j.eiar.2025.107912.

Data availability

No data was used for the research described in the article.

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