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SCIENCE FOR OCEAN ACTION

MPAs in relation to Climate Change for Northern Ireland

A report commissioned by Ulster Wildlife

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Ulster Wildlife

Foreword

Marine Protected Areas and the future with Climate Change in Northern Ireland?

Climate change is reshaping our seas, from warmer waters to changing ocean chemistry, making it harder for sensitive species to thrive. Northern Ireland's Marine Protected Area (MPA) network helps safeguard precious habitats and species. This report examines if the current Marine Protected Areas are located in the best places, which are likely to stay suitable as the climate changes. By mapping areas where the ocean is more likely to stay stable, called climate change refugia, and those that are more at risk, known as hotspots, it recommends ways to improve protection by:

- Expanding MPAs to cover climate-resilient zones
- Helping understand the most vulnerable species and areas
- Using evidence and collaboration to plan smarter

To protect marine life into the future, we need smarter, joined-up conservation that's guided by climate science—and grounded in real action from leaders, communities, and scientists alike. To ensure greater protection of the marine environment we must:

- Strengthen climate resilience in MPA design
- Prioritise climate-vulnerable species and habitats
- Integrate climate change into MPA monitoring & decision-making
- Facilitate cross-sector and cross-border collaboration
- Encourage strategic planning and investment
- Communicate and engage

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Executive summary

This study was commissioned to provide novel insight into the potential for climate-smart Marine Protected Area (MPA) management in Northern Ireland's marine waters, a criterion which had not yet been assessed in detail. We build on the knowledge that climate change is experienced by marine organisms through changes in many ecosystem conditions simultaneously. This co-occurrence of multiple stressors can lead to an underestimation of climate change vulnerability of a particular site when only ocean warming is considered, and thus lead to ineffective conservation. Designing and managing MPA sites and networks that can be effective in an ocean under multiple climate stressors therefore necessitates holistic vulnerability analyses. Accordingly, we estimate here how climate-driven ocean change (across various ocean characteristics) affects the conditions required by species and habitat features of higher interest to the Northern Ireland MPA network. Specifically, we assess the climate-resilience of MPA sites, seabed and megafauna features.

We estimate that almost 50% of Northern Ireland's marine waters may be climate-resilient areas, which harbour biogenic and non-biogenic habitats in MPAs, and unique seabed communities occurring within broadscale, non-biogenic habitats. Six of Northern Ireland's MPAs are either located in or largely overlap climate-resilient areas of the seabed. However, the majority (18 of 24) overlap in a much smaller extent or not at all with climate resilient-areas. We also found that 78% (14 of 18) of seabed habitat features have low climate-resilience or are climate vulnerable, and all marine mammal and seabird species rely on areas that are climate-vulnerable. This suggests that the current MPA network is not providing climate-resilient protection to the majority of marine species features in Northern Ireland.

We further assessed which other areas could be explored in the future to increase the resilience of the MPA network, and of its species and habitats, to climate change. In some cases, careful consideration of trade-offs and synergies with maritime sectors may provide a way forward. In other cases, careful monitoring, reduction of other human pressures and strong global action on greenhouse gas emissions may the most important route to a sustainable and thriving marine ecosystem in Northern Ireland.

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1. Introduction

Marine ecosystems are highly dynamic and determining whether climate change is a driver of changes in habitat conditions, or of species distributions, requires careful assessment of both environmental and species mean trends over time, as well as their variability (Hawkins and Sutton 2012). For these reasons ocean climate modelling (i.e. physical and biogeochemical modelling; species distribution modelling; ecosystem modelling) that can be used to generate past and future projections of those variables is a powerful decision-support tool for those designing and assessing the status of Marine Protected Areas (MPAs). Specifically, modelling can be used to help practitioners design MPAs that are adaptive to the effects of climate change (i.e. climate-smart MPAs, McLeod, Salm et al. 2009), or to assess the potential climate-resilience of currently designated MPAs.

Long-term warming patterns, as well as the response of species and habitats of interest to this change, are beginning to be considered in MPA management (Kyprioti, Almpanidou et al. 2021, D'Agata and Maina 2022). However, climate change is experienced by marine organisms through changes in many more ecosystem attributes simultaneously. These attributes include extreme weather events such as heatwaves and cold snaps, ocean acidification, deoxygenation, and changes in productivity and circulation patterns, all occurring at different speeds and with different magnitudes over space and time (Henson, Beaulieu et al. 2017, Pörtner, Roberts et al. 2019). These so-called multiple-stressors can act synergistically or antagonistically, with species and ecosystem function responses not necessarily predictable from the analyses of the distribution of individual stressors alone (Queirós, Fernandes et al. 2015, Hewitt, Ellis and Thrush 2016). Locally, this can lead to an underestimation of the vulnerability of a particular site to climate change and thus to ineffective conservation: in the tropics but also in temperate regions, including across the North East Atlantic (Bieg, Vallès et al. 2024). Designing and managing MPA sites and networks that can be effective in the face of a multiple-stressor ocean under the pressure of climate change therefore necessitates more holistic vulnerability analysis of how MPA features are affected in these various ways, simultaneously (Queirós, Talbot et al. 2021).

1.1 MPA vulnerability assessment: ecosystem-level climate signal detection

In recognition of the multi-faceted pressure of climate change on wild species and habitats, multiple methods have emerged in the scientific literature to support MPA design and management. Of critical concern is the identification of areas where the speed and magnitude of climate-driven change is likely to cause substantial ecological impacts that render MPAs ineffective. Such areas are frequently referred to as “climate change hotspots”, and several methods exist for their estimation. Of equal value to MPA siting and management, are areas where the pace and magnitude of climate-driven change is more limited, and especially climate-resilient sites, frequently referred to as “climate change refugia”. Differences between methods can cause ambiguity in between-study comparisons, and in the inference of ecological significance where climate change hotspots or refugia or climate-resilient sites are identified. It is therefore seen as best-practice to employ statistically objective approaches in calculations and the use of transparency in the communication of the criteria employed to estimate the location of such sites.

In all cases, estimation of climate-change sensitivity can be done backward- and forward-looking. In the first instance, observational time-series datasets can be used, whilst future change can only be assessed via modelling projections.

In this study, we employ spatial meta-analysis of ocean climate modelling time series. This is a peer-reviewed, statistically defined method, co-developed with practitioners, and which has been widely employed to assess where and when climate-driven ocean changes present significant ecosystem shifts affecting species and habitats, in support of MPA management and Marine Spatial Planning (Queirós, Huebert et al. 2016, Queirós, Talbot et al. 2021, Queirós, Kay et al. 2024, Queirós, Talbot et al. 2024, Queirós, Talbot et al. 2024, Talbot, Jontila et al. 2024). In contrast with other methods, this approach allows for the investigation of the effects of climate change as a multiple-stressor process experienced by multiple species and habitats. Specifically, multiple modelling time-series datasets are first selected to as accurately as possible represent the ecosystem conditions needed by species or habitats groups of interest to an MPA site or network. By determining the current conditions (i.e. the last 20 years) under which species and habitats

occur, the time-series are then analysed together to estimate if and when, at the ecosystem level, each site enters a new climate-driven state that exceeds the expected natural variability of conditions at present and whether those changes are consistent with climate trends. For instance: where temperatures exceed the historical variability at the site, pH is substantially lower than what is observed now, dissolved oxygen is substantially lower than at present, and so on for all datasets deemed necessary for inclusion in a given analysis. The greater the departure in individual variables from the present conditions, and the greater the number of variables for which this occurs, the stronger the climate signal emerging at the ecosystem level (Queirós, Talbot et al. 2021).

With all datasets analysed together, this method delivers an objective classification of sites as:

i) **Climate change refugia** (climate-sensitive sites, where present variability is not exceeded when all variables are taken together);
ii) **Climate change hotspots** (where present variability is exceeded consistently with climate trends); or
iii) **Bright spots** (sites where conditions improve temporarily, despite long-term regional climate trends).

Under this method of analysis, climate change hotspots exhibit a marked departure from current conditions; they represent sites entering a new ecosystem state consistent with expected climate change trends, and as such, species, habitats or level of ecosystem function observed in the present may not be observed in the future. Hotspots are not necessarily deemed to have no value for conservation, because modelling methods do not estimate whether species will be able to adapt fast enough to a changing environment. Indeed, this potential is poorly quantified in nature, but such an outcome seems unlikely given the speed of climate change and current patterns of biodiversity loss (Pörtner, Scholes et al. 2021). Similarly, climate change refugia in turn represent areas where future ecosystem function and species diversity may be comparable to the present day, in the future. Bright spots are a third category of sites estimated by this method, indicating where a new ecosystem state also emerges at a site, but where observed trends are not in line with the predominant climate change trends in the

region (e.g. cooling when warming is expected; species abundances increasing when decline is expected).

These three different outcomes reflect local scale differences in the rate and direction of change in environmental conditions motivated by differences in the expression of climate change processes as a whole, and will affect whether an MPA is likely to continue to host the same species and habitats it was designated to help conserve. In all cases, the ecosystem state is defined by all the variables selected for analysis, and the classification is time-bound by the selection of the (20-year) periods contrasted.

Furthermore, the climate-resilience of sites is in this way defined as a result of explicit statistical criteria, detailed in Queirós (2021). In summary, the method takes into account the current and future mean of each variable analysed, their variability, how many years are included to define the present and the future state, and how the change in each variable relates to the overall change, across all datasets.

Once the climate change vulnerability assessment of the region of interest is carried out in this way, the location of identified climate change refugia becomes especially important in MPA management. Specifically, where refugia overlap with currently designated sites, they indicate areas where conservation is likely to continue to deliver the same level of protection offered at present because a similar ecosystem state (or species occurrence pattern) is expected to be present in the future. Climate change refugia identified in areas outside of the MPA network, where species and habitats of conservation interest co-occur, may also offer the opportunity to consider whether new boundaries for a site (or indeed new sites within a network) may be of interest to deliver effective conservation of a (given set of) features, given the local expression of climate change. This approach was co-developed with practitioners to help understand the natural resilience of sites to climate change and help deliver effective conservation action into the future.

2. Assessing the future of Northern Ireland's MPAs under climate change

Building on previous assessments, this study was commissioned by Ulster Wildlife to provide novel insight into the potential for climate-smart MPA management in Northern Ireland's marine waters, a criterion which had not yet been assessed in detail.

The Northern Ireland MPA network is estimated to cover around 36% of its waters, and includes 48 sites under five types of designation: Special Areas of Conservation ("SAC"); Special Protection Areas ("SPA"); Marine Conservation Zones ("MCZ"); Areas of Special Scientific Interest ("ASSI", intertidal only); and RAMSAR sites (protecting coastal wetlands). This report focuses on the 24 truly marine sites within the network (SAC, SPA and MCZs, 35.5% of Northern Ireland's waters, 2,420 km^2), which include: 20 sites covering 2,022 km^2 of inshore waters; and 4 sites covering 398 km^2 of Northern Ireland's offshore waters. Of these, 1 site spreads across Northern Ireland's inshore and offshore waters (North Channel SAC). We consider that the site spread across Welsh and adjacent to Northern Irish offshore waters (North Anglesey Marine/Gogledd Môn Forol SAC) is not part of the NI MPA network.

Focusing on Northern Ireland's MPAs, this study then delivers three objectives:

> **Objective i.** Assess the potential for climate-resilient marine conservation in Northern Irish waters.
>
> **Objective ii.** Climate change gap analysis of features.
>
> **Objective iii.** Identify potential areas for future MPA assessment.

2.1 Data and methods

We applied the modelling data analysis methods described in Section 1.1 to Northern Ireland's marine waters. Here, MPAs are predominantly designated for benthic species and habitats, but special cases include designations to protect marine megafauna species, such as: *Cepphus grille* (black guillemot, bird); *Halichoerus grypus* (grey seal, marine mammal); *Phoca vitulina* (harbour seal, marine mammal); and *Phocoena phocoena* (harbour porpoise, marine mammal). Correspondingly, we analysed modelling datasets representative of environmental drivers of Northern Ireland's benthic habitats that are affected by climate change and, separately, datasets representative of the

pelagic environmental drivers and prey fields affecting those pelagic megafauna species.

Each modelling dataset analysed is a time-series for a modelled variable resulting from simulations carried out with either an ecosystem model (a couple physical-biogeochemical model) or a multiple-species distribution model, where species compete for resources and respond to environmental drivers (Supplementary Information, Table A1). For each time point in the time-series, the value of each variable (e.g. temperature; the abundance of species x) is estimated across a grid which is a map of the marine waters of Northern Ireland. The specific data and time periods considered are further detailed in Supplementary Information. This data had been previously analysed to estimate the location and extent of long-term climate change refugia and hotspots (Section 1.1), at the UK and Northern Ireland scales, publicly available in the report *Early Warning System: Climate-smart spatial management of UK fisheries, aquaculture and conservation* (2024, https://indd.adobe.com/view/4fdcfc0d-fd86-4365-8fcb-fed57e978f3a; for more information please see:

www.mccip.org.uk/all-uk/solutions/mspace
www.smmr.org.uk/funded-projects/marine-spatial-planning-addressing-climate-effects/.

All modelling datasets included in that study have been validated against observations in the marine waters of Northern Ireland and the result of that analysis can be found in www.mccip.org.uk/sites/default/files/2025-01/5.%20MSPACE_Report_EarlyWarningSystem_Annex1_V3.pdf

In the current report, we refined those analyses by estimating how the location of identified climate change refugia and hotspots for benthic habitats and pelagic megafauna relate to the distribution of MPAs in Northern Ireland, and their potential consequences for individual marine species and habitats of particular conservation importance. The group of species and habitats considered in the current study (hereafter, "features") builds on Cornwaithe et al. (2018), and on Queirós et al. (2024), in accordance with the UK MPA Features List.

Objective i: Assess the potential for climate-resilient marine conservation in Northern Irish waters.

First, we employed the peer-reviewed method described in Section 1.1 (Queirós, Talbot et al. 2021, 2024) to estimate the location and extent

of long-term climate change refugia for benthic species and habitats, and for pelagic megafauna, in Northern Ireland's marine waters. We considered the 0-200nm limit as the definition of marine waters, excluding intertidal and wetland habitats.

We then carried out more detailed analyses, comparing those distributions with observational datasets documenting the current distribution of benthic features and pelagic megafauna occurring in Northern Ireland's MPAs, including those used as designation criteria. This step provides a measure of the current level of climate-resilient conservation delivered by the current MPA network (site-based analysis).

Objective ii: Climate change gap analysis of features.

We then estimated, for each feature, the extent of their distribution for which the current MPA network provides climate-resilient conservation (feature-based analysis). That is, we estimated the overlap between the current distribution of each feature and that of long-term climate change refugia relevant for that specific feature, considering the contribution of each MPA site to that overlap (where possible). We identify a climate change gap where an estimated portion of the feature's distribution occurs in a climate change hotspot.

Objective iii: Identify potential areas for future MPA assessment.

We also estimated the location of sites outside the current MPA network, where features of conservation interest occur in climate change refugia.

2.2 Analyses summary

This study provides a forward-looking analysis of Northern Ireland's MPA network, contrasting the present 20-year time-period (2006-2025) with all subsequent 20-year time periods, to the end of the 21st century. In each analysis, two possible futures are considered, as described by greenhouse gas emissions trajectories. These Representative Concentration Pathways ("RCP"), as used by the Intergovernmental Panel on Climate Change (Van Vuuren, Edmonds et al. 2011), are described in Supplementary Information and represent two likely futures: a moderate global level of emissions (RCP4.5), and a global higher level of emissions (RCP8.5). Considering more than one RCP is necessary, as the degree of future action on climate change represents a source of "scenario uncertainty" in climate modelling (Payne, Barange et al. 2015).

All analyses employ the methods of spatial meta-analysis described in Section 1.2, which have been extensively used in similar peer-reviewed studies to help design climate-smart conservation and marine planning approaches (Queirós, Huebert et al. 2016, Queirós, Talbot et al. 2021, Queirós, Kay et al. 2024, Queirós, Talbot et al. 2024, Queirós, Talbot et al. 2024, Talbot, Jontila et al. 2024). A more detailed technical description of the statistical methodology used is provided in the Supplementary Information section.

3. Results

3.1 Objective i: Vulnerability of Northern Ireland's MPAs to climate change

We estimate that a total area of 3,182.2 km^2, equating to 46.7% of Northern Ireland's marine waters, may host climate-resilient benthic habitats as it harbours long-term (2026-2069) climate change refugia with high agreement between scenarios (RCP4.5 and RCP8.5, Figure 1). The remainder area is identified as a climate change hotspot for benthic habitats (Figure 1).

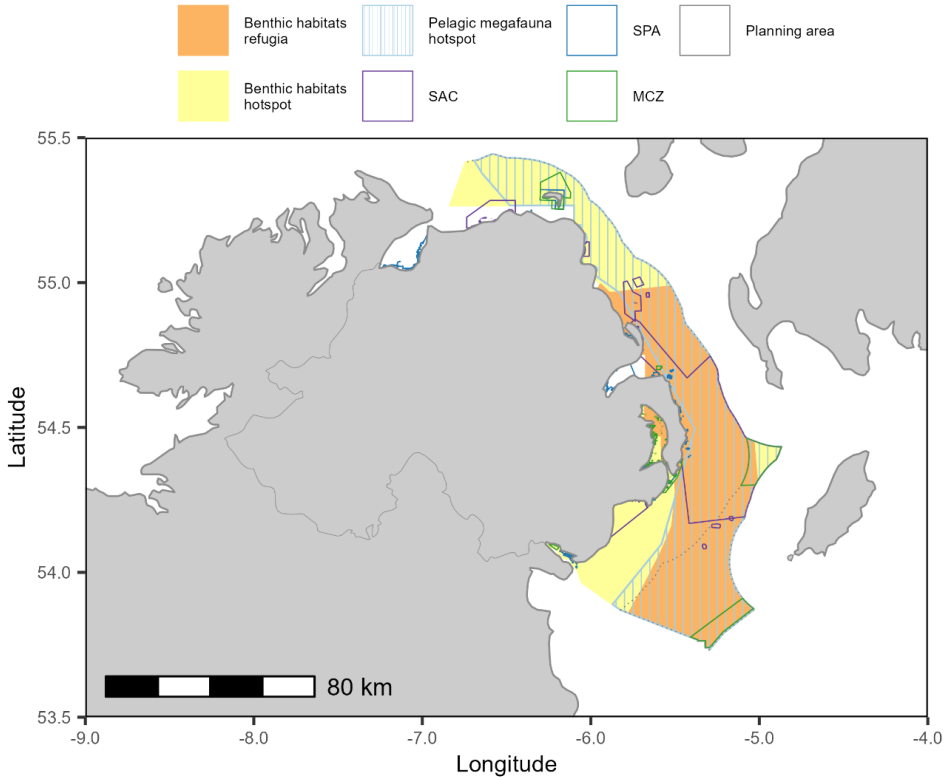


***Figure 1**: Areas hosting long-term climate change refugia and climate change hotspots in Northern Ireland's marine waters per feature group, with high agreement between emissions scenarios (RCP4.5 and RCP8.5), relative to the location of MPAs.*

This distribution affects all of the marine biogenic habitats in MPAs in Northern Ireland, both those created by animals as well as vegetated habitat (Supplementary Information Figures A1 and A2). Benthic hotspots also affect unique communities harboured by broadscale, non-biogenic habitats (Supplementary Information Figures A3-5).

The most climate-resilient MPAs with regard to benthic habitats overlap 100% with climate change refugia (Table 1): Queenie Corner MCZ; the Pisces Reef Complex SAC; and the Outer Belfast Lough MCZ (Figure 1). The Maidens SAC and the Strangford Lough MCZ and SAC overlap moderately with climate change refugia for benthic habitats (76% and 52-55%, respectively, Table 1). In the majority, benthic habitats overlap in a much smaller extent or not at all with climate resilient-areas, and no MPAs in Northern Ireland occur in climate change refugia for pelagic megafauna (Table 1).

Table 1: *Estimated climate-resilience of MPA sites in Northern Ireland.*

MPA name	Designating feature type	Area in benthic habitats refugia (km^2)/% of total MPA in benthic refugia	Area in pelagic megafauna refugia (km^2)/% of total MPA in megafauna refugia
Belfast Lough Open Water SPA	Pelagic megafauna	NA	0/0%
Carlingford Lough MCZ	Benthic habitats	0/0%	NA
Carlingford Lough SPA	Pelagic megafauna	NA	0/0%
Killough Bay SPA	Pelagic megafauna	NA	0/0%
Larne Lough SPA	Pelagic megafauna	NA	0/0%
Lough Foyle SPA	Pelagic megafauna	NA	0/0%
Murlough SAC	Pelagic megafauna and benthic habitats	0/0%	0/0%
North Channel SAC	Pelagic megafauna	NA	0/0%
Outer Ards SPA	Pelagic megafauna	NA	0/0%
Outer Belfast Lough MCZ	Benthic habitats	2.51/100%	NA
Outer Belfast Lough SPA	Pelagic megafauna	NA	0/0%
Pisces Reef Complex SAC	Benthic habitats	8.73/100%	NA
Queenie Corner MCZ	Benthic habitats	145.95/100%	NA
Rathlin Island MCZ	Benthic habitats	0/0%	NA
Rathlin Island SAC	Benthic habitats	0/0%	NA
Rathlin Island SPA	Pelagic megafauna	NA	0/0%
Red Bay SAC	Benthic habitats	0/0%	NA
Skerries and Causeway SAC	Pelagic megafauna and benthic habitats	0/0%	0/0%
South Rigg MCZ	Benthic habitats	55.62/39%	NA
Strangford Lough MCZ	Benthic habitats	85.12/52%	NA
Strangford Lough SAC	Benthic habitats	85.12/55%	NA
Strangford Lough SPA	Pelagic megafauna	NA	0/0%
The Maidens SAC	Pelagic megafauna and benthic habitats	56.7/76%	0/0%
Waterfoot MCZ	Benthic habitats	0/0%	NA

3.2 Objective ii: climate-resilient protection offered by Northern Ireland's MPA network to features of high conservation value

As expected, we found a high level of potential climate-change vulnerability of seabed habitats to climate change. 78% of seabed habitat features (14 of 18) were found to have low climate-resilience or to be climate vulnerable within their current distributional range. Of these, only 14% (2 of 14) have >30% of their climate resilient range inside the MPA network (Table 2).

When we assessed species features occurring in MPAs, including those used as designation criteria, we found that 33% (33 of 100) had moderate to high climate-resilience across their distribution (Table 3) by overlapping in 50% or more of their range with the corresponding type of climate change refugia (Figure 1). In turn, this indicates that 2 thirds of species features, 67%, have low climate-resilience or are climate-vulnerable, by overlapping in less than 50% of their range with the corresponding types of climate change refuge (Table 3). Only 12% (12 of 100) of the total species features have high or moderate climate-resilience where this occurs within the MPA network. For those 67 species features that were found to have low climate-resilience or to be climate-vulnerable across their distributional range, most (89%, 60 of 67 species) have less than 30% of that climate-resilient fraction of their range within MPAs (Table 3). This suggests the current MPA network is not providing climate-resilient protection to the majority of marine species features in Northern Ireland.

3.2.1 The most climate-resilient seabed habitats

Contrasting Figure 1 with the spatial distribution of seabed habitat features occurring in Northern Ireland's Marine Protected Areas, including those used as site designation criteria, we estimate the climate-resilience levels listed in Table 2.

No seabed habitat feature was found to occur in climate-resilient areas over 100% of their range in Northern Ireland. Seabed habitats found to occur with >80% or 50–80% in climate change refugia were identified as highly or moderately climate resilient. 22% (4 of 18) of features fell within this group, with all others (78%) co-occurring with refugia in less than 50% of their range. The former include Seapens and burrowing

megafauna; *Modiolus modiolus* beds; Low

energy circalittoral rock; and Subtidal mud. (Table 2). However, the fraction of the distribution of these habitats that is climate-resilient and occurs within MPAs is very low (0-26%). There is substantial opportunity to expand protection in resilient areas for: Seapens and burrowing megafauna; Low energy circalittoral rock and Subtidal mud. This indicates that even for the very few seabed habitat features that fitted the highest categories of climate-resilience found (moderate or high climate-resilience) the current MPA network is not fit for purpose. Patches of these habitats in unprotected climate-resilient sites leaves them open to other impacts.

3.2.2 The most climate-vulnerable seabed habitats

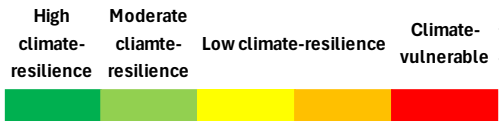
Based on Table 2, seabed habitats for which their Northern Ireland range was found to be less than 30% within benthic climate change refugia were classified as climate-vulnerable (Table 2). Less than 30% of the extent of the range of *Sabelaria alveolata* reefs and High energy circalittoral rock occur in climate-resilient benthic habitat. For *Philine aperta* and Virgularia mirabilis on infralittoral mud, Deep sea bed and Low energy infralittoral rock, that number is less than 3%. In addition, looking at all seabed habitat features, Only 11% (2 of 18) have >30% of their climate resilient range within the MPA network, while a further 11% have between 10% and 30% of their climate resilient range in the network. Some habitat features (*Philine aperta* and *Virgularia mirabilis* on infralittoral mud, Low energy circalittoral rock, Low energy infralittoral rock, Deep sea bed and Maerl) have 0% of their climate resilient ranges inside MPAs. That climate change affects most of the range of listed seabed habitats suggests that management of other human pressures will be extremely important alongside monitoring, to ensure strategies for their prevalence in Northern Ireland's waters into the future can be found.

3.2.3 The most climate-resilient species

The most climate-resilient species features identified have moderate to high climate-resilience, overlapping across their range in more than 50% or more than 80% (respectively) with the correct type of climate refuge. 33 species fitted these categories, with those potentially faring the best (>80% of range in a climate refuge, 7 species) including several species of sponges, molluscs and crustaceans (Table 3).

Table 2: *Climate-resilience of features occurring in Northern Ireland's Marine Protected Areas, including those used as site designation criteria. We suggest the colour scale bellow to help classify features based on their climate-resilience. The greater the extent of the habitat or species range inside climate change refugia, the greater the resilience. We consider that for a given level of overlap with climate change refugia, a feature is more climate-resilient if it occurs in an MPA as this will hopefully bring benefits in human activity management that can enhance climate-resilience.*

Climate change classification				
% feature in climate-resilient habitat	>80%	>50-80%	>30-50%	≤30%
% feature in climate-resilient habitat in MPA	>80%	>50-80%	>30-50%	≤30%
% feature in climate-resilient outside MPA	>80%	>50-80%	>30-50%	≤30%



Feature:	**MPA name**	**Present in MPA? (Y/N)**	**MPA designation criterion? (Y/N)**	**Area of climate-resilient feature (km²) /% of feature area in NI** (% NI waters (area) covered by climate-resilient feature)	**Area of climate-resilient feature in NI MPAs (km²)/ % feature area that is climate-resilient & protected** (% NI waters covered by climate-resilient & protected feature)	**Area of climate-resilient feature in NI outside MPAs (km²)/ % feature that is climate-resilient and unprotected** (% NI waters covered by climate-resilient unprotected habitat)
Subtidal *Mytilus* beds	Strangford Lough MCZ	Y	Y	3.45 / 44% (0.05%)	3.45 / 44% (0.05%)	0 / 0% (0%)
Seapens and burrowing megafauna	South Rigg MCZ	Y	Y	2403.15 / 82% (35.43%)	222.81 / 8% (3.28%)	2180.34 / 74% (32.146%)
	Strangford Lough	Y	N			
	Pisces Reef Complex SAC	Y	N			
	Queenie Corner MCZ	Y	Y			
Maerl	Red Bay SAC	Y	Y (Supplementary Information sandbanks	2.57 / 42% (0.04%)	0 / 0% (0%)	2.57 / 42% (0.04%)

			covered by water all the time)			
***Sabellaria alveolata* reef**	Skerries and Causeway SAC	Y	Y	26%*	9%*	16%*
	The Maidens SAC	Y	Y			
***Modiolus modiolus* beds**	Strangford Lough MCZ	Y	Y	5.16 / 50% (0.08%)	2.66 / 26% (0.04%)	2.51 / 24% (0.04%)
***Zostera* beds**	Strangford Lough MCZ	Y	Y	3.72 / 33% (0.05%)	3.72 / 33% (0.05%)	0 / 0% (0%)
	Waterfoot MCZ	Y	Y			
	Skerries and Causeway SAC	Y	Y (Supplementary Information sandbanks covered by water all the time)			
Deep sea bed	Rathlin MCZ	Y	Y	1.35 / 2% (0.02%)	0 /0% (0%)	1.35 / 2% (0.02%)
Low energy infralittoral rock	Strangford Lough MCZ	Y	Y	0.06 / 1% (0.001%)	0 (0%)	0.06 / 1% (0.001%)
Moderate energy infralittoral rock	Strangford Lough MCZ	Y	Y	1.41 / 43% (0.02%)	0.3 / 9% (0.004%)	1.1 / 34% (0.02%)
	The Maidens SAC	Y	N			
High energy infralittoral rock	Strangford Lough MCZ	Y	N	11.94 / 48% (0.18%)	0.35 /1% (0.005%)	11.59 /47% (0.17%)
	Rathlin MCZ	Y	N			
	Red Bay SAC	Y	N			
	Murlough SAC	Y	N			
	Skerries & Causeway SAC	Y	N			

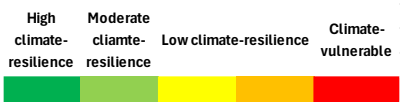
Low energy circalittoral rock	Pisces Reef Complex SAC	Y	Y (Supplementary Information Reef)	1.00 / 58% (0.01%)	0 / 0% (0%)	1 /58% (0.01%)
	Strangford Lough MCZ	Y	N			
Moderate energy circalittoral rock	Rathlin MCZ	Y	N	4.13 / 30% (0.06%)	1.42 / 10% (0.02%)	2.71 / 19% (0.04%)
	South Rigg MCZ	Y	Y			
	The Maidens SAC	Y	Y (Supplementary Information Reef)			
	Murlough SAC	Y	N			
High energy circalittoral rock	Rathlin MCZ	Y	Y	2.38 / 16% (0.04%)	0.007 / 0.2% (0.0001%)	2.37 / 15.8% (0.03%)
	Skerries and Causeway SAC	Y				
	Murlough SAC	Y	N			
Subtidal coarse sediments	South Rigg MCZ	Y	Y	748.22 / 37% (11.03%)	36.59 / 5% (0.54%)	711.63 / 32% (10.49%)
	Skerries and Causeway SAC	Y	Y (Supplementary Information sandbanks covered by water all the time)			
Subtidal sand	South Rigg MCZ	Y	Y	344.18 / 47% (5.07%)	18.29 / 5% (0.27%)	325.89 / 42% (4.8%)
	Red Bay SAC	Y	Y (Supplementary Information sandbanks covered by water all the time)			
	Waterfoot MCZ	Y	Y			
	Outer Belfast Lough MCZ	Y	Y			
Subtidal mud	South Rigg MCZ	Y	Y	2095.95 / 79% (30.9%)	173.22 / 8% (2.55%)	1922.73 / 71% (28.35%)
	Queenie Corner MCZ	Y	Y			
	Carlingford Lough MCZ	Y	Y			

Subtidal mixed sediments	South Rigg MCZ	Y	Y	171.33 / 49% (2.53%)	0.25 / 1% (0.004%)	171.09 / 48% (2.52%)
	Red Bay SAC	Y	Y (Supplementary Information sandbanks covered by water all the time)			
	Skerries and Causeway SAC	Y	Y (Supplementary Information sandbanks covered by water all the time)			
***Philine aperta* and *Virgularia mirabilis* on infralittoral mud**	Carlingford Lough MCZ	Y	Y	0 / 0% (0%)[Ŧ]	0 /0% (0%)	0 / 0% (0%)

*Distribution data is in point format – area cannot be calculated. % habitat resilient calculated as total number of occurrence records falling in refugia/total number of occurrence records in NI waters. % habitat resilient & protected calculated as total resilient records in MPAs/ total number of records in NI waters.
[Ŧ] Distribution map of habitat unavailable. Calculations based on area of MCZ in which the feature occurs.

Table 3: *Climate-resilience of species designated as Priority Marine Features (PMF) in Northern Irish waters (inshore and offshore), based on occurrence data. To ease the interpretation of our findings, we suggest the colour scale bellow to help classify features based on their climate-resilience. The greater the extent of the habitat or species range inside climate change refugia, the greater the resilience. We consider that for a given level of overlap with climate change refugia, a feature is more climate-resilient if it occurs in an MPA as this will hopefully bring benefits in human activity management that can enhance climate-resilience. Occurrence data downloaded from NBN Atlas March 2025, https://nbnatlas.org/.*

Climate change classification				
% species in climate-resilient habitat	>80%	>50-80%	>30-50%	≤30%
% feature in climate-resilient habitat in MPA	>80%	>50-80%	>30-50%	≤30%
% feature in climate-resilient outside MPA	>80%	>50-80%	>30-50%	≤30%



Priority Marine Feature	Group	MPA occurrence	Total occurrences in climate-resilient sites in NI / as % of total occurrences [a]	Total occurrences in climate-resilient sites inside NI MPAS / as % of total occurrences [b]	Total occurrences in climate-resilient sites outside NI MPAS / as % of total occurrences [c]
Ascophyllum nodosum var. mackayi	Alga - brown	Strangford Lough MCZ	5 /71.42%	5 /71.42%	0 /0%
Carpomitra costata	Alga - brown	Rathlin MCZ Red Bay SAC The Maidens SAC	16 /34.04%	15 /31.91%	1 /2.13%
Desmarestia dresnayi	Alga - brown	Rathlin MCZ The Maidens SAC	7 /50%	7 /50%	0 /0%
Atractophora hypnoides	Alga - red	Rathlin MCZ Carlingford Lough MCZ Red Bay SAC	1 /33.33%	0 /0%	1 /33.33%
Phymatolithon calcareum	Alga - red	Red Bay SAC The Maidens SAC Strangford Lough MCZ	43 /60.56%	7 /9.86%	36 /50.7%
Schmitzia hiscockiana	Alga - red	Rathlin MCZ Strangford Lough MCZ	5 /27.78%	4 /22.22%	1 /5.56%
Schmitzia neapolitana	Alga - red	Carlingford Lough MCZ	0 /0%	0 /0%	0 /0%

Stenogramme interrupta	Alga - red	Rathlin MCZ Strangford Lough MCZ Larne Lough SPA Red Bay SAC Skerries and Causeway SAC Waterfoot MCZ	73 /50.69%	17 /11.81%	56 /38.89%
Cepphus grylle	Aves	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Sterna hirunda	Aves	Strangford Lough SPA Carlingford Lough SPA Belfast Lough SPA	0 /0%	0 /0%	0 /0%
Sterna paradisaea	Aves	Strangford Lough SPA Outer Ards SPA Belfast Lough SPA	0 /0%	0 /0%	0 /0%
Sterna sandvicensis	Aves	Larne Lough SPA Strangford Lough SPA Carlingford Lough SPA	0 /0%	0 /0%	0 /0%
Sterna dougalii	Aves	Larne Lough SPA	0 /0%	0 /0%	0 /0%
Larus melanocepahlus	Aves	Larne Lough SPA	0 /0%	0 /0%	0 /0%
Rissa tridactyla	Aves	Rathlin Island SPA	0 /0%	0 /0%	0 /0%
Uria aalga	Aves	Rathlin Island SPA	0 /0%	0 /0%	0 /0%
Alca torda	Aves	Rathlin Island SPA	0 /0%	0 /0%	0 /0%
Breeding seabird assemblage*	Aves	Rathlin Island SPA	0 /0%	0 /0%	0 /0%
Mergus serrator	Aves	Carlingford Lough SPA	0 /0%	0 /0%	0 /0%
Pentapora foliacea	Bryozoa	Rathlin MCZ The Maidens SAC	1 /1.64%	1 /1.64%	0 /0%
Bugula turbinata	Bryozoa	Rathlin MCZ	8 /29.63%	6 /22.22%	2 /7.41%

		Strangford Lough MCZ Carlingford Lough MCZ Skerries and Causeway SAC Pisces Reef Complex SAC			
Alcyonium digitatum	Cnidaria	Skerries and Causeway SAC Rathlin MCZ The Maidens SAC Outer Belfast Lough MCZ Strangford Lough MCZ Murlough SAC Red Bay SAC Waterfoot MCZ Pisces Reef SAC South Rigg MCZ Carlingford Lough MCZ	797 / 43%	396 / 21%	401 / 22%
Alcyonium hibernicum	Cnidaria	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Arachnanthus sarsi	Cnidaria	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Aureliania heterocera	Cnidaria	Rathlin MCZ Strangford Lough SAC Red Bay SAC The Maidens SAC	9 /31.03%	6 /20.69%	3 /10.34%
Caryophyllia inornata	Cnidaria	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Caryophyllia smithii	Cnidaria	Skerries and Causeway SAC Rathlin MCZ Red Bay SAC	389 /32.55%	290 /24.27%	99 /8.28%

		Outer Belfast Lough MCZ The Maidens SAC Strangford Lough MCZ Murlough SAC			
Diphasia alata	Cnidaria	Rathlin MCZ Pisces Reef Complex SAC The Maidens SAC	49 /42.98%	47 /41.22%	2 /1.75%
Diphasia nigra	Cnidaria	Rathlin MCZ The Maidens SAC	15 /65.21%	15 /65.21%	0 /0%
Edwardsia timida	Cnidaria	Rathlin MCZ Strangford Lough MCZ	4 /66.67%	4 /66.67%	0 /%
Halecium plumosum	Cnidaria	Rathlin MCZ Strangford Lough MCZ Carlingford Lough MCZ Skerries and Causeway SAC	13 /27.08%	11 /22.92%	2 /4.17%
Haliclystus auricula	Cnidaria	Rathlin MCZ Strangford Lough MCZ Red Bay SAC Skerries and Causeway SAC Waterfoot MCZ	7 /36.84%	1 /5.26%	6 /31.57%
Lytocarpia myriophyllum	Cnidaria	Rathlin MCZ The Maidens SAC Pisces Reef Complex SAC	25 /52.08%	23 /47.92%	2 /4.17%
Parazoanthus anguicomus	Cnidaria	Rathlin MCZ	46 /36.22%	46 /36.22%	0 /0%

		The Maidens SAC			
Parazoanthus axinellae	Cnidaria	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Polyplumaria flabellata	Cnidaria	Rathlin MCZ The Maidens SAC	51 /57.95%	49 /55.68%	2 /2.27%
Stomphia coccinea	Cnidaria	Rathlin MCZ Strangford Lough MCZ Red Bay SAC The Maidens SAC	24 /70.59%	1 /2.94%	23 /67.65%
Tamarisca tamarisca	Cnidaria	Rathlin MCZ Strangford Lough MCZ	33 /78.57%	2 /4.76%	31 /73.81%
Atelecyclus rotundatus	Crustacea	Rathlin MCZ Strangford Lough MCZ Red Bay SAC Skerries and Causeway SAC Waterfoot MCZ	64 /64%	4 /4%	60 /60%
Cestopagurus timidus	Crustacea	Rathlin MCZ	12 /85.71%	0 /0%	12 /85.71%
Corystes cassivelaunus	Crustacea	Outer Belfast Lough MCZ Skerries and Causeway SAC Rathlin MCZ Red Bay SAC The Maidens SAC Strangford Lough MCZ Murlough SAC	18 /13.14%	2 /1.46%	16 /11.68%
Homarus gammarus	Crustacea	Rathlin MCZ Skerries and Causeway SAC	102 /34.34%	73 /24.58%	29 /9.76%

		The Maidens SAC Outer Belfast Lough MCZ Strangford Lough MCZ Murlough SAC			
Inachus leptochirus	Crustacea	Rathlin MCZ Red Bay SAC Strangford Lough MCZ	14 /48.27%	0 /0%	14 /48.27%
Munida rugosa	Crustacea	Rathlin MCZ Red Bay SAC Strangford Lough MCZ Skerries and Causeway SAC The Maidens SAC Waterfoot MCZ Pisces Reef Complex SAC	124 /38.16%	55 /16.92%	69 /21.23%
Nephrops norvegicus	Crustacea	Strangford Lough MCZ Outer Belfast Lough MCZ Queenie Corner MCZ South Rigg MCZ Murlough SAC	296 / 63%	142 / 30%	154 / 33%
Palinurus elephas	Crustacea	Rathlin MCZ Skerries and Causeway SAC The Maidens SAC	3 /7.69%	3 /7.69%	0 /0%
Anseropoda placenta	Echinodermata	Rathlin MCZ	220 /77.74%	26 /9.19%	194 /68.55%

		The Maidens SAC			
Antedon petasus	Echinodermata	Rathlin MCZ The Maidens SAC Strangford Lough MCZ	6 /28.57%	1 /4.76%	5 /23.81%
Asterina phylactica	Echinodermata	Rathlin MCZ Skerries and Causeway SAC Strangford Lough MCZ	4 /28.57%	2 /14.29%	2 /14.29%
Astropecten irregularis	Echinodermata	Rathlin MCZ Strangford Lough MCZ Murlough SAC	159 /53.36%	19 /6.38%	140 /46.98%
Atrina fragilis	Echinodermata	Rathlin MCZ South Rigg MCZ	7 /43.74%	1 /6.25%	6 /37.5%
Labidoplax media	Echinodermata	Strangford Lough MCZ	14 /37.84%	2 /5.41%	12 /32.43%
Leptasterias muelleri	Echinodermata	Skerries and Causeway SAC Rathlin MCZ Red Bay SAC The Maidens SAC Outer Belfast Lough MCZ Strangford Lough MCZ Murlough SAC Carlingford Lough MCZ	175 /41.57%	107 /25.42%	68 /16.15%
Leptosynapta bergensis	Echinodermata	Strangford Lough MCZ	45 /67.16%	2 /2.99%	43 /64.17%
Paracucumaria hyndmani	Echinodermata	Strangford Lough MCZ	0 /0%	0 /0%	0 /0%
Porania pulvillus	Echinodermata	Rathlin MCZ Strangford Lough MCZ	66 /25.78%	27 /10.55%	39 /15.23%

		Murlough SAC Red Bay SAC The Maidens SAC Waterfoot MCZ Pisces Reef Complex SAC			
Solaster endeca	Echinodermata	Rathlin MCZ Strangford Lough MCZ Red Bay SAC	114 /65.9%	22 /12.71%	92 /53.18%
Thyonidium drummondii	Echinodermata	Strangford Lough MCZ	9 /20.93%	9 /20.93%	0 /0%
Halichoerus grypus	Mammalia	The Maidens SAC	0 /0%	0 /0%	0 /0%
Phoca vitulina	Mammalia	Murlough SAC	0 /0%	0 /0%	0 /0%
Phocoena phocoena	Mammalia Mammalia	North Channel SAC Skerries and Causeway SAC	0 /0%	0 /0%	0 /0%
Aequipecten opercularis	Mollusca	Skerries and Causeway SAC Rathlin MCZ Red Bay SAC The Maidens SAC Outer Belfast Lough MCZ Strangford Lough MCZ Murlough SAC Pisces Reef Complex SAC Queenie Corner MCZ	372 /51.96%	120 /16.76%	252 /35.2%
Arctica islandica	Mollusca	Outer Belfast Lough MCZ	158 /61.72%	65 /25.39%	93 /36.33%

Cerastoderma glaucum	Mollusca	Larne Lough SPA	4 /100%	0 /0%	4 /100%
Chlamys varia	Mollusca	Strangford Lough MCZ	19 /53.98%	160 /45.45%	30 /8.52%
Crenella decussata	Mollusca	Strangford Lough MCZ Larne Lough SPA The Maidens SAC	306 /84.07%	10 /2.75%	296 /81.32%
Cumanotus beaumonti	Mollusca	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Cuthona concinna	Mollusca	Rathlin MCZ Strangford Lough MCZ	18 /60%	16 /53.33%	2 /6.66%
Erato voluta	Mollusca	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Eubranchus doriae	Mollusca	Rathlin MCZ The Maidens SAC	1 /25%	1 /25%	0 /0%
Pecten maximus	Mollusca	Outer Belfast Lough MCZ Strangford Lough MCZ Pisces Reef Complex SAC Queenie Corner MCZ	234 /35.62%	114 /17.35%	120 /18.26%
Thecacera pennigera	Mollusca	The Maidens SAC	0 /0%	0 /0%	0 /0%
Tonicella marmorea	Mollusca	Rathlin MCZ Strangford Lough MCZ Carlingford Lough MCZ	25 /50%	20 /40%	5 /10%
Antho brattegardi	Porifera	Rathlin MCZ The Maidens MCZ	8 /40%	7 /35%	1 /5%
Axinella damicornis	Porifera	Rathlin MCZ Skerries and Causeway SAC	0 /0%	0 /0%	0 /0%
Axinella dissimilis	Porifera	Rathlin MCZ	17 /17.17%	15 /15.15%	2 /2.02%

		Skerries and Causeway SAC			
		The Maidens SAC			
Biemna variantia	Porifera	Strangford Lough MCZ	8 /88.89%	8 /88.89%	0 /0%
Clathria barleei	Porifera	Rathlin MCZ	22 /84.62%	22 /84.62%	0 /0%
		The Maidens SAC			
Eurypon coronula	Porifera	Strangford Lough MCZ	1 /100%	1 /100%	0 /0%
Hymedesmia cohesibacilla	Porifera	Rathlin MCZ	4 /57.14%	4 /57.14%	0 /0%
		The Maidens SAC			
Hymedesmia rathlinia	Porifera	Rathlin MCZ	19 /27.54%	15 /21.74%	4 /5.79%
		The Maidens SAC			
Hymerhabdia typica	Porifera	Rathlin MCZ	1 /4.76%	1 /4.76%	0 /0%
		The Maidens SAC			
Iophon hyndmani	Porifera	Rathlin MCZ	86 /39.45%	78 /35.77%	8 /3.67%
		Strangford Lough MCZ			
		Murlough SAC			
		Red Bay SAC			
		The Maidens SAC			
		Waterfoot MCZ			
		Skerries and Causeway SAC			
Lissodendoryx jenjonesae	Porifera	Rathlin MCZ	23 /31.51%	23 /31.53%	0 /0%
		The Maidens SAC			
Microciona elliptichela	Porifera	Rathlin MCZ	9 /90%	7 /70%	2 /20%
		The Maidens SAC			
Mycale (Mycale) lingua	Porifera	Rathlin MCZ	0 /0%	0 /0%	0 /0%

Mycale cf. contarenii	Porifera	Strangford Lough MCZ Larne Lough SPA	2 /66.67%	1 /33.34%	1 /33.34%
Mycale similaris	Porifera	Strangford Lough MCZ	8 /11.76%	8 /11.76%	0 /0%
Plocamiancora arndti	Porifera	Rathlin MCZ The Maidens SAC Strangford Lough MCZ Carlingford Lough MCZ	23 /56.09%	23 /56.09%	0 /0%
Spanioplon armaturum	Porifera	Rathlin MCZ The Maidens SAC Strangford Lough MCZ	5 /33.33%	5 /33.33%	0 /0%
Spongionella pulchella	Porifera	Rathlin MCZ The Maidens SAC	11 /28.21%	11 /28.21%	0 /0%
Stelletta grubii	Porifera	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Stryphnus ponderosus	Porifera	Rathlin MCZ	0 /0%	0 /0%	0 /0%
Tethya hibernica	Porifera	Rathlin MCZ The Maidens SAC	2 /16.67%	2 /16.67%	0 /0%
Archidistoma aggregatum	Tunicata	Rathlin MCZ The Maidens SAC Skerries and Causeway SAC	7 /22.58%	2 /6.45%	5 /16.13%
Boltenia echinata	Tunicata	Rathlin MCZ Strangford Lough MCZ Murlough SAC The Maidens SAC	9 /40.91%	6 /27.27%	3 /13.64%
Diazona violacea	Tunicata	Rathlin MCZ The Maidens SAC	1 /5.26%	1 /5.26%	0 /0%

Pycnoclavella stolonialis	Tunicata	Rathlin MCZ The Maidens SAC Strangford Lough MCZ	27 /55.1%	19 /38.77%	8 /16.33%
Pyura microcosmus	Tunicata	Rathlin MCZ Strangford Lough MCZ Carlingford Lough MCZ	11 /32.35%	6 /17.64%	5 /14.71%
Synoicum incrustatum	Tunicata	Rathlin MCZ The Maidens SAC	2 /5.56%	2 /5.56%	0 /0%

[a] % habitat resilient = total number of records falling inside climate change refugia/total number of records in NI waters.
[b] % habitat resilient & protected = total records in MPAs in climate change refugia/ total number of records in NI waters.
[c] % habitat resilient & unprotected = total records outside MPAs in climate change refugia/ total number of records in NI waters.
*: " Breading Seabird Assemblage" is a designation criterion for Rathlin Island SPA. Because no refuge for pelagic megafauna was found around Rathlin Island the classification is presentation as is. If a refuge was found in this area, we would not be able to provide this classification for this specific criterion as such, since the analysis is done as species level.

Species with moderate resilience (26 species or 26%) included a wider diversity of organisms beyond those groups (which in this case also included the very long-lived bivalve *Arctica islandica*), and also featured algae, several slow growing hydroid species and other cnidaria, starfish and other echinoderms. Of these 26 species, only 8 had more than 50% of their range in climate change refugia and protected by MPAs.

3.2.4 The most climate-vulnerable species

Most species had low climate-resilience across their range, or were found to be climate-vulnerable (Table 3). All birds and mammal species fit into the latter category, including the iconic black guillemot *Cepphus grille*, harbour porpoise *Phocoena phocoena*, grey seal *Halichoerus grypus*, and harbour seal *Phoca vitulina*. This suggests that protecting pelagic megafauna in Northern Ireland's marine waters into the future will require careful consideration of human activities to limit impacts on these populations already struggling with significant habitat change and changes in their diets. Only 7 out of 67 species that fall into these lower two categories of climate-resilience (Table 3) had at least 30% of their climate-resilient range within MPAs, whilst for the majority the numbers were close

to (or) 0%. Clearly, climate change presents a substantial challenge to the conservation of marine species in Northern Ireland, which are likely to impact the way in which these species interact with, and are affected by, human activities.

3.3 Objective iii: Potential future areas for MPA assessment

The MPA network overlaps in many areas with climate change hotspots for benthic species, habitats and pelagic megafauna (those used as designation criteria). However, there are further areas that accommodate refugia, at least for benthic species and habitats beyond currently designated sites, though no such sites are identified here that could be used directly to help protect prey and habitats for pelagic megafauna.

Areas that could be explored for further MPA siting assessment are located inshore, to the east and west of the Maidens SAC, and south of the North Channel SAC (Figure 1).

This area also harbours Threatened and/or Declining habitats (as classified by OSPAR) which are estimated to be in poor condition due to seabed contact fishing gears, and broader benthic communities varying between poor status to moderate and good (Sciberras, Marra et al. 2023). Seabed extractive activities vary between low to moderate and high (Sciberras, Marra et al. 2023). Bottom trawling is prevalent throughout, and light pollution is prevalent in coastal areas (Queirós, Kay et al. 2024). Trade-offs against such activities could thus be considered where they bring benefits to nature and people. A more detailed analysis of what activities take place in those areas, that could serve as a starting point for that process of consideration of new sites for the Northern Ireland MPA network, can be found in Queirós et al. 2024.

4. Concluding remarks

The analysis of findings presented here highlights that the Northern Ireland MPA network is vulnerable to climate change, and that this vulnerability is deeply reflected in the way that the network, saving a small number of species and habitats, does not by and large provide a climate-resilient refuge for designated features. This is not an uncommon finding when we assess MPA networks across the United Kingdom and beyond. But it is a finding that highlights the urgency to develop more sustainable approaches to protect ocean wildlife, and the livelihoods of those that

depend on the health of these ecosystems, into the future.

Our findings suggest that almost half of Northern Ireland's marine waters represent climate change hotspots. These areas should not be seen necessarily as having no conservation value. Climate change hotspots, as defined here, simply represent areas which are very vulnerable to climate change. For this reason, limitation of other types of human pressures on the foodweb in these areas (e.g. through fisheries reduction) will be especially important, as it can sometimes help promote the ability of species to cope with climate change locally (Hughes, Baird et al. 2003). And while this can happen, increased climate-resilience has not always been observed where human activities are restricted through conservation measures, in part due to the limited ability of researchers to attribute causality in studies in nature, and in part because of the complexity of underlying ecological mechanisms (Bates, Cooke et al. 2019). Namely, another human pressure does not necessarily lead to the loss of the species in an assemblage that are the most resilient to climate change, such that a restriction of that activity does not necessarily lead to an increase in abundance of species more resilient to climate pressures. But maintaining the genetic diversity of populations, numbers of species, the integrity of foodwebs and habitat complexity by reduction of human pressures may reduce the potential for the occurrence of strong trophic cascades and other ecological processes that can exacerbate and accelerate biodiversity loss, while helping maintain ecosystem function (Bates, Cooke et al. 2019). If those outcomes are observed through reduction of human pressures, then climate-resilience may potentially increase. In parallel, areas identified as climate change refugia are the areas where we expect species and ecosystems to have the best chance of persisting into the future, and thus present an opportunity to help limit biodiversity loss. For this reason, they likely deserve focused efforts to protect them. Where the balance of needs between nature protection and access of human activities to marine space lies is for society to determine.

The evidence presented here, building on previous analyses, indicates that there is potential to enhance the climate-resilience of the Northern Ireland MPA network with regard to benthic habitats. However, for pelagic megafauna, some of our most vulnerable species, such outcomes will likely depend on

reducing emissions, and cross border coordination for the protection of feeding grounds, residence and nursery areas, and of migration corridors. A more holistic approach to the management of conservation is needed, as it is a key route to ocean health and sustainable human activity (Crowder and Norse 2008). Marine planning has a role to play in this process, by providing a wider view of human activities and objectives for Northern Irish marine waters, which hold over 50% of the nation's biodiversity.

5. Supplementary Information

5.1.Modelling datasets used

This report uses a range of publicly available ocean climate modelling for Northern Irish marine waters. These were primarily produced in UK Research and Innovation, Natural Environmental Research Council National Capability, and European research framework modelling projects. The physical biogeochemical modelling data used in the analyses of benthic habitats and pelagic megafauna was produced using the coupled Proudman Oceanographic Laboratory Coastal Ocean Modelling System ("POLCOMS", Holt and James, 2001). - European Regional Seas Ecosystem Model ("ERSEM", Butenschön, Clark et al. 2015). These simulations were generated as part of the Horizon 2020 programme CERES, and are in line with modelling used within the 6th Assessment Report of the Intergovernmental Panel on Climate Change. Additional species distribution modelling data used in the pelagic megafauna analysis was generated using the Size Spectrum Dynamic Bioclimate Envelope Model ("SS-DBEM", Fernandes, Cheung et al. 2013), also developed during the CERES programme. These data are all publicly available (Kay, Clark et al. 2020, Miller, Clark et al. 2020, Sailley, Kay et al. 2020). Where additional prey species of relevance to pelagic megafauna in Northern Ireland were needed, SS-DEBM runs were provided from the FP7 programme DEVOTES. Those datasets are available upon request from Jose Fernandes (AZTI), and the employed scenarios were consistent with the 5th Assessment Report of the Intergovernmental Panel on Climate Change (Fernandes, Papathanasopoulou et al. 2017, Queirós, Talbot et al. 2021). Both models (POLCOMS-ERSEM and SS-DBEM) represent state-of-the-art modelling tools, and are widely recognised as having a good track record globally, and particularly, in the NE Atlantic region (Kay 2023, Queirós, Kay et al. 2023). The climate modelling datasets were forced using global greenhouse gas concentration scenarios (i.e. Representative Concentration Pathways, "RCP", Van Vuuren, Edmonds et al. 2011) used by the Intergovernmental Panel on Climate Change, specifically, RCP4.5 and RCP8.5. RCP4.5 (the "slowly declining emissions" scenario) assumes strong curbs in global emissions toward climate change mitigation, from 2050 onwards, leading to a mean global warming by the end of the century of ~2.4 °C. Contrastingly, emissions continue to rise

steadily throughout the 21st century under RCP8.5 (the "growing emissions" scenario), leading to mean global warming of ~4.3°C. The two scenarios correspond to a mean warming of sea surface temperature of about 1°C and 2°C by the end of the 21st century, respectively, in the physical modelling dataset used, which is a low to moderate rise compared to a range of global climate models. A small percentage of species distribution modelling projections used in the pelagic megafauna analyses were generated under RCP2.6 (the "strongly declining emissions" scenario) when no equivalent could be found under RCP4.5, and these derive from the FP7 programme DEVOTES. For species distribution modelling datasets used as prey in analyses for pelagic megafauna, the scenarios employed combine RCP with more general views about climate change mitigation and environmental concerns, into a type of scenario termed shared socio-economic pathways ("SSP"), as also used by the IPCC (O'Neill, Kriegler et al. 2014). These modelling datasets, which describe commercially targeted species, therefore include an element of fishing mortality in addition to a natural mortality term. The specific modelling datasets used and their sources are clearly listed in Table A1.

5.2. Temporal and spatial resolution of analyses

All physical-biogeochemical modelling datasets analysed have the spatial resolution of the physical model simulations used (POLCOMS) which is a regular grid of 0.1° latitude x 0.1° longitude, approximately 5-7km x 11km per grid cell (or 60-80 km2). This is a regional model, parameterised for the North Western European Shelf, with 40 vertical layers which are more closely resolved in shallower areas. We analysed surface, bottom, seabed or vertically integrated data, as needed and described below. Modelling data from the SS-DBEM has a coarser grid of 0.5° latitude x 0.5° longitude. These datasets were therefore projected onto POLCOMS's grid without further processing, to allow for joint analysis of data where needed. Spatial meta-analysis of modelling datasets was then carried out per group of species (Table A1) using the methodology described in Section 1.1 (Queirós, Talbot et al. 2021).

5.3. Other spatial data used

The results from the climate modelling analyses were then interpreted in the context of the current distributions of MCZs, SACs, and SPAs in Northern Ireland. The overlay of modelling data with this additional spatial

information allowed us to identify opportunities for the location of new MPAs, or expansion of existing MPAs, into areas harbouring climate change refugia for benthic habitats.

5.4. Summary figure and shapefile creation

To facilitate the use of information contained in this report, we created a summary plot (Figure 1) that summarises long-term patterns that emerge from the spatial-meta analysis of modelling data, providing an overview of the distribution of climate change refugia and climate change hotspots in Northern Irish waters. We restricted the analyses leading to the creation of this figure to the period between 2026-2069, covering the year immediately after the period used as the present in the analyses (2006-2025), and extending beyond the mid-century. To this end, we processed the outputs of the analyses, in both climate change scenarios. Results from each analysis were saved in the form of matrices containing values of -1 (representing a climate change hotspot), 0 (representing a climate change refugia) or 1 (representing a climate change bright spot) for each cell in the model domain. There were therefore 25 matrices, each contrasting each possible 20 year future period with the present, for each of the two greenhouse gas emissions scenario considered, so 50 matrices in total, per group of variables considered. These matrices were summed to create a single master document which contained values ranging from -50 (indicating a cell that was always a hotspot), to 50 (indicating a cell was always a bright spot). We considered a cell to be appearing as a long-term hotspot (or bright spot) if it appeared in at least 80% of the time slices (e.g. values of < -40 for hotspots, or > -10 for refugia). Bright spots appeared rarely and fleetingly, so no shapefiles were created for bright spots. Once the values for the 80% threshold had been determined, we used the “terra” package in R to convert all cells that met the threshold condition to polygons, which were then plotted in Figure 1.

Table A1: Modelling datasets used in spatial-metanalyses considered in this report. For most features analysed in this report (Tables 2 & 3), modelling data analyses relied on benthic habitat datasets below. The exceptions were pelagic megafauna (Table 3), for which pelagic environmental variables and prey fields were analysed instead: *Cepphus grille* (black guillemot, bird), *Halichoerus grypus* (grey seal, marine mammal), *Phoca vitulina* (harbour seal, marine mammal), and *Phocoena Phocoena* (harbour porpoise, marine mammal).
Scenarios employed in the generation of modelling datasets include Representative Concentration Pathways RCP 4.5 (moderate emissions) and RCP8.5 (higher emissions) as used by Intergovernmental Pannel on Climate Change (Van Vuuren, Edmonds et al. 2011). "MSY" reflects the fishing effort employed in the generation of modelling datasets for prey species which are commercially exploited. MSY 0.6 represents a scenario where a fish stock is managed globally toward sustainability, and MSY 0.8 represents a scenario where a fish stock is managed globally to avoid overfishing (Sailley, Kay et al. 2020).
More information here and here.

Model type	Modelled variable	Units	Sectoral analysis	Model	Source	Institute	Scenario	Time period	Predicted outcome	Source
Physical-biogeochemical	Net primary production	Kg C m^{-3} s^{-1}	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical-biogeochemical	Potential energy anomaly (stratification)	J m^{-3}	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Physical-biogeochemical	Water column sum of phytoplankton carbon	Kg C m^{-3}	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical-biogeochemical	Bottom dissolved oxygen	mmol m^{-3}	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical-biogeochemical	Bottom non-living organic carbon	Kg C m^{-3}	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical-biogeochemical	Bottom saturation state of aragonite	scalar	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)

Physical-biogeochemical	Bottom sea water pH	scalar	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical-biogeochemical	Bottom sea water potential temperature	°C	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Physical-biogeochemical	Bottom sea water salinity	PSU	Benthic habitats	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2021)
Physical-biogeochemical	Surface dissolved oxygen	mmol m^{-3}	Pelagic megafauna	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical-biogeochemical	Surface sea water potential temperature	°C	Pelagic megafauna	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Physical-biogeochemical	Surface sea water salinity	PSU	Pelagic megafauna	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical-biogeochemical	Net primary production	Kg C m^{-3} s^{-1}	Pelagic megafauna	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Physical	Summer thermal front strength	scalar	Pelagic megafauna	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Physical	Winter thermal front strength	scalar	Pelagic megafauna	POLCOMS-ERSEM	Kay - CERES	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Species distribution	*Clupea harengus*	Abundance	Pelagic megafauna	SS-DBEM	Sailley - CERES	PML	RCP 4.5 MSY 0.6; RCP8.5 MSY 0.8	2006-2099	Decreased	IPCC (2022); Townhill, Couce et al. (2023)
Species distribution	*Merlangius merlangus*	Abundance	Pelagic megafauna	SS-DBEM	Fernandes - DEVOTES	PML/AZTI	RCP2.6; RCP8.5	2006-2098	Decreased	Pinnegar, Wright et al. (2020), IPCC (2022)
Species distribution	*Micromesistius poutassou*	Abundance	Pelagic megafauna	SS-DBEM	Fernandes - DEVOTES	PML/AZTI	RCP2.6; RCP8.5	2006-2098	Decreased	IPCC (2022); Townhill, Couce et al. (2023)
Species distribution	*Scomber scombrus*	Abundance	Pelagic megafauna	SS-DBEM	Sailley - CERES	PML	RCP 4.5 MSY 0.6; RCP8.5 MSY 0.8	2006-2098	Decreased	IPCC (2022); Pinnegar, Wright et al. (2020)

Species distribution	*Sprattus sprattus*	Abundance	Pelagic megafauna	SS-DBEM	Sailley - CERES	PML	RCP 4.5 MSY 0.6; RCP8.5 MSY 0.8	2006-2098	Decreased	IPCC (2022); Pinnegar, Wright et al. (2020)

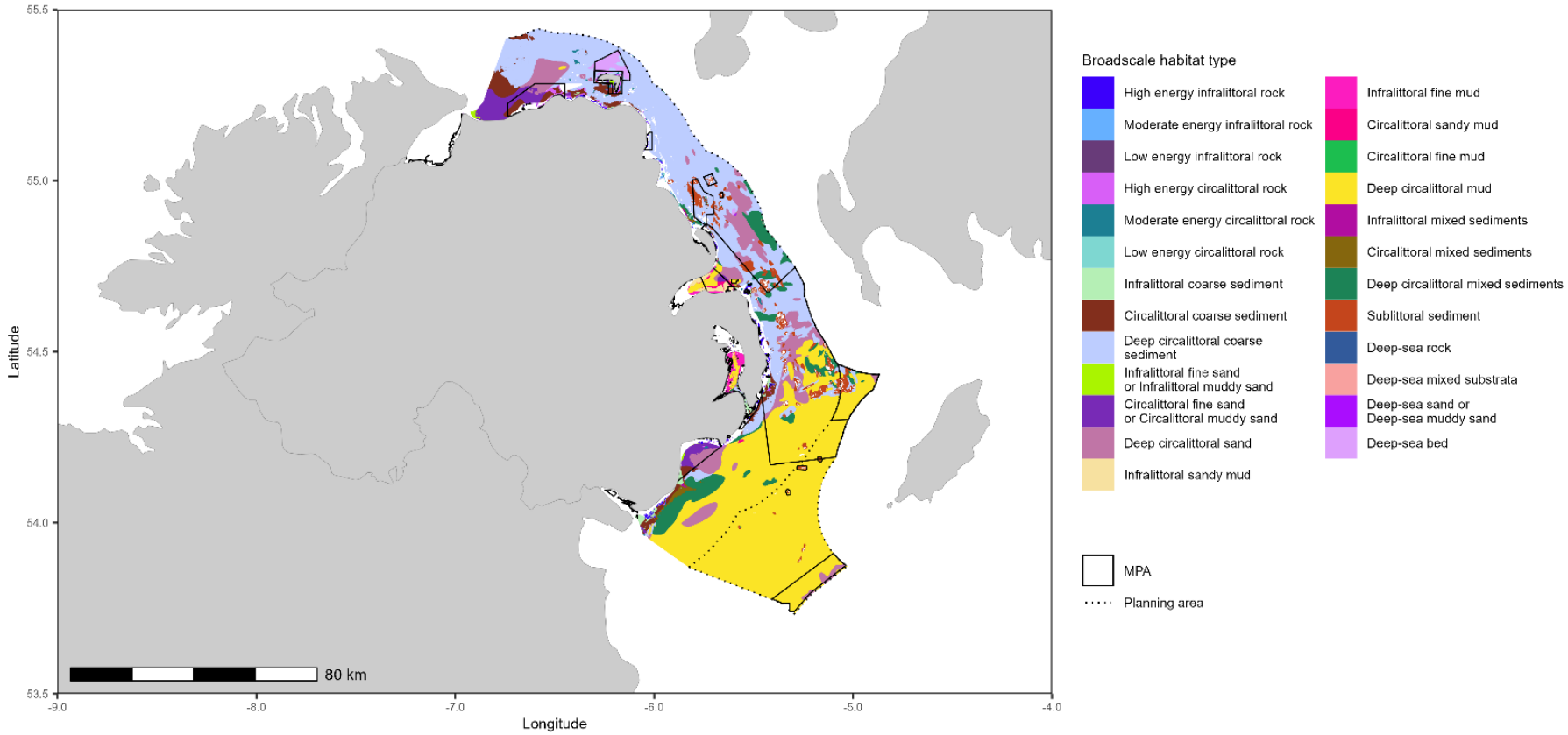


Figure A1: Broad-scale sedimentary marine habitat types in in Northern Ireland's waters relative to the location of MPAs.

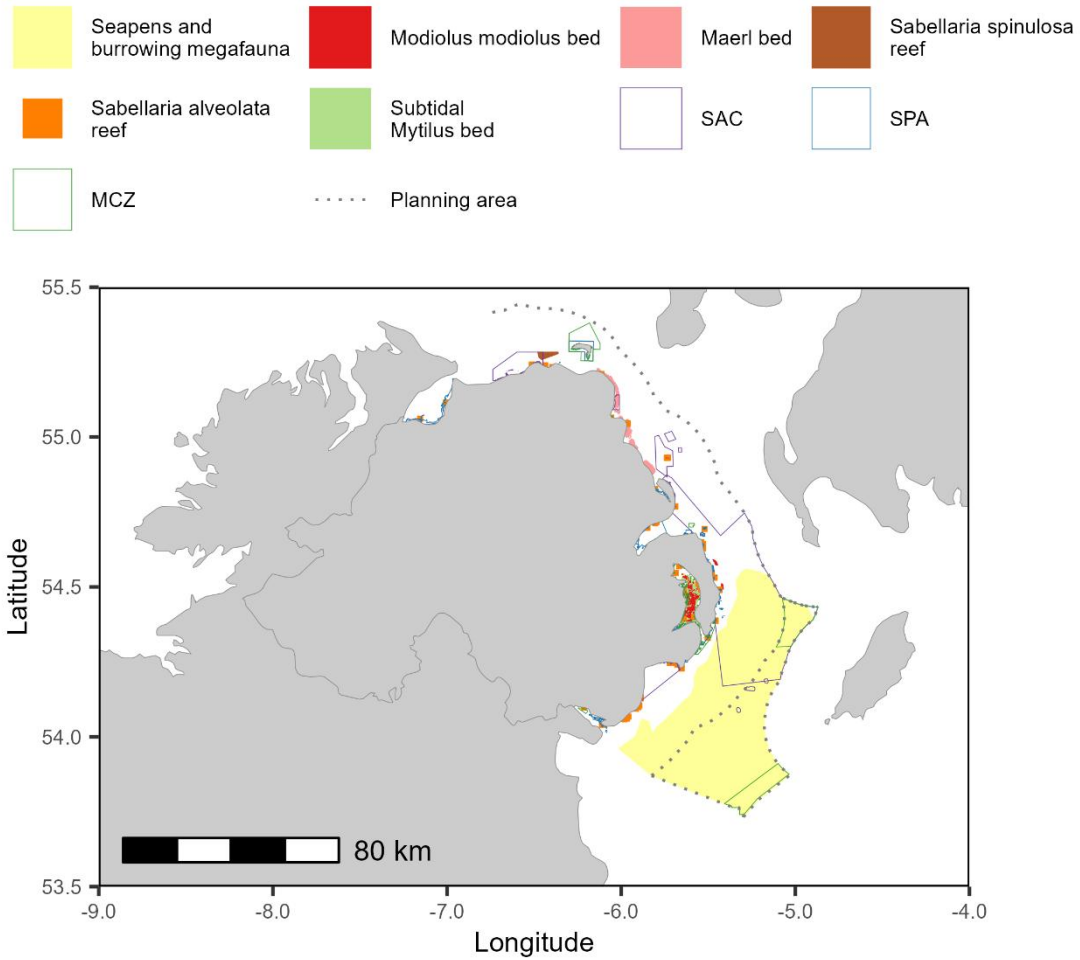


Figure A2: Biogenic habitats in Northern Ireland's marine waters relative to the location of MPAs.

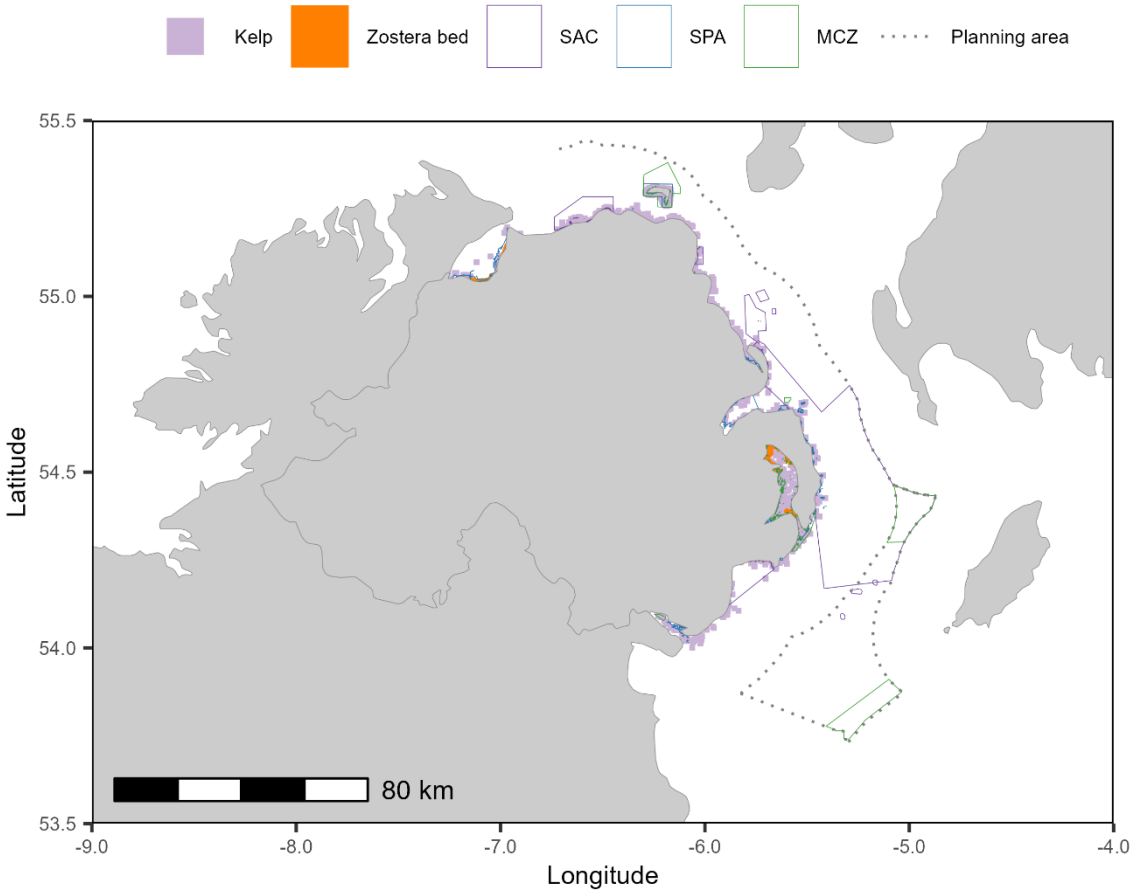


Figure A3: Vegetated habitats in Northern Ireland's marine waters relative to the location of MPAs.

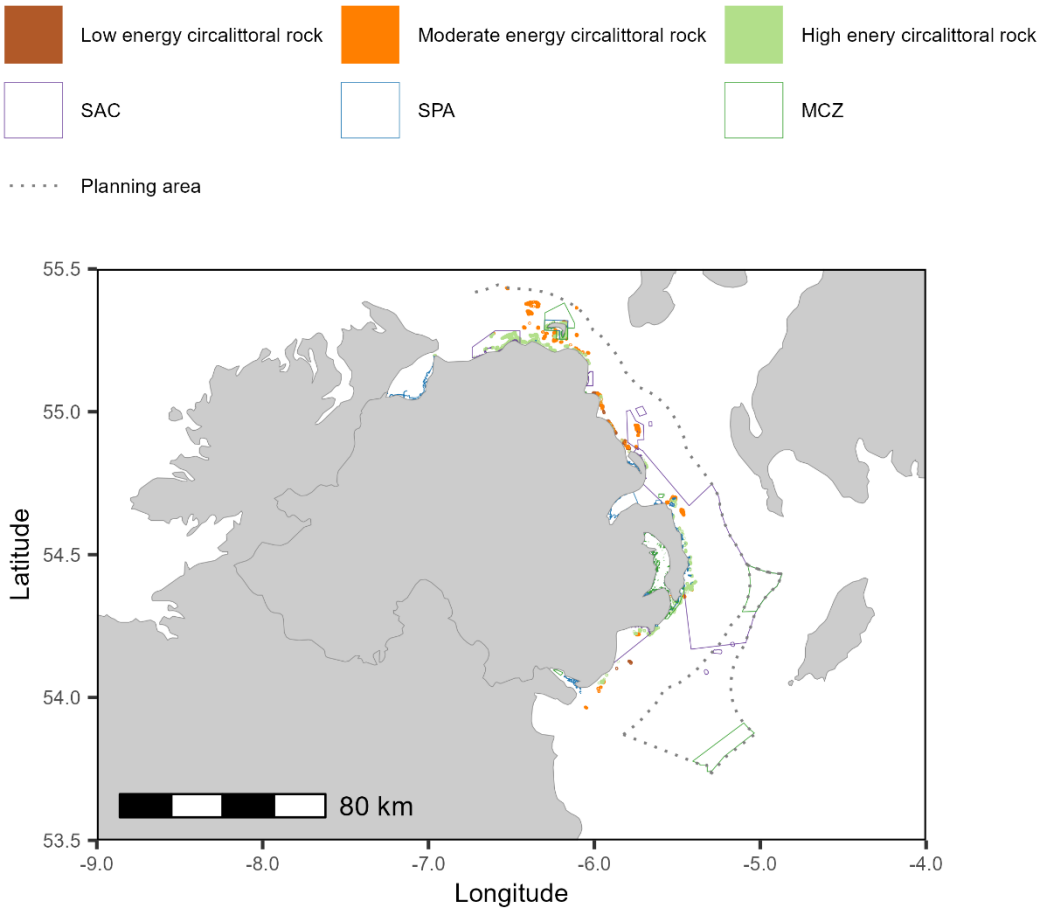


Figure A4: Circalittoral rock habitat in Northern Ireland's waters relative to the location of MPAs.

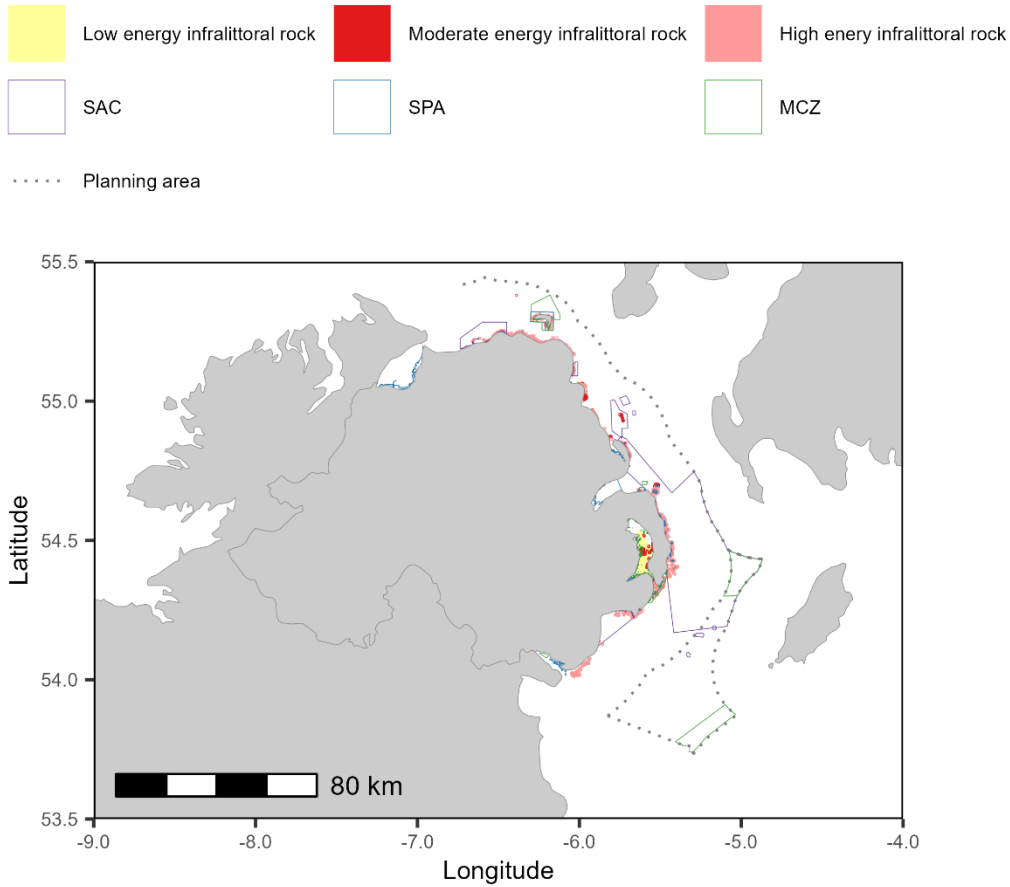


Figure A5: Infralittoral rock habitats in Northern Ireland's waters relative to the location of MPAs.

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