

The Habitat Dependency Index: A new tool for quantifying species-habitat relationships

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ABSTRACT

Habitat loss is a key threat to ecosystems and species that rely on them, with direct consequences for human well-being. Quantifying the degree to which species depend on specific habitats is critical for many fields of knowledge, such as conservation biology or economic valuations, yet poses a complex challenge. We introduce a new method to objectively quantify how much species depend on a habitat by integrating their life-cycle habitat associations. Through a comprehensive literature review focusing on 36 species associated with kelp forests, we demonstrate how this ‘Habitat Dependency Index’ (HDI) effectively discriminates between closely related species and captures differences in their reliance on kelp forests. We suggest this new HDI constitutes a powerful tool for understanding the role of marine habitats in supporting fisheries, biodiversity, and other ecosystem services. Moreover, the approach is broadly applicable and can provide essential information for managing both aquatic and terrestrial ecosystems.

1. Introduction

Humans are threatening global ecosystems, causing habitat degradation and biodiversity loss with devastating consequences for ecological functions and provisioning of ecosystem services (Chaplin-Kramer et al., 2019, Chase et al., 2020, Wernberg et al., 2024). Since the Millennium Ecosystem Assessment (2005), there has been growing awareness of the need to manage biodiversity, habitats, and human well-being

together in order to address the global crisis (Tittensor et al., 2019, Boyce et al., 2022). However, it has been generally unsuccessful in ecological conservation (Misiune et al., 2022), increasing the need to explicitly link habitats to the flow of benefits and services to humans to help change people’s perceptions of conservation value. This, in turn, is needed to meet the ambitious goals for habitat conservation and restoration set out by the Global Biodiversity Framework and the Sustainable Development Goals (Díaz et al., 2020, Misiune et al., 2022), while

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focusing on ecosystem functions that provide important services to humans (Bateman et al., 2013, IPBES, 2019).

Coastal habitats play a key role in supporting ocean ecosystems (Seitz et al., 2013, Barbier, 2017, Blampied et al., 2022), providing a wide range of benefits including the provision of food, regulation of carbon and nutrient flows, and cultural and recreational experiences (Barbier, 2017). Unfortunately, many coastal habitats are threatened and degraded by human activities such as coastal development or pollution, eroding their capacity to support species and the ecosystem services they provide (Halpern et al., 2008, Wernberg et al., 2024). Understanding habitat dependency—how species rely on specific habitats throughout their life cycles—is essential to recognize the ecological function of coastal habitats and understand the consequences of their loss. This knowledge of dependency can help to identify key species, prioritize protection efforts, or predict species responses to environmental changes, allowing better assessments of how habitat loss impacts biodiversity and ecosystem stability, guiding targeted management actions to preserve coastal habitats (Liquete et al., 2016, Sievers et al., 2019, Chetcuti et al., 2020, Blampied et al., 2022).

Attributing habitat dependency to species is challenging, especially in the marine realm where many species have complex life histories, with varying diet and habitat requirements at different life stages, and often have open populations and rather small to large distributional ranges (Caley et al., 1996, Seitz et al., 2013, Eggertsen et al., 2022). For instance, many coastal fishes have planktonic larvae and depend on pelagic spawning areas, juveniles that depend on shallow water vegetation such as kelp forests and seagrass meadows as nursery areas, and adults that move between estuaries and different offshore habitats in search of food, shelter, or mates (Rice, 2005, Seitz et al., 2013). In addition, some species have bottleneck stages of survival in their life cycle that determine their ultimate abundance (Caddy, 2008), such as sea urchins transitioning from cryptic juveniles to adults exposed to predators (Scheibling, 1996). Generalist species may be able to use many different types of coastal habitats (Zarco-Perello et al., 2022), whereas specialist species require specific conditions or habitats to thrive (Pandit et al., 2009). Moreover, in ecology, occurrence is often assumed to imply habitat dependency (Redhead et al., 2016), which can obscure the actual consequences of habitat loss on species abundance and patterns of biodiversity. For example, some sea urchin's species are typically found in kelp forests, yet they also survive in the absence of kelp (Filbee-Dexter and Scheibling, 2014, Day et al., 2024).

The ecological value of a habitat is intrinsically linked to the species and processes it supports (Kremen, 2005, Díaz et al., 2018). To assess the ecological importance of a habitat in supporting species, it is necessary to understand how dependent species are on that habitat. This involves assessing the extent to which species can persist and maintain their ecological function if the habitat is degraded or disappears entirely (Fig. 1). For instance, understanding the dependency of a commercially fished species on its habitat is essential for attributing economic benefits of the habitat derived from fishing (Jordan et al., 2012, Abrantes et al., 2019). Knowledge of habitat dependency helps predict how habitat changes might affect fish stocks and assists sustainable management practices (Seitz et al., 2013). Likewise, if the habitat is important for vulnerable species (e.g., IUCN listed), charismatic species that drive tourism or species that have cultural significance, knowing the habitat dependency is essential to prioritize conservation efforts (Sievers et al., 2019).

Here we present a new approach for overcoming key limitations associated with attributing the relative weight of species-habitat dependencies. We define habitat dependency as a quantitative measure of how dependent a species is on a specific habitat across all stages of its life cycle (Sievers et al., 2019). We introduce a 'Habitat Dependency Index' (HDI) that quantifies species' habitat dependency by integrating information on habitat functions across multiple life stages. The HDI is designed for application to any marine habitat and all taxonomic groups, regardless of life history, and could also be adapted for other aquatic or

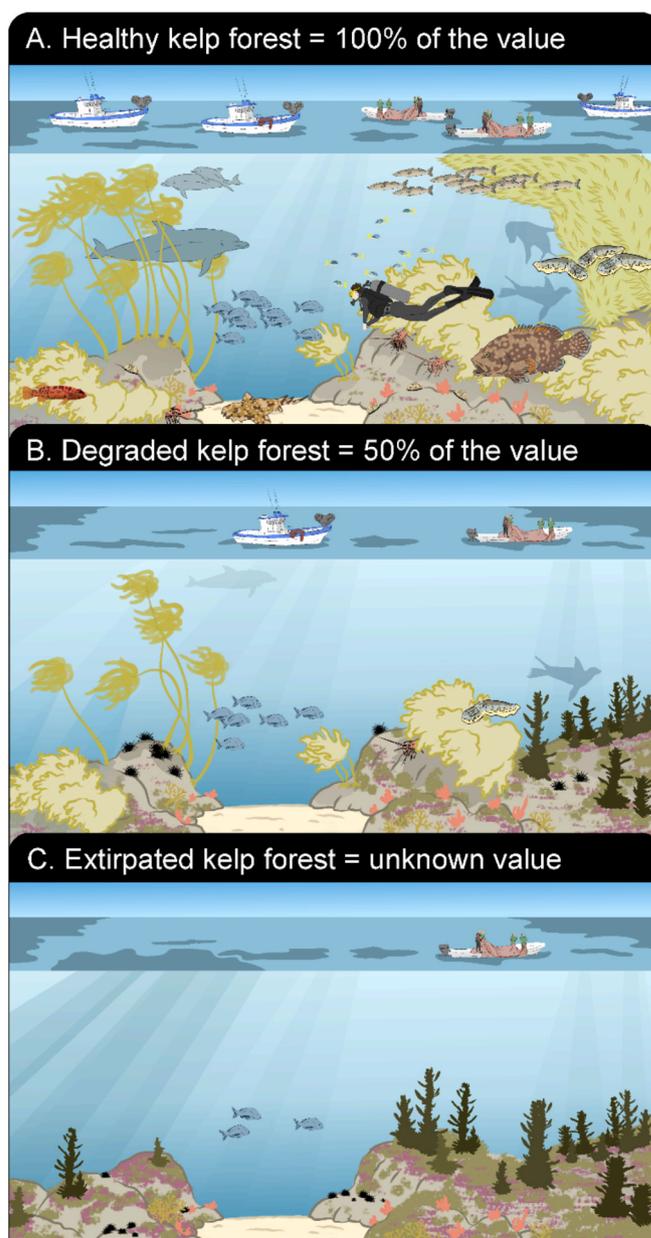


Fig. 1. Infographic illustrating how changes in the availability or quality of habitats impact their ecological value, using the kelp forest as an example. A) Represents a healthy kelp forest as a fully functional ecosystem, valued at 100% of its potential ecological contribution. B) Represents a degraded kelp forest, where biodiversity and habitat quality have been reduced, resulting in only 50% of its original value. C) Represents an extirpated kelp forest, with its ecological value becoming unknown. Infographic by Antoine Minne.

terrestrial environments. Using kelp forests as a case study, we demonstrate how the HDI can be derived for a number of species representing different taxonomic groups and life histories. In addition, we explore the potential limitations and applications of HDI in different research fields, such as the valuation of ecosystem services, ecosystem-based management and biological conservation.

2. Habitat dependency index

The 'Habitat Dependency Index' (HDI) summarizes habitat dependency of a species based on three ecological habitat functions – feeding, shelter and reproduction – each measured by two or three indicators from each phase of the species' life cycle (Fig. 2; Table 1, S1, S2

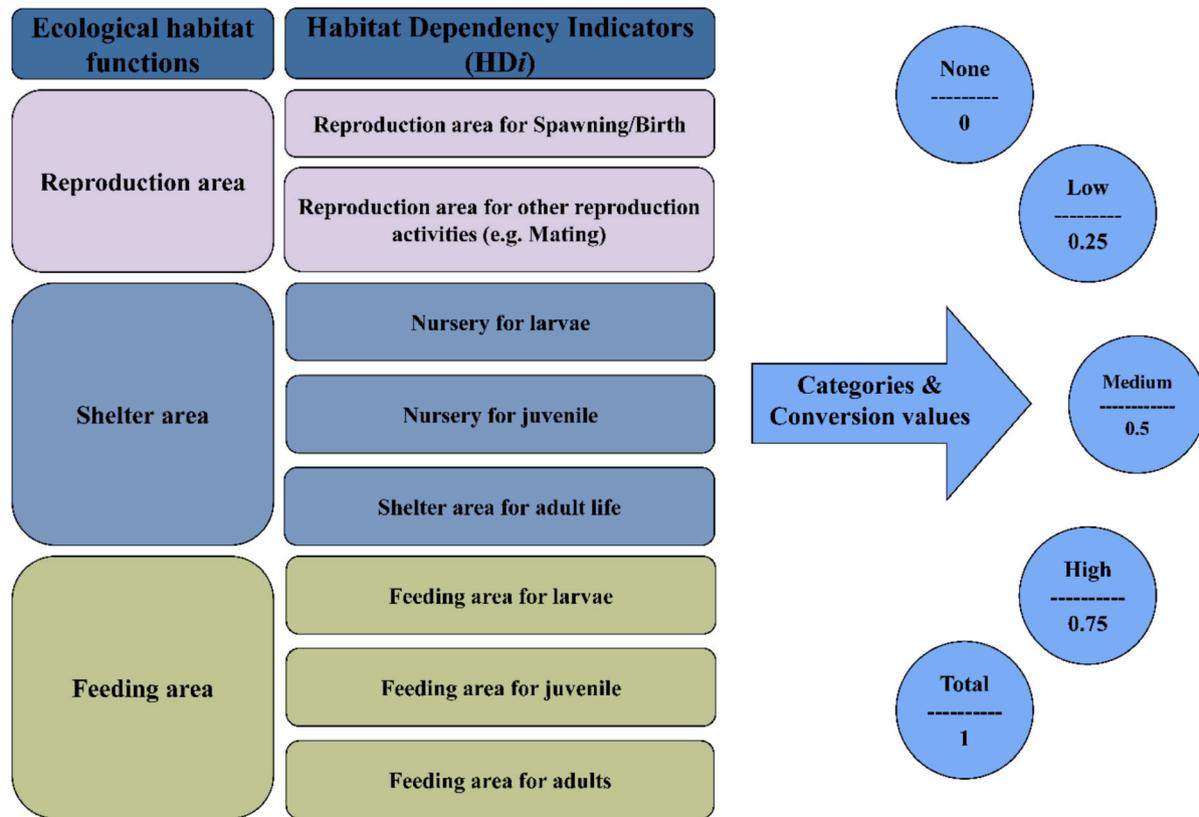


Fig. 2. Habitat dependency indicators for invertebrates, fishes (sharks included), and tunicates showing: i) the ecological habitat function valued, ii) their respective indicators according to life cycle stages of the species, and iii) the potential categories to assign to each indicator with their respective transformation values. Definitions of each item are detailed in the Appendix 1, Supplementary Information.

Table 1

Categories and index values of the Habitat Dependency Index (HDI) with their respective description attributes. * When one indicator is valued with “complete dependency”, and the confidence value is “high”, the final value will automatically be set to “1”.

Habitat Dependency Index (HDI)	Index values	Attributes
Complete dependency	0.76–1*	The species’ survival is fully dependent on the habitat. One or more life stages depend critically on the habitat and cannot complete its life cycle without it. If the habitat disappears, so does the species.
High dependency	0.51–0.75	The species is highly, but not critically, dependent on the habitat. One or more life stages depend strongly on the habitat, so a change in the habitat would severely affect the species. The species may be able to substitute the habitat with other habitats of similar characteristics.
Moderate dependency	0.26–0.50	The species is moderately dependent on the habitat. Changes in the habitat would not lead to major changes for the species. These species are often generalists and can be found in several habitats.
Low dependency	>0–0.25	The species has low habitat dependency, and changes in the habitat would only lead to minor changes for the species. The species is found in the habitat but develops its life cycle mostly in other habitats.
No dependency	0	The species has no dependency on the habitat. Changes in the habitat will have no consequences for the species.

and S3, [Supplementary Information](#) and [Supplementary Notes 1](#)). Each indicator is assessed on a qualitative 5-category scale: none, low, medium, high, and complete dependency, based on available evidence. A conversion ordinal scale transforms indicator categories to a common scale of dependency, from 0 to 1, with 0 being the lowest dependency and 1 the highest (Fig. 2; see Table 2 for detailed definitions). Aggregating indicators into a single HDI value for each species allows for comparisons across species and habitats. There are several ways to aggregate the indicators into the HDI, the simplest of which is to use the means of the three habitat-functions-averaged indicators, weighted by the number of indicators used to estimate the dependency of each function, following Equation (1):

$$HDI_{weighted\ average} = \frac{2*HDI_{reproduction} + 3*HDI_{shelter} + 3*HDI_{feeding}}{8} \quad (1)$$

where *i* is each of the indicators by habitat function. This approach

reflects the average dependency of the species across feeding, shelter and reproduction functions, maintaining equal importance among the indicators and habitat functions, simplifying interpretation of the HDI.

Another approach to aggregating the indicator values could be to use the product of habitat-functions-averaged indicators, following Equation (2):

$$HDI_{product} = 1 - ((1 - (\overline{HDI}_{reproduction})) \times (1 - (\overline{HDI}_{shelter})) \times (1 - (\overline{HDI}_{feeding}))) \quad (2)$$

where *i* is each of the indicators by habitat function. This approach could be meaningful where dependency propagates through successive life stages, emphasizing cumulative habitat dependency and life-stage interactions. Yet another approach could be to use the maximum value among all indicators as this would emphasize the most critical dependency, regardless of other indicators. In any case, as the indicators

Table 2
Description of how to select the correct category of each HDI.

Categories	Conversion values	Description of how to select the correct category for each Habitat Dependency Indicator
None	0	This category is selected when observed data confirm the species never uses the habitat for the activity during the assessed life stage.
Low	0.25	This category is selected when the species uses the habitat occasionally (e.g., <5–10 % of observations) for the development of this activity during the life stage assessed, without relying on it as a primary habitat. Observations indicate that the species predominantly occurs in other habitats during this life stage, with occasional presence in this habitat.
Medium	0.50	This category is selected when a species uses multiple habitats with similar frequency during the assessed life stage. Such species, often generalists, engage in the same activity across these habitats without showing a specific dependency on any one habitat.
High	0.75	This category is selected when the species primarily relies on the habitat for the development of this activity during the life stage assessed. While individuals may occur in other habitats at lower frequencies (e.g., <5–10 % of observations), the species shows a significant reliance on this habitat.
Total	1	This category is selected when the habitat is essential for the species' survival during the assessed life stage. This dependency is demonstrated by the species' inability to complete vital biological processes (e.g., reproduction, growth) without the habitat.

represent key stages of a species' life cycle, an indicator value of "complete dependency" implies that the species cannot persist without the habitat, and as such, the HDI should attain the maximum value (HDI = 1).

2.1. Uncertainty for the HDI

Indicators are also accompanied by a confidence category based on the quantity and quality of available evidence, translated into a confidence value from 0 to 1: no confidence, low confidence, medium confidence, and high confidence (more detail in [Table S4, Supplementary Information](#)). The confidence estimates for each individual indicator are used to calculate the uncertainty for the HDI and then, can be expressed as standard deviation or confidence limits. To do so, we used a beta distribution since it is defined on an interval [0, 1] that aligns with our confidence scales ([Gupta and Nadarajah, 2004](#)) and Monte Carlo simulations ([Smith, 2002](#)) to obtain the most probable value and the uncertainty (range including 99 % of the simulated values) of the HDI value for each species (but see [Supplementary Note 2](#) for a more detailed information).

2.2. Assigning dependency to each indicator

Indicator values should ideally be based on a review of all available information about possible habitat associations for each species. Evidence of dependency can include, but is not limited to: observations of presence (or absence) of the species in the habitat in field surveys, (e.g. diver observations, remote underwater video systems, environmental DNA), observations of foraging in the habitat (e.g. from gut contents or stable isotopes), observations of reproduction occurring in the habitat, and experiments linking the species to the habitat (e.g., food preference experiments or predator avoidance experiments). The dependency at any life stage, on any of the habitat functions, may take different forms. For example, feeding functions can be fulfilled in several ways, such as the provision of a feeding area (e.g., coral reef for a predator) or providing the actual food items (e.g., coral reef for a corallivore). Importantly, the review of available information should not be restricted to the focal habitat alone but should also include alternative habitats with which the species could also be associated. A restricted focus could inflate the dependency value by overlooking the possibility that habitat functions could be provided by alternative habitats. Once all the information is obtained for all indicators, they are assigned to one of five dependency categories (none, low, medium, high, and total dependence; see [Supplementary Notes 3](#) for more detailed information).

The level of confidence associated with the indicator values can similarly be assessed from the extent and quality of available evidence used to assess each dependency category (see [Table S4, Supplementary Information](#)). No evidence for dependency would provide "No confidence". This is typically the case for poorly studied species without specific information about the habitat of their life stages. "Low

confidence" would refer to very limited scientific information, anecdotal knowledge, interviews, photo data with low confidence, information from grey literature sources or expert knowledge. For example, for rockfish with no information about their association with kelp forests, but with a distribution that overlaps with the distribution of kelp forests, they should be classified as having some dependency. "Medium confidence" would refer to information coming from, for example, scientific documents, public monitoring data and other information limited in space and time. Finally, when life stage information is well documented by scientific data in space and time, this would constitute "High confidence".

3. Habitat dependency of kelp forest species

To illustrate the application of the HDI, 36 species commonly associated with kelp forests were identified. These species encompassed a wide taxonomic range – including 5 mollusks, 7 crustaceans, 4 echinoderms, 13 fishes, 6 mammals, and 1 bird – representing diverse life histories and covering a broad geographical distribution. In addition, these species also represented different ecosystem services including fished species (provisioning services), endemic species (biodiversity services) and charismatic species (cultural services) ([Fig. 3 and Table S5, Supplementary Information](#)). To obtain information to assign indicator values, we conducted a systematic search using the Web of Science and Google Scholar, covering all databases, collections, and years between 1900 and 2022. For each species and indicator, we used the search terms "species name" combined with "kelp forest", "kelp bed", "habitat", "feeding", "feeding area", "reproduction area", "reproduction habitat", "feeding habitat", "shelter area", "shelter habitat", "larvae", "pups", "juvenile", "adult". For each species, documents were screened for relevant indicator information, focusing on titles and abstracts. Those passing the initial screening underwent further review. When possible, at least 10 references per indicator were used to assign the appropriate category ([Supplementary Data](#)).

The index captured and differentiated the dependency of species on kelp forests, detecting differences between species in different taxonomic groups and within the same genus ([Fig. 3; Table S6, Supplementary Information](#)). Focusing on individual indicators revealed that the most important function of kelp forests was as a shelter area for juvenile ($\overline{HDI}_{\text{juvenile}} = 0.49 \pm 0.07$; mean \pm mean standard deviation of simulated values) and adult ($\overline{HDI}_{\text{adult}} = 0.45 \pm 0.07$) individuals followed by feeding area ($\overline{HDI} = 0.47 \pm 0.07$ and 0.42 ± 0.07 , respectively). Kelp forests were also important habitats for reproduction as a spawning or birth area across the analysed species ($\overline{HDI} = 0.36 \pm 0.08$), and for other reproduction activities like mating ($\overline{HDI} = 0.35 \pm 0.07$). Mammals were dependent on kelp forests during their breeding; however, larval stages of other species were the least dependent on kelp forests ($\overline{HDI}_{\text{feeding}} = 0.24 \pm 0.06$ and $\overline{HDI}_{\text{shelter}} = 0.25 \pm 0.07$). Many marine groups have planktonic larval stages, so it is not surprising that

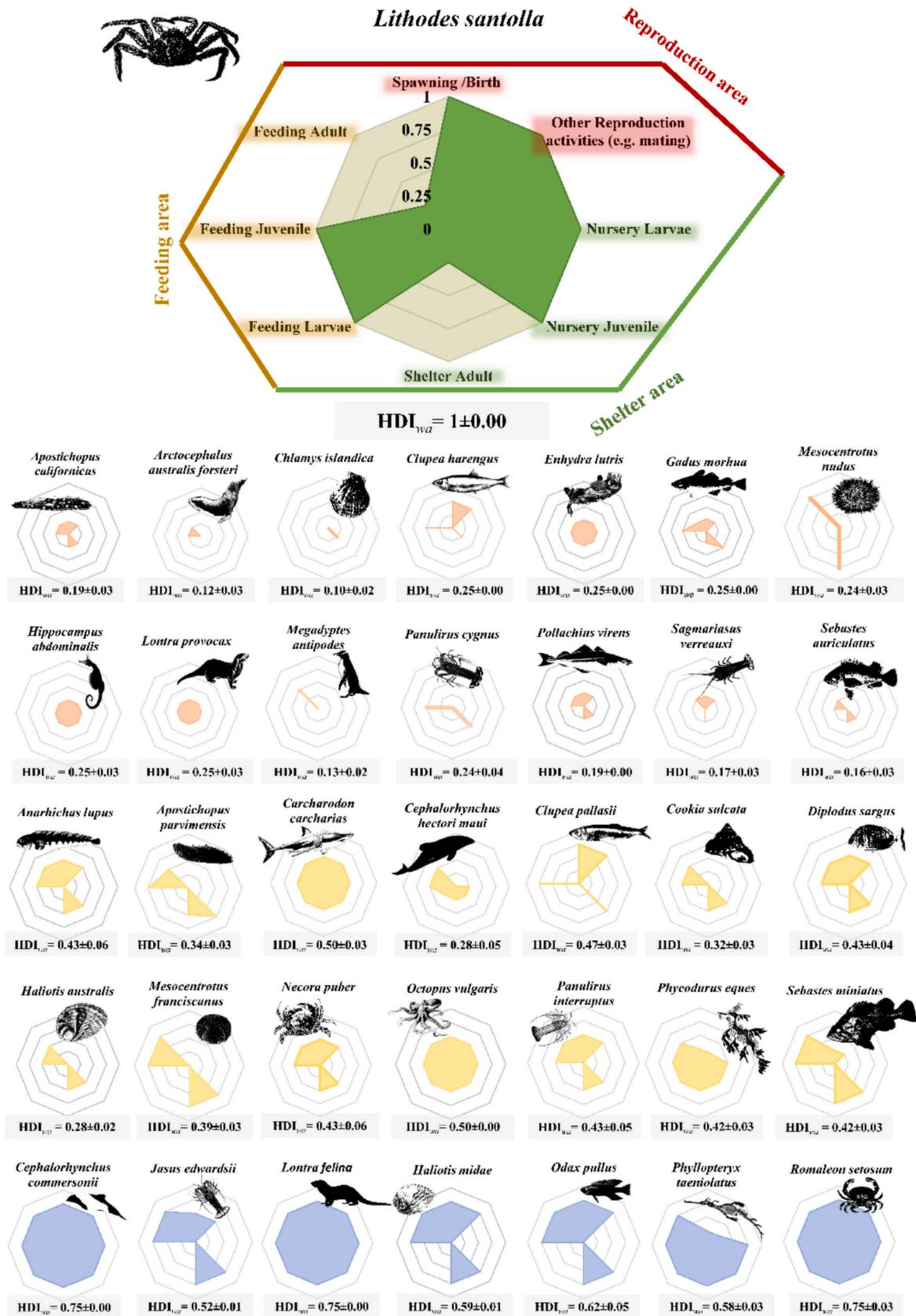


Fig. 3. Habitat dependency of kelp forest species. Spider plots represent the set of indicator values for each species, where the HDI is the weighted average (\pm standard deviation) of the estimated values). The *Lithodes santolla* plot serves as a key for all plots. Shaded areas within the plots correspond with the Habitat Dependency Index. Spider plots organized by dependencies: low (orange), medium (yellow), high (blue) and complete (green).

25 out of 36 species were not dependent on kelp forests during this phase (Houde et al., 2009, McEdward, 2020). Yet there were exceptions such as the crustacean *Lithodes santolla* which completes most of its life cycle activities in the kelp forest and is totally dependent on kelp during larval and juvenile stages (Fig. 3) (Tapella et al., 2012) or the rock lobster *Jasus edwardsii*, that depended on kelp forests for recruitment (Hinojosa et al., 2014).

Closely related species might be expected to have similar dependencies on kelp forests. However, the HDI differed substantially between taxonomic groups and across life histories, with species distributed across all index categories. The index discriminated against differences in habitat dependency, even between species of the same genus. For example, the dolphins *Cephalorhynchus hectori maui* ($HDI_{wa} = 0.28 \pm 0.05$) and *Cephalorhynchus commersonii commersonii* ($HDI_{wa} = 0.75 \pm 0.05$), and the abalones *Haliotis australis* ($HDI_{wa} = 0.28 \pm 0.02$) and *Haliotis midae* ($HDI_{wa} = 0.59 \pm 0.01$) showed contrasting HDI's. Similar differences were found for sea otters (*Lontra provocax* vs. *Lontra felina*), sea cucumbers (*Apostichopus californicus* vs. *Apostichopus parvimensis*), and fishes (*Clupea harengus* vs. *Clupea pallasii*) (Fig. 3). Commercial species such as lobsters and rock fishes are commonly associated with kelp forests, however, HDI_{wa} scores revealed that these associations do not always imply a high dependency. For example, rocky lobsters *Panulirus cygnus* ($HDI_{wa} = 0.24 \pm 0.04$), *Sagmariasus verreauxi* ($HDI_{wa} = 0.17 \pm 0.03$) have low dependency while *Panulirus interruptus* ($HDI_{wa} = 0.43 \pm 0.05$), and *Jasus edwardsii* ($HDI_{wa} = 0.52 \pm 0.01$) have moderate and high dependency respectively. Similarly, the rockfish *Sebastes auriculatus* ($HDI_{wa} = 0.16 \pm 0.03$) has low dependency, whereas *Sebastes miniatus* ($HDI_{wa} = 0.42 \pm 0.03$) shows moderate dependency.

3.1. Comparisons among approaches

The analysis of 36 species revealed distinct patterns of kelp forest dependency across three estimation approaches. The mean dependency values were $HDI_{wa} = 0.38 \pm 0.03$ (mean \pm mean standard deviation of simulated values), $HDI_p = 0.70 \pm 0.05$, and $HDI_{max} = 0.53 \pm 0.08$. HDI_{wa} and HDI_{max} approaches showed similar dependency distributions, with most species falling into low ($n = 14$ and $n = 10$, respectively), moderate ($n = 14$ and $n = 13$), and high ($n = 7$ and $n = 12$) dependency categories, and only one species (*Lithodes santolla*) exhibiting complete dependency on kelp forests (Fig. S1; Table S6, Supplementary Information). In contrast, the HDI_p approach demonstrated a marked shift towards higher dependency, classifying 17 species as completely dependent on kelp forests and the remaining species showing either high ($n = 11$) or moderate ($n = 8$) dependency, and none categorized as having low dependency. The multiplicative effect of the HDI_p approach increase significantly the HDI value in all species in contrast to the other approaches. Most species with low dependency in the HDI_{wa} and HDI_{max} approaches, had moderate or high dependency with HDI_p. For instance, the sea otter (*Enhydra lutris*) and the seahorse (*Hippocampus abdominalis*) both have HDI_{wa} and HDI_{max} values of 0.25 ± 0 , while their HDI_p values are 0.58 ± 0 . This pattern is consistent across species, with those showing moderate or high dependency in HDI_{wa} and HDI_{max} often classified as having complete dependency under HDI_p. For example, *Cookia sulcata* has moderate dependency according to the HDI_{wa} (0.32 ± 0.05) and HDI_{max} (0.50 ± 0) approaches, while showing high dependency using the product approach ($HDI_p = 0.69 \pm 0.03$). Similarly, *Clupea pallasii* showed moderate dependency with the HDI_{wa} approach (0.47 ± 0.03) and high dependency with the HDI_{max} approach (0.75 ± 0.10) but shows complete dependency using the product approach ($HDI_p = 0.89 \pm 0.03$).

4. Applications for the HDI

Understanding the relative dependency of species on their habitat is important in many fields of science and management, where the HDI could provide a useful metric (Hughes et al., 2009, Sievers et al., 2019,

McCormick et al., 2021). In conservation biology, for example, the HDI could be used to rank the potential risk to species from habitat loss. This would be relevant for species included in the IUCN Red List of Threatened Species under different categories of conservation status, such as charismatic and endemic species. For instance, all charismatic species included in our assessment of kelp forest species are also included in the IUCN Red list (Table S5, Supplementary Information). In this context, understanding their habitat dependencies would enhance their IUCN assessments to better understand the risk of extinction and guide the identification of critical habitats for conservation efforts (Sievers et al., 2019).

The HDI can also be applied to economic valuation of ecosystem services linked to known species, including provisioning services like commercial and subsistence fisheries, as well as cultural services such as recreational fishing and wildlife watching (Table SN1, Supplementary Notes 4) (Bouma and Van Beukering, 2015, Pascoe et al., 2016, McCormick et al., 2021). The absence of standardized methods to accurately attribute economic values to habitats often leads to over-simplification, assuming that all species inhabiting the same area are equally and entirely reliant on that habitat (Stål et al., 2008, Jänes et al., 2020). This assumption can lead to substantial over-estimation of a habitat's economic value based on the presence of species that may not be critically dependent on the habitat, and an under-estimation when the habitat plays a crucial role in supporting species during specific life stages where those species are not consistently present or easily observable in the habitat itself (National Research Council, 1999). Thus, economic values can be adjusted using the HDI to only attribute the proportion that is dependent on the habitat in question (see Supplementary Notes 4 for more information on how to apply the HDI to economic valuations) (Bouma and Van Beukering, 2015, Jackson et al., 2015, Pascoe et al., 2016, McCormick et al., 2021).

Ecosystem-Based Management usually does not consider species-habitat dependency and life cycle knowledge and, as a consequence, over- or underestimate the relative importance of different habitats (Lauria et al., 2015). The HDI could therefore provide valuable data for distribution and habitat suitability models, which often require detailed information about species-habitat relationships, helping to improve their accuracy and predictive power (Jones and Cheung, 2015, Lauria et al., 2015). In vulnerability and risk assessments, the HDI could be useful to understand the potential impacts of different threats or management actions on species based on their dependency on particular habitats (Chin et al., 2010, Jones and Cheung, 2015, Lauria et al., 2015, Yoshikawa et al., 2023). Finally, the HDI can be integrated into spatial planning practices to identify high conservation value areas and manage human activities. For example, by highlighting regions with high HDI scores, planners can prioritize critical habitats essential for species survival, ensuring they receive appropriate conservation measures such as the designation of marine protected areas (Dunsworth and Northway, 1998, Stagoll et al., 2010).

Adapting the Habitat Dependency Index to terrestrial ecosystems would be straightforward. Like marine species, terrestrial species depend on habitats for key functions including reproduction, shelter, and feeding at different stages of their life cycle. However, the indicators would need to be adapted according to the specific biological context. For example, to address the unique life cycles of terrestrial arthropods, which exhibit two distinct types of developmental pathways, indicator tables would require tailoring to accurately capture habitat dependencies for both pathways: species with gradual metamorphosis (e.g., grasshoppers) undergo three life stages (egg, nymph, and adult) each with distinct habitat requirements (Latchinsky et al., 2011). Species with complete metamorphosis (e.g., butterflies) go through four life stages (egg, larva, pupa, and adult; Gilbert and Singer, 1975). These stages often involve drastically different ecological niches and habitat needs where, for instance, larvae may rely on specific host plants for feeding, while adults may depend on entirely different habitats for mating and dispersal.

5. Limitations of the HDI

Despite its utility in quantifying habitat dependencies, the HDI also has assumptions and limitations which can vary based on the chosen aggregation method. For example, the HDI_{wa} approach assumes equal importance among indicators which may not fully capture the complexity of species-habitat relationships in some circumstances. This assumption could lead to underestimating critical dependencies at specific life stages, life stage transitions or for particular habitat functions. For instance, reproduction area might be more critical than shelter for some species, while shelter area could be vital for others (Sievers et al., 2019). On the other hand, the HDI_p approach could capture multiplicative effects of habitat dependency emphasizing critical dependencies. However, assuming that dependencies are multiplicative rather than additive, may not accurately reflect ecological realities for many species. For example, generalist species with medium values across multiple indicators may receive higher HDI_p scores, potentially leading to misclassification of their actual habitat dependencies. Finally, using the HDI_{max} approach could emphasize critical habitat dependencies, providing a conservative estimate and highlighting key vulnerabilities. Nonetheless, it may overestimate overall dependency, lose information across life stages, and reduce species differentiation.

Another limitation is the lack of data or other information on how habitats are used for many marine species. The index depends on this information for all species and indicators, thus, gaps in availability of data or differences in data quality can lead to over- or underestimation of habitat dependency for some species, complicating comparisons between species and propagation of unknown errors. Moreover, due to the complexity of the ecological associations, the index is unlikely to fully capture the intricate, dynamic and scale-dependent nature of these relationships. For example, the HDI may not reflect the consequences of habitat loss at small scales or over a short duration, and the scales and time windows where it does are likely to vary across species and environments. Complicating matters further, large-scale habitat loss from marine ecosystems are often also associated with abiotic changes (e.g. loss of kelp forest after MHWs where larval influx, water temperature and turbidity also change) (Steneck et al., 2002, Wernberg et al., 2016, Norderhaug et al., 2020a).

One of the key aspects of species' habitat dependency that remains unresolved is the potential for strong intraspecific variation among populations. Cod, for example, have distinct ecotypes (Sodeland et al., 2022) with different dependencies on kelp forests. Coastal cod more or less completes its entire life cycle on the inner coast where kelp forests dominate (Norderhaug et al., 2020b), while North Sea cod spawns offshore (Sodeland et al., 2022) far away from kelp forests. Therefore, regional or population-level assessments of habitat dependency may be required for some species.

6. Future research directions

Here, we developed an index to determine the habitat dependencies for a number of species linked to kelp forests. Future research should focus on extending these dependencies to a broader range of species associated with kelp forests and other major habitats. In particular, determining habitat dependencies for other major marine habitats would enhance our understanding of their ecological importance and inform conservation and restoration efforts. Future research should also focus on refining and validating the indicators using ecological monitoring data to provide empirical evidence supporting the utility of the index and its application. One approach could be to use historical monitoring data to test if HDI estimates align with observed habitat and species changes. Such validation would strengthen the HDI's value as a predictive tool for conservation and management.

7. Conclusions

The Habitat Dependency Index (HDI) provides a standardized method to compare habitat dependencies across species and regions, offering transparent measures of known uncertainty. Ecological studies often equate species presence with habitat dependency, primarily focusing on adults (Efford and Dawson, 2012). The strength of the HDI comes from its comprehensive consideration of key ecological functions (feeding, space, and reproduction) across species' life stages, reflecting the complex nature of species-habitat relationships. Furthermore, the HDI incorporates confidence categories based on the quality of available evidence, thus improving upon traditional assessments. While some methodologies quantify dependency using residency indices (for fish) or stable isotopes (for consumer-resource relationships), the former are limited to fishes (Scott et al., 1999), while the latter are constrained by available isotopic data, primarily focus on adult life stages (Jänes et al., 2020), and the spatiotemporal variation limits the ability to compare results in time and space. Additionally, in areas where habitats are difficult to differentiate, it may be difficult to clearly distinguish the absolute contribution of each habitat to the species (Hindell, 2006, Connolly and Waltham, 2015, Jänes et al., 2020).

This index is designed to be intuitive, enabling easy interpretation for both specialists and non-specialists. The HDI is flexible and can be used across different spatial scales. This aspect allows for ecosystem services calculations to be comparable between regions, making the HDI particularly valuable for international economic and climate policy, and conservation strategies (Druckenmiller, 2022). Still, the flexibility of the overall index approach to using different calculation methods enhances its utility and adaptability for different research questions to be addressed. The HDI represents an important step forward in quantifying the degree to which species rely on specific habitats, offering a robust and objective tool for ecosystem managers, policymakers, and researchers to make more detailed decisions about the importance of habitats, their conservation or ecosystem valuations, thereby contributing to more effective and sustainable management of our ecosystems.

CRedit authorship contribution statement

Cristina Piñeiro-Corbeira: Led the Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Johanna Zimmerhackel:** Writing – original draft, Investigation, Conceptualization. **Rodolfo Barreiro:** Writing – review & editing, Formal analysis. **Scott Bennett:** Writing – review & editing, Investigation, Data curation. **Michael Burton:** Writing – review & editing, Investigation, Data curation. **Aaron M. Eger:** Writing – review & editing, Investigation, Data curation. **João N. Franco:** Writing – review & editing, Investigation, Data curation. **Camille Lavoie:** Writing – review & editing, Investigation, Data curation. **Laura Rogers-Bennett:** Writing – review & editing, Investigation, Data curation. **Samuel Starko:** Writing – review & editing, Investigation, Data curation. **Mads Thomsen:** Writing – review & editing, Investigation, Data curation. **Karen Filbee-Dexter:** Writing – original draft, Visualization, Supervision, Investigation, Data curation, Conceptualization. **Kjell Magnus Norderhaug:** Writing – original draft, Visualization, Supervision, Investigation, Data curation, Conceptualization. **Thomas Wernberg:** Writing – original draft, Visualization, Supervision, Project administration, Investigation, Funding acquisition, Data curation, 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.ecolind.2025.113612>.

Data availability

Data will be made available on request.

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