

# A Climate-resilient Path for Ireland's Marine Protected Areas Network



**FAIR SEAS**

# A Climate-resilient Path for Ireland's Marine Protected Areas Network



*Addendum chapter to Revitalising Our Seas report: Identifying Areas of Interest for Marine Protected Area Designation in Irish Waters*

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**Figure 2:** Areas in which long-term climate change refugia were identified for megafauna reliant on pelagic species and habitats (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069.

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Figure 5: Areas in which long-term climate change refugia were identified for benthic species other than megafauna (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069. The grey line is the Irish National Marine Planning Framework boundary.

**Figure 6:** Areas in which long-term climate change refugia were identified for forage fish (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069. The grey line is the Irish National Marine Planning Framework boundary.

**Figure 7:** Representative example of mean change in individual forage fish species abundance by mid-century (2041-2060), relative to the present (2006-2025), under RCP 4.5 (top) and RCP 8.5 (bottom). Change is measured using Hedges *g*, which is the standardized mean change estimator, centered around 0 (no change), and placing all species in the same scale to help comparison across species. Green shading shows where species abundances are projected to decrease in comparison to the present; pink shading shows areas where abundances are projected to increase. Herring: *Clupea harengus* (left). Sardine: *Sardina pilchardus* (middle). Sprat: *Sprattus sprattus* (right). The grey line is the Irish National Marine Planning Framework boundary.

## GLOSSARY

**Areas of interest:** areas proposed in the Revitalising Our Seas report as priorities for the siting of new Marine Protected Areas. These areas were defined as those where a species or habitat of interest was present and in high densities. The species and habitats of interest include seabed habitats, commercially exploited species, cetaceans, elasmobranchs, and breeding and non-breeding birds.

**Bright spot:** a site where multiple environmental conditions are improved, and the ecosystem enters a new ecosystem state beyond its natural, historical variability, or its variability in a reference period (*sensu*<sup>2</sup>). In this case, the new state is defined by trends that are inconsistent with expected mean long-term climate change trends for the surrounding region. E.g. cooling where the long-term trend is warming; increased dissolved oxygen where the long-term trend is deoxygenation<sup>3</sup>. Such conditions are linked to climate cycles and oscillations, and changes in circulation patterns, and tend to be short-to medium-term events (i.e. they do not persist in the long-term).

**Climate change hotspot:** a site where a climate signal emerges. That is, a site where climate pressures drive an ecosystem into a new mean ecosystem state, beyond its natural, historical variability, or its variability in a reference period (*sensu*<sup>4,5</sup>).

**Climate change refuge:** a site where the mean ecosystem state remains within the range of its natural, historical variability, or that in a reference period (i.e. within its 95% confidence interval in that period).

**Climate change resilient habitats:** where climate change refugia are observed (*sensu*<sup>6</sup>).

**Climate signal:** when the mean state of the ecosystem exceeds the range of its natural, historical variability or that in a reference period (i.e. its 95% confidence interval in that period). In this chapter, the reference period is the period of 2006-2025 (hereafter “the present”).

1 E. Hawkins & R. Sutton (2012). Time of emergence of climate signals. *Geophysical Research Letters* 2012 Vol. 39 Issue

2 Queirós et al. (2021) Bright spots as climate-smart marine spatial planning tools for conservation and blue growth. *Global Change Biology*. 27: 5514-5531.

3 *ibid*

4 Hawkins & Sutton, *op. cit.*

5 Queirós, *op. cit.*

6 *ibid*



Portsalon Beach,  
Co. Donegal

# Executive Summary

Extreme weather events, and long-term changes in our coasts and our seas are a present reminder of the breakdown of the global climate system. As efforts to limit the pace of climate change take shape, and climate action unfolds, it is likely that excess greenhouse gas emissions presently in our atmosphere may continue to impact our marine ecosystems, as part of our natural world, for decades and centuries to come. The need to introduce immediate action to preserve areas of our ecosystems that may, in the meantime, be less sensitive to those changes—climate change refugia—is thus widely recognised. Such sites may serve as the seed banks where our marine biodiversity may be preserved in the interim, until such a time when the global pressure of climate change has been reduced. To this end, modelling projections that estimate the degree of climate change experienced by marine species and habitats under different possible futures are thus invaluable tools with which to inform the design of conservation mechanisms to protect such “climate-resilient” sites, including well-managed marine protected area networks.

In this chapter, we employ state-of-the-art methods for the analyses of climate modelling projections for ocean species and habitats, to identify the location of climate change refugia in Irish waters. We find that more than half of Irish waters host such sites, and that many of these areas overlap with Areas of Interest that presently host key species and habitats of high conservation value in high densities. Bringing such climate change refugia under an expanded, well-managed marine protected area network would thus offer the opportunity to preserve such species and habitats, not just now, but for decades to come. A climate-resilient path is therefore possible for Irish marine conservation. This may serve as an effective route to meet Ireland’s commitments within the EU 2030 Biodiversity Strategy, and help protect our seas for future generations.

# 1 Introduction

The Irish government wants to meet its commitment to support the EU Biodiversity Strategy target and protect at least 30% of the Irish Maritime Area by 2030. At present, marine and coastal nature protected areas (in the form of Special Areas of Conservation, SACs and Special Protection Areas, SPAs, together known as the Natura 2000 Network) cover only 9% of Irish waters<sup>7</sup>. Meeting this 2030 target thus represents the ambition to at least triple the Irish marine conservation area network. The Revitalising Our Seas Report has suggested that the current state of marine conservation protection in Ireland is not sufficient to provide the necessary levels of protection and restoration recommended in the Irish Government's Marine Protected Area (MPA) Advisory Group report, and that the health of many marine habitats and species within protected areas is declining or unknown. This decline has been linked, at least partially (e.g. in Lough Hyne<sup>8</sup>), to ongoing changes in the global climate system, as observed around the world. Indeed, climate change, enhanced harvesting of ocean resources, and increased use of coastal areas towards economic growth, are together contributing to the deterioration of coastal and marine ecosystems globally<sup>9</sup>. Addressing climate change will thus be a key part of ensuring that the expansion to Ireland's marine protected area network delivers effectively on its ambitions.

It is widely accepted that, to be effective in a changing ocean, protected areas need to be planned and managed to consider climate-driven shifts in designation features such as species and habitat distributions<sup>10</sup>. Recent peer-reviewed research from

this team has already highlighted how the sensitivity of Irish waters to these and other climate change driven pressures varies over space and time, and this in turn depends on the magnitude of increased future greenhouse gas emissions we come to experience<sup>11</sup>. Indeed, some habitats and species are sensitive to climate change, but in other areas they are resilient, at least for some time<sup>12,13</sup>. This heterogeneity in sensitivity can be capitalised upon in the designation of new marine protected areas to ensure effective protection of species and habitats in climate-resilient sites, not just now but into the future<sup>14,15</sup>. In this chapter, we update and expand that evidence base, identifying the location and extent of Irish waters representing key habitats for species of conservation value which exhibit climate change resilience. We then further assess whether Areas of Interest proposed for the siting of new Irish MPAs in the Revitalising Our Seas Report could also be used to harness that natural climate resilience within these marine ecosystems. Specifically, we identify areas of Ireland's marine area which may be climate-resilient throughout the 21<sup>st</sup> century, with regard to habitat conditions and prey availability required for the persistence of key species groups of conservation value highlighted in the Revitalising Our Seas Report. Section 2 details how we assess spatial and temporal patterns in the distribution of climate-resilient areas, and provides summary maps conveying where such sites occur in the long-term and with high agreement between different possible greenhouse emissions futures. This new chapter of the report is thus expected to help inform a more climate-resilient path for a new MPA network in Ireland.

<sup>7</sup> Marine Protected Area Advisory Group (2020). Expanding Ireland's Marine Protected Area Network: A report by the Marine Protected Area Advisory Group. Report for the Department of Housing, Local Government and Heritage. 59pp.

<sup>8</sup> Trowbridge et al. (2019) No 'silver bullet': Multiple factors control population dynamics of European purple sea urchins in Lough Hyne Marine Reserve, Ireland. *Estuarine, Coastal and Shelf Science* 226:106-271.

<sup>9</sup> Pörtner et al. (2019). IPCC special report on the ocean and cryosphere in a changing climate Intergovernmental Panel on Climate Change: Geneva, Switzerland. 755 pp.

<sup>10</sup> Gaines et al. (2010). Designing marine reserve networks for both conservation and fisheries management. *Proceedings of the National Academy of Sciences* 107:18286-18293.

<sup>11</sup> Trowbridge, *op. cit.*

<sup>12</sup> E. Hawkins & R. Sutton (2012). Time of emergence of climate signals. *Geophysical Research Letters* 2012 Vol. 39 Issue

<sup>13</sup> Trowbridge, *op. cit.*

<sup>14</sup> Hawkins & Sutton, *op. cit.*

<sup>15</sup> Queirós et al. (2021) Bright spots as climate-smart marine spatial planning tools for conservation and blue growth. *Global Change Biology*. 27: 5514-5531.

## Revitalising Our Seas

Identifying Areas of Interest for Marine Protected Area Designation in Irish Waters



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## FAIR SEAS

The Fair Seas campaign is led by a coalition of Ireland's leading environmental non-governmental organisations and networks.

- BirdWatch Ireland
- Coastwatch
- Coomhola Salmon Trust
- Friends of the Irish Environment
- Irish Environmental Network
- Irish Whale and Dolphin Group
- Irish Wildlife Trust
- SWAN-Sustainable Water Network

At Fair Seas, we seek to protect, conserve and restore Ireland's unique marine environment. Our ambition is to see Ireland become a world leader in marine protection, giving our species, habitats and coastal communities the opportunity to thrive.

Fair Seas aims to build a movement of ocean stewardship across Ireland that energises and empowers people, to advocate for ambitious and robust legislation, provide impartial scientific data and research, and propose a network of effective well-managed marine protected areas.

[www.fairseas.ie](http://www.fairseas.ie)

“The Revitalising Our Seas report has suggested that the current state of marine conservation protection in Ireland is not sufficient to provide the necessary levels of protection and restoration recommended in the Irish Government's Marine Protected Area (MPA) Advisory Group report...”

## 2 Identifying biologically meaningful and climate-resilient sites

### 2.1 Methodology

Marine ecosystems are highly dynamic so 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<sup>16</sup>. In this context, ocean climate modelling (i.e. physical and biogeochemical modelling; species distribution modelling; ecosystem modelling) is an essential decision-support tool for decision-makers designing spatial policy interventions that are adaptive to the effects of climate change, such as the siting of marine protected areas, i.e. climate-smart<sup>17</sup>. There is a rich evidence basis that has explored different methodologies with which to support this process. Nevertheless, the implementation of climate-resilient MPAs remain infrequent, and when this does occur, consideration is due primarily to the (long-term) velocity of ocean warming and species response to this<sup>18</sup>. Long-term warming is indeed a key driver of marine biodiversity re-distribution<sup>19</sup>. However, climate change is experienced by marine organisms through changes in many more ecosystem attributes simultaneously, including extreme weather events such as heatwaves and cold snaps, ocean acidification, deoxygenation, and changes in productivity and circulation patterns, all occurring over space and time at different speeds and with different magnitudes<sup>20</sup>. One way to assess when and where those changes present significant ecosystem shifts affecting ecosystem conditions required by

species and habitats of conservation value (and where and when they do not) is to undertake spatial meta-analysis of ocean climate modelling time-series to detect the time of emergence of an ecosystem-level climate change signal<sup>21</sup>. In contrast with other techniques, this approach allows for the investigation of the effects of climate change as a multiple stressor process experienced by multiple species and habitats<sup>22</sup>. Spatial meta-analysis (of those many modelling time-series simultaneously) then allows for the objective classification of sites as: i) climate-resilient (i.e. climate change refugia); ii) climate-sensitive (i.e. climate change hotspots); or iii) temporarily improving in condition despite long-term regional climate trends (i.e. bright spots)<sup>23</sup>. The detection of climate sensitive sites identifies an area entering a new ecosystem state that may not be able to sustain the number of species or level of ecosystem function it has in the present, consistently with expected climate change trends in the region<sup>24</sup>. Conversely, the detection of climate-resilient sites (or refugia) identifies when and where it will likely do so<sup>25</sup>, in line with the definition of resilience used by the Irish Government's MPA Advisory Group report<sup>26</sup>. Bright spots represent a third category, where a new ecosystem state also emerges, but when observed trends are not in line with the predominant climate change trends in the region (e.g. cooling when warming is expected; species increase when decline is expected<sup>27</sup>). These three different outcomes reflect local scale differences in the rate and direction of change in environmental

“For each group of species, and each of two greenhouse gas emissions scenarios, we analysed all modelling time-series selected using spatial meta-analysis.”

conditions (as species respond to them) as a result of ocean circulation patterns and climate cycles or oscillations<sup>28</sup>. The location of climate change refugia and bright spots thus offers the opportunity for policy makers and other stakeholders to design spatial policy interventions (such as MPA networks) that build on the natural resilience of ecosystems to climate change, creating the potential to deliver effective conservation of species and habitats into the future. Such mechanisms may thus serve as nature-based solutions to help deliver climate change adaptation for ocean biodiversity, and thus help deliver on the ambition set out in the EU Biodiversity Strategy for 2030.

Based on analyses in the Revitalising Our Seas report, we sought numerical modelling datasets that represent as best as possible habitat conditions required by species listed in that report, as well as species distribution modelling for prey species. Specifically, we undertook dedicated modelling data analyses for: benthic (or seabed) and pelagic (or water column) species; megafauna species (considering birds, large fish species and mammals) focusing on whether they explore predominantly benthic or pelagic habitats; and forage fish (small pelagic fish preyed upon by many species of conservation value, as well as by the fishing industry). “Habitat conditions” were defined as the prevailing physical, biogeochemical conditions and food availability that species depend on, and the modelling dataset analysed is described in Annex 1 Table A1, for each group of species.

For each group of species, and each of two greenhouse gas emissions scenarios, we analysed all modelling time-series selected using spatial meta-analysis<sup>29</sup>. The analyses contrasted a present time-period (2006-2025) with all subsequent 20 year time periods, to the end of the 21<sup>st</sup> century. In each contrast, and for each species, each cell in the common model domain (Annex 1) was then classified as a: climate change refuge, a climate change hotspot, or a bright spot. The emissions scenarios considered are described in Annex 1, and represent a moderate global level of emissions (Representative Concentration Pathway (“RCP”) 4.5) or a high level of emissions (RCP8.5<sup>30</sup>), as used by the Intergovernmental Panel on Climate Change. The results for each temporal contrast, for each group of species and scenario was then processed to estimate the long-term location of climate change refugia, where there was agreement between scenarios. A more detailed description of the statistical methodology and datasets analysed is provided in Annex 1.

This method of analysis has already been deployed in globally distributed research programmes informing on climate-resilient conservation in Ireland<sup>31</sup>, the UK<sup>32</sup>, Tanzania<sup>33</sup>, Philippines<sup>34</sup> and Vietnam<sup>35</sup>, and is currently being deployed across 14 locations within the European Union (futuremares.eu). We now employ this approach in this chapter, to estimate what part of areas of interest proposed for the siting of new MPAs in Ireland may also be climate-resilient (i.e. climate refugia or bright spots).

16 E. Hawkins and R. Sutton (2012). Time of emergence of climate signals. *Geophysical Research Letters*. 39

17 McLeod et al. (2009). Designing marine protected area networks to address the impacts of climate change *Frontiers in Ecology and the Environment*. 7: 362-370.

18 Tittensor et al. (2019) Integrating climate adaptation and biodiversity conservation in the global ocean.” *Science Advances* 5: eaay9969.

19 Marine Protected Area Advisory Group (2020). Expanding Ireland's Marine Protected Area Network: A report by the Marine Protected Area Advisory Group. Report for the Department of Housing, Local Government and Heritage. 59pp.

20 Pörtner et al. (2022). Climate change 2022: Impacts, adaptation and vulnerability. IPCC Geneva, Switzerland.

21 Queirós et al. (2021) Bright spots as climate-smart marine spatial planning tools for conservation and blue growth. *Global Change Biology*. 27: 5514-5531.

22 *ibid*

23 *ibid*

24 *ibid*

25 *ibid*

26 Marine Protected Area Advisory Group, *op. cit.*

27 Queirós, *op. cit.*

28 Queirós et al. (2021) Bright spots as climate-smart marine spatial planning tools for conservation and blue growth. *Global Change Biology*. 27: 5514-5531.

29 *ibid*

30 D. P. Van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, et al. (2011) *Climatic Change 2011 Vol. 109 Issue 1-2 Pages 5*

31 Queirós, *op. cit.*

32 A. M. Queirós, S. Kay, M. Sciberras et al. (2023) Early-warning system: Climate-smart spatial management of UK fisheries, aquaculture and conservation. A report of the NERC/ESRC Marine Spatial Planning Addressing Climate Effects project. DOI: 10.14465/2023.msp02.tec

33 A. M. Queirós, E. Talbot, F. E. Msuya et al. (in review) Long-term climate change and extreme weather limit marine ecosystem resilience and sustainable development in the Western Indian Ocean

34 E. Talbot, J.-B. S. Jontila, B. J. Gonzales et al. (in review). Incorporating “climate-readiness” into tropical spatial fisheries management strategies

35 A. M. Queirós, H. Talbot, S. Kay, S. Saille and T. le Vu Hoang (2022) Climate-smart spatial planning assessment in support of conservation and blue growth in Da Nang city's marine environment. A report from the ACCORD project. DOI: 10.17031/dxfj-a468.

# 3 Climate-resilient sites within the proposed MPA network expansion

The modelling data analyses carried out in this chapter indicate that there are opportunities to ensure that the projected expansion of the Irish MPA network includes climate-resilient sites, where species and habitats of conservation value may be protected into the future. Overall, 60% of Irish National Marine Planning Framework area (“NMPFa”) (which includes the Exclusive Economic Zone (“EEZ”) and the territorial seas) is thought to overlap with long-term climate change refugia for at least one group of species considered in this report (281, 501km<sup>2</sup>, equivalent to 67% of the Irish EEZ, Fig. 1). If we consider only sites presently designated, the extent of the NMPFa that is within marine Natura 2000 sites in long-term climate change refugia amounts to only 7% (33, 663 km<sup>2</sup>, equivalent to 8% of the Irish EEZ). Conversely, if areas proposed in the Revitalising Our Seas report were to become designated MPAs, then 26% of the Irish EEZ (121, 140 km<sup>2</sup>, equivalent to 29% of the Irish EEZ) would be in protected areas that are also located in long-term climate change refugia, representing 69% of the new areas proposed for conservation in the report (Fig.1). As we define long-term climate change refugia as areas emerging as such for at least 40 years into the future, with high agreement between scenarios (Annex 1), placing MPAs within these areas may thus represent a no regrets decision when it comes to conservation: an opportunity to support the effective conservation of marine species and habitats for decades to come. The majority of these areas occur in offshore regions, and inshore areas to the East and North West coast of Ireland.

**Figure 1.** Total area of National Marine Planning Framework area covered by climate change refugia for at least one group of species considered in this chapter (i.e. refugia for pelagic habitats, pelagic megafauna, benthic habitats and benthic megafauna were merged). Identified refugia appeared consistently – for at least 40 years within the period of 2026 and 2069 – with high agreement between greenhouse gas emissions scenarios (RCP4.5 and RCP8.5).

With regard to specific species and habitat groups, long-term climate change refugia for megafauna reliant on pelagic habitats were identified primarily in deep offshore areas, which are in the majority of cases unprotected at present. Areas of interest (AOIs) identified in the Revitalising Our Seas report overlap with one of these refugia off the SW tip of Irish Waters, around the biologically important Porcupine Seabight (Fig. 2). Some of these areas overlap with fishing grounds and oil and gas lease areas, and detailed spatial and temporal patterns for these species can be found in Annex 2 Figure A1.

**Figure 2.** Areas in which long-term climate change refugia were identified for megafauna reliant on pelagic species and habitats (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069.

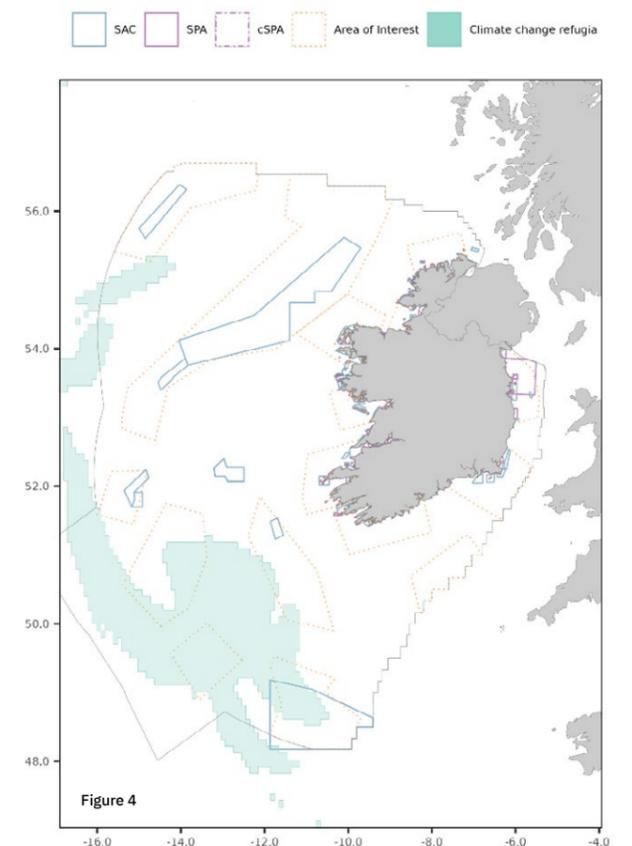
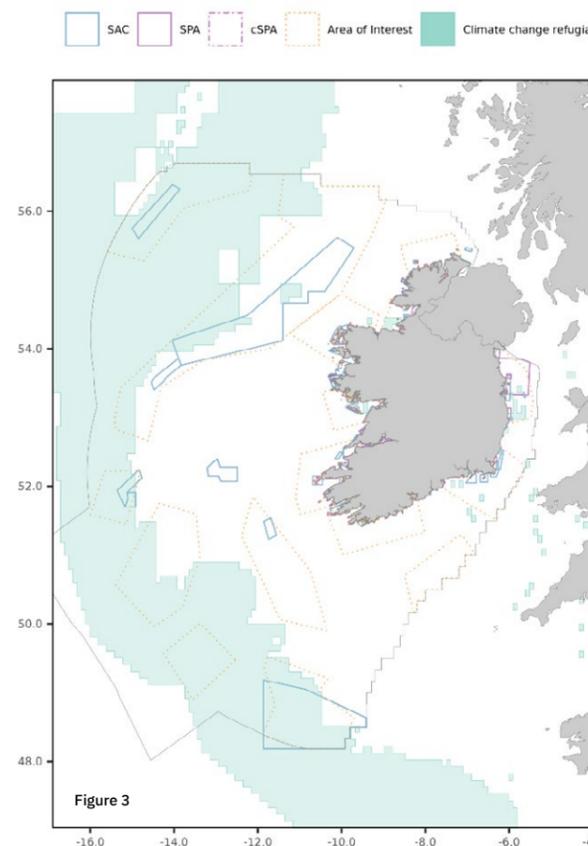
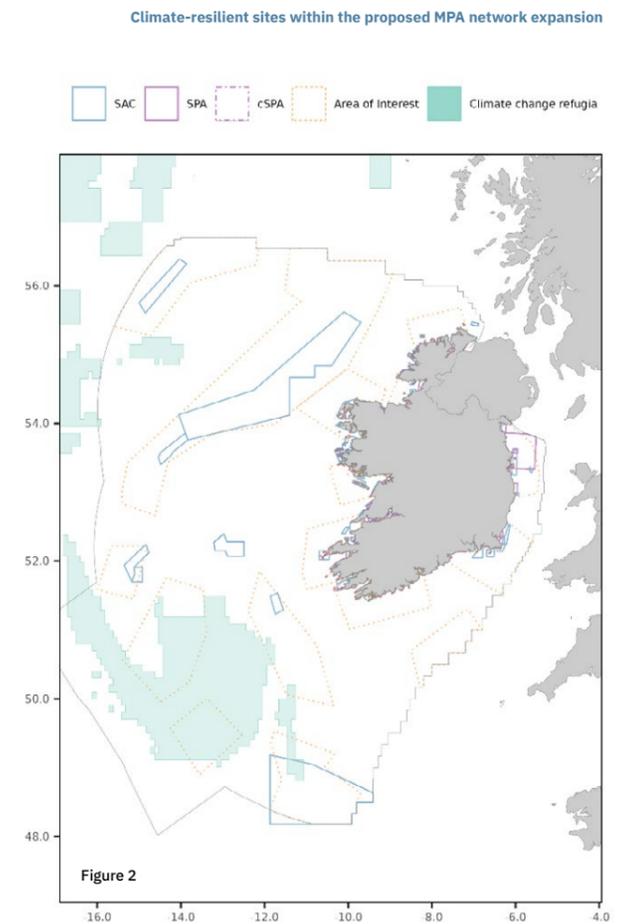
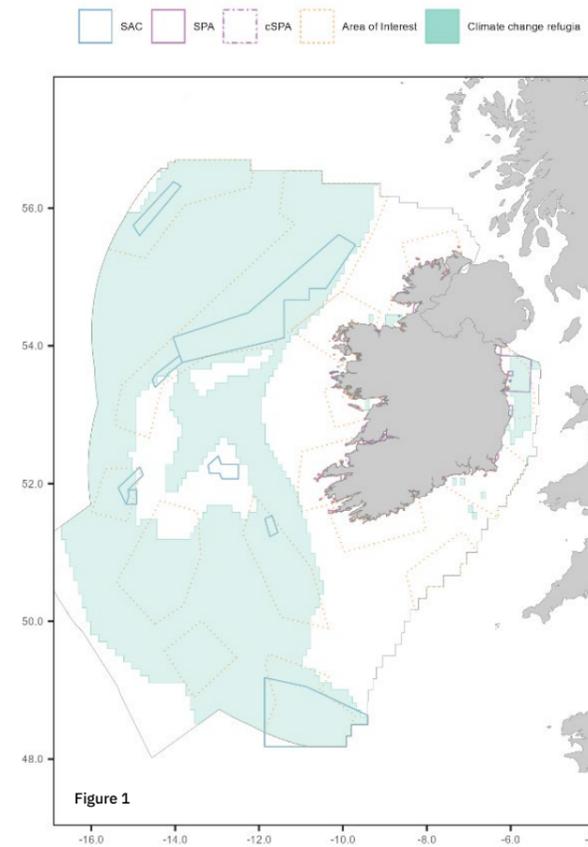
For megafauna reliant on benthic habitats, long-term climate change refugia were also identified in offshore areas around the Rockall Trough, Rockall Bank and Porcupine Seabight (Fig. 3), in some areas that are already protected by SACs, and overlapping with AOIs identified in the Revitalising Our Seas report. In those areas, fishing and oil and gas license leases overlap with some of the refugia found (Annex 2 Fig.A2). Smaller refugia were identified in inshore areas off the coasts of Sligo, Galway, Dublin and Waterford (Fig. 3), many of which are covered by AOIs identified in the Revitalising Our Seas report. In these areas, a degree of fishing, wastewater discharges and light pollution co-occurs. Detailed spatial and temporal patterns for this group of species can be found in Annex 2 Figure A2.

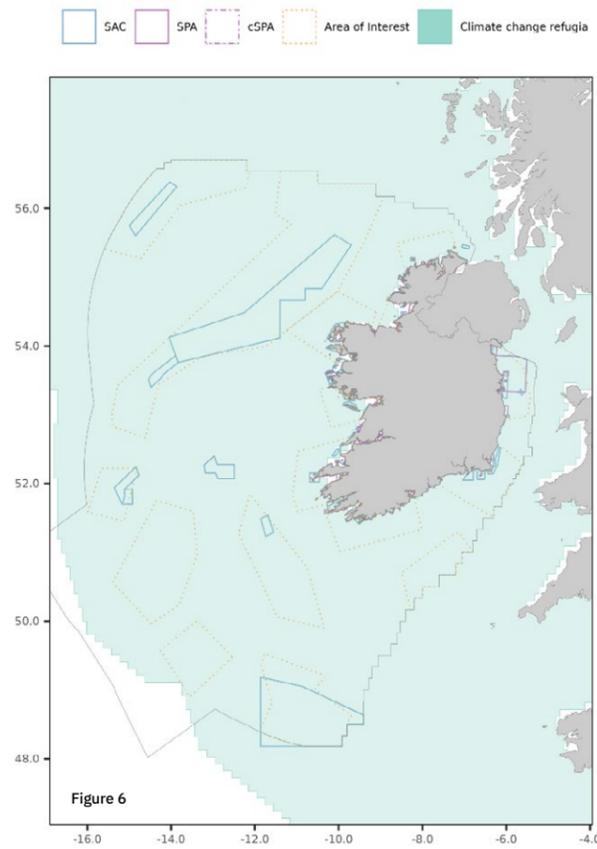
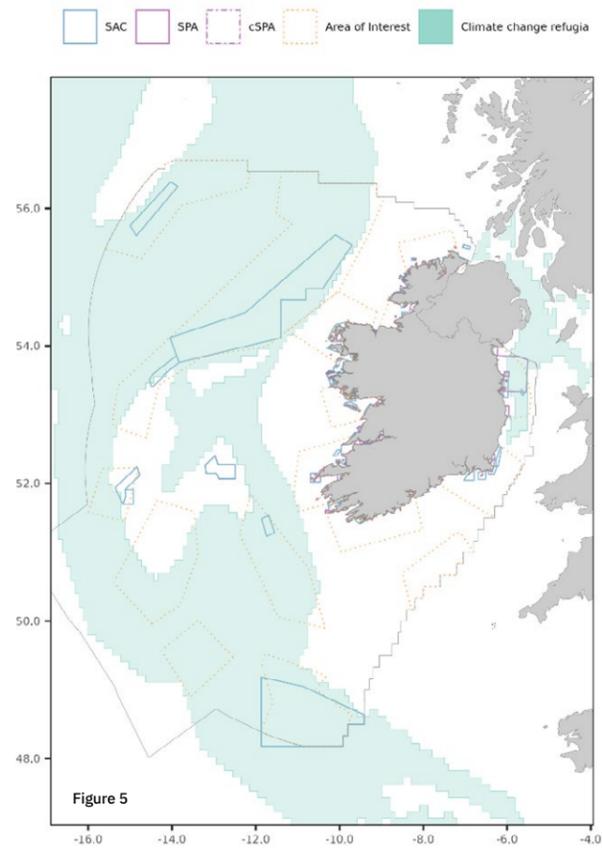
**Figure 3.** Areas in which long-term climate change refugia were identified for megafauna reliant on benthic species and habitats (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069. The grey line is the Irish National Marine Planning Framework boundary.

Long-term climate refugia for other pelagic species were found to concentrate in offshore areas to the W and SW of the Irish EEZ, around the Porcupine Seabight, and the NW around the Rockall (Fig. 4). Only one currently designated SPA is located in a climate refugia, but several of the offshore AOIs identified in the Revitalising Our Seas report lie in areas that are projected to remain at least partly climate-resilient (Fig. 4). These areas also host fishing and oil and gas leases at present, with spatial and temporal patterns shown in Annex 2 Figure A3.

**Figure 4.** Areas in which long-term climate change refugia were identified for pelagic habitats (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069. The grey line is the Irish National Marine Planning Framework boundary.

Long-term climate change refugia for other benthic species were found to be more extensive than for other groups. They were found in some inshore waters on the East Coast (where the Dublin cSPA is located, Fig. 5).





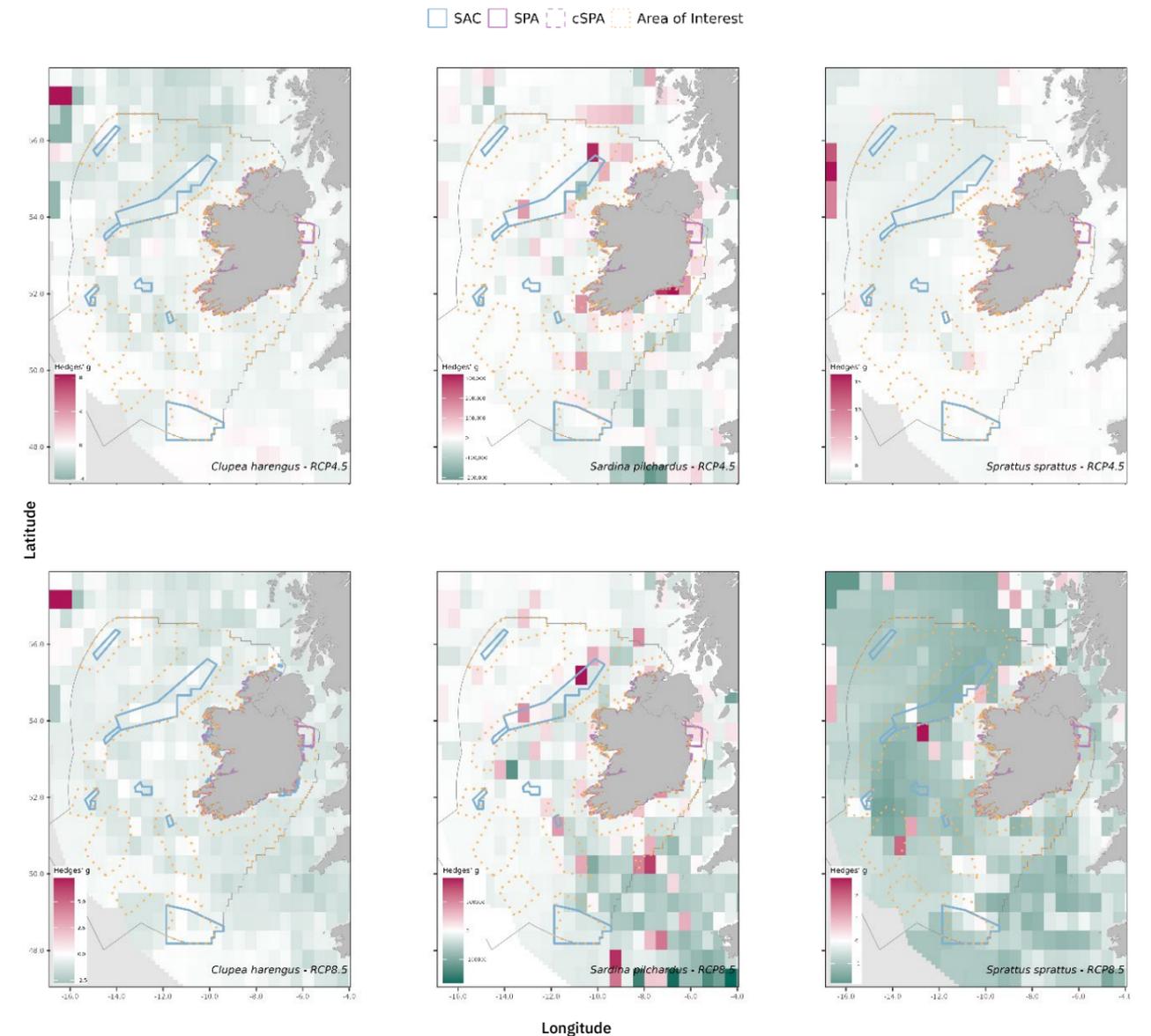
In these inshore areas, refugia overlap partially with areas where capital and maintenance dredging occurs, and where light pollution can be extensive (Annex 2, Fig.4). The latter can be ecologically meaningful for benthic species nearshore<sup>36</sup>. Long-term climate change refugia for benthic species were, however, more generally distributed in deeper offshore areas beyond the continental shelf to the W and SW (Fig.5). In these areas, they overlap with the Southern Canyons SAC, where highly diverse deep-water seabed fauna occurs within the dead coral matrix<sup>37</sup>. These areas also experience extensive fishing activity, and host oil and gas wells and license leases. Detailed spatial and temporal patterns can be found in Annex 2 Figure A4.

**Figure 5.** Areas in which long-term climate change refugia were identified for benthic species other than megafauna (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069. The grey line is the Irish National Marine Planning Framework boundary.

Long-term climate refugia for the forage fish species we analysed (*Clupea harengus*, *Sardina pilchardus* and *Sprattus sprattus*) cover the whole of the NMPFa (Fig. 6). However, because such a small number

of datasets was used in this spatial meta-analysis (Annex 1), this result may be unreliable. Figure 7 thus illustrates results per species, exploring individual species abundance changes patterns. Those results suggest that herring and sprat are expected to decline across most of the NMPFa under both greenhouse gas emissions scenarios considered, whilst sardine remain stable in some areas, or increase, in most cases. These results are in line with previous analyses for the region<sup>38</sup>. They do however suggest that key offshore areas explored by birds as foraging grounds, and also identified as potential sites for MPAs in the Revitalising Our Seas report, may be at risk of climate change effects on key, cold water prey such as herring and sprat. However, an increase in abundance of warm affiliated species such as sardine may limit some of that impact. This analysis overlooks the effects of climate change on sand eel species that are also key forage fish species, for which no species distribution modelling could be found at the time of this report.

**Figure 6.** Areas in which long-term climate change refugia were identified for forage fish (green). Refugia appeared consistently (Annex 1) across both emissions scenarios (RCP4.5 and RCP8.5), between 2026 and 2069. The grey line is the Irish National Marine Planning Framework boundary.



**Figure 7:** Representative example of mean change in individual forage fish species abundance by mid-century (2041-2060), relative to the present (2006-2025), under RCP 4.5 (top) and RCP 8.5 (bottom). Change is measured using Hedges' g, which is the standardized mean change estimator, centered around 0 (no change), and placing all species in the same scale to help comparison across species. Green shading shows where species abundances are projected to decrease in comparison to the present; pink shading shows areas where abundances are projected to increase. Herring: *Clupea harengus* (left). Sardine: *Sardina pilchardus* (middle). Sprat: *Sprattus sprattus* (right). The grey line is the Irish National Marine Planning Framework boundary.

<sup>36</sup> Davies, T. W., McKee, D., Fishwick, J. et al. (2020). Biologically important artificial light at night on the seafloor. *Scientific reports*, 10(1), 12545.

<sup>37</sup> Site synopsis: Southern Canyons SAC. (2023). Department of Housing, Local Government and Heritage. 2pp. url: [SITE SYNOPSIS \(npws.ie\)](https://www.npws.ie/SYNOPSIS)

<sup>38</sup> Pinnegar, Wright et al. (2020) Impacts of climate change on fish, relevant to the coastal and marine environment around the UK. MCCIP Science Review. 456-481.

# 4 Discussion

In this chapter, we used peer-reviewed methods for the analysis of marine climate change modelling (physical biogeochemical modelling and species distribution modelling)<sup>39</sup> to assess the spatial distribution of climate change resilience in Irish waters. These analyses allowed us to establish the location of long-term climate change refugia for marine species which may support effective conservation into the future, despite climate change pressures in the broader region. More specifically, we were able to establish that a substantial proportion of areas proposed for the siting of new Marine Protected Areas in Ireland, in the Revitalising Our Seas report, are indeed climate-resilient. The value of these sites is thus not only limited to what species occur there at present, as highlighted in the remainder of the report; it also extends into the ability to provide protection for species and habitats that may be effective in the long-term, as climate change unfolds. Protecting some of these sites would thus be in line with recommendations made in the recent Irish Government's Marine Protected Area Advisory Group report<sup>40</sup>. The ambition to establish climate-resilient MPAs is not restricted to Ireland, it is a global one<sup>41</sup>. With unprecedented climate-driven changes and extreme weather such as super heat-waves taking place in Irish waters as a result of climate change as recently as September 2023, as around the world<sup>42</sup>, it is time we deliver on this ambition, and design MPA networks that are climate-smart by design.

It is prudent to remember that there are different sources of uncertainty in ocean climate modelling<sup>43</sup>. The results presented here were generated using models (Annex 1) that have been found to reproduce observations in the North East Atlantic region<sup>44</sup>, and which are thus suitable for analyses focused in Ireland. Many of the areas we identified here as climate change refuges are located in the SW of the Irish NMPFa. This is consistent with previous analyses for the region<sup>26</sup>. Those analyses found a reduced expression of some long-term climate change trends, and in some cases, a temporary reversal of trends, potentially linked to climate cycles and basin-scale oceanographic processes, in this case the Atlantic Multidecadal Oscillation<sup>45</sup> and a changing Atlantic Meridional Overturning Circulation<sup>46</sup>. Such effects are known to modify the regional expression of climate trends and to cause significant departure from expected long-term (century-scaled) mean climate change signals within the short and medium term (years to decades)<sup>47</sup>. The results reported here estimate the location of long-term climate change refugia for different groups of species, for at least 40 years. Placing them under conservation mechanisms such as well-managed marine protected areas may thus represent a key time-buying strategy to support broader Irish marine biodiversity until such a time when we have globally reduced the pace of climate change.

39 Queirós, A. M., E. Talbot, N. J. Beaumont et al. (2021). Bright spots as climate-smart marine spatial planning tools for conservation and blue growth. *Global Change Biology* 27: 5514-5531.

40 Marine Protected Area Advisory Group (2020). Expanding Ireland's Marine Protected Area Network: A report by the Marine Protected Area Advisory Group. Report for the Department of Housing, Local Government and Heritage. 59pp.

41 D. P. Tittensor, M. Beger, K. Boerder et al. (2019). Integrating climate adaptation and biodiversity conservation in the global ocean. *Science Advances*. 5: eaay9969

42 IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change..

43 M. R. Payne, M. Barange, W. W. Cheung et al. (2016) Uncertainties in projecting climate change impacts in marine ecosystems. *ICES Journal of Marine Science* 2015 73: 1272-1282

44 A. M. Queirós, S. Kay, M. Sciberras et al. (2023) Early-warning system: Climate-smart spatial management of UK fisheries, aquaculture and conservation. A report of the NERC/ESRC Marine Spatial Planning Addressing Climate Effects project. DOI: 10.14465/2023.msp02.tec

45 G. McCarthy, E. Gleeson and S. Walsh. (2015) The influence of ocean variations on the climate of Ireland. *Weather*. 70: 242-245.

46 G. D. McCarthy, D. A. Smeed, S. A. Cunningham et al. Atlantic Meridional Overturning Circulation, MCCIP Science Review. Marine Climate Change Impacts Partnership. DOI: 10.14465/2017.arc10.002-atl

47 N. Bindoff, W. W. Cheung, J. Kairo et al. (2019) Changing Ocean, Marine Ecosystems, and Dependent Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

# Annex 1

## Supplementary technical information

**A1. Modelling datasets used**

This report uses a wealth of state-of-the-art publicly available ocean climate modelling for Irish marine waters, primarily derived from UK Research and Innovation, Natural Environmental Research Council National Capability, and European research framework modelling projects. Use of publicly available modelling datasets ensured all data were readily available for consultation at the time of report publication, that the report could be delivered without delay, without extra cost to our funders.

Physical biogeochemical modelling data 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 H2020 programme CERES, and are in line with modelling used within the 6<sup>th</sup> Assessment Report of the Intergovernmental Panel on Climate Change. Species distribution modelling data used 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 species of interest to Ireland were found to be needed for this report, SS-DEBM runs were made available from the FP7 programme DEVOTES. Those datasets are available upon request from Jose Fernandes (AZTI), and employed scenarios were consistent with the 5<sup>th</sup> 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 analysed ocean 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 8.5 are contrasted in each of the report's focal sector analyses. These two scenarios were chosen because, at the time of the study, they were seen to represent a likely range of future global greenhouse gas and aerosol concentrations (Bindoff, Cheung et al. 2019, Hausfather and Peters 2020, Schwalm, Glendon et al. 2020, Masson-Delmotte, Zhai et al. 2022). 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 21<sup>st</sup> century under RCP8.5 (the "growing emissions" scenario), leading to mean global warming ~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 21<sup>st</sup> 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 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. Notably, all scenarios considered overshoot the Paris Agreement goal of keeping global warming below 1.5°C, and are a good illustration of the current progress in global emissions cuts at the time of this report (United Nations Environment Programme 2022). As climate action accelerates, lower emissions scenarios should be considered.

For species distribution modelling datasets used as prey in analyses for megafauna, and those used in the forage fish analyses, 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 species also targeted commercially, thus include an element of fishing mortality in addition to a natural mortality term. For each analysis described in this chapter, the specific modelling datasets used and their sources are clearly listed in Table A1.

**Table A1: Modelling datasets used in spatial -metanalyses, for different species groups considered in this report. "MSY" reflects the fishing effort used in species distribution modelling datasets pertaining to commercial species, whereby e.g. MSY is a fishing effort leading to a mortality rate that is 6 times the advised Maximum Sustainable Yield for the species (Sailley et al. 2020).**

Model type	Modelled variable	Units	Species group	Model
Physical-biogeochemical	Net primary production	Kg C m <sup>-3</sup> s <sup>-1</sup>	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Potential energy anomaly (stratification)	J m <sup>-3</sup>	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Water column sum of phytoplankton carbon	Kg C m <sup>-3</sup>	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Bottom dissolved oxygen	mmol m <sup>-3</sup>	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Bottom non-living organic carbon	Kg C m <sup>-3</sup>	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Bottom saturation state of aragonite	scalar	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Bottom sea water pH	scalar	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Bottom sea water potential temperature	°C	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Bottom sea water salinity	PSU	Benthic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Net primary production	Kg C m <sup>-3</sup> s <sup>-1</sup>	Pelagic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Potential energy anomaly (stratification)	J m <sup>-3</sup>	Pelagic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Water column sum of phytoplankton carbon	Kg C m <sup>-3</sup>	Pelagic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Surface dissolved oxygen	mmol m <sup>-3</sup>	Pelagic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Surface sea water pH	scalar	Pelagic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Surface sea water potential temperature	°C	Pelagic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Surface sea water salinity	PSU	Pelagic habitats	POLCOMS-ERSEM

w	Institute	Scenario	Time period	Predicted outcome	Source
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased, decreased productivity	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased, decreased productivity	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2021)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased, decreased productivity	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)

Table A1– Continued

Model type	Modelled variable	Units	Species group	Model
Physical	Winter surface thermal front strength	scalar	Pelagic habitats	POLCOMS-ERSEM
Physical	Heatwave duration	days	Pelagic habitats	POLCOMS-ERSEM
Physical-biogeochemical	Surface dissolved oxygen	mmol m <sup>-3</sup>	Pelagic megafauna	POLCOMS-ERSEM
Physical-biogeochemical	Surface sea water potential temperature	°C	Pelagic megafauna	POLCOMS-ERSEM
Physical-biogeochemical	Surface sea water salinity	PSU	Pelagic megafauna	POLCOMS-ERSEM
Physical-biogeochemical	Net primary production	Kg C m <sup>-3</sup> s <sup>-1</sup>	Pelagic megafauna	POLCOMS-ERSEM
Physical	Summer thermal front strength	scalar	Pelagic megafauna	POLCOMS-ERSEM
Physical	Winter thermal front strength	scalar	Pelagic megafauna	POLCOMS-ERSEM
Species distribution	<i>Clupea harengus</i>	Abundance	Pelagic megafauna	SS-DBEM
Species distribution	<i>Merlangius merlangus</i>	Abundance	Pelagic megafauna	SS-DBEM
Species distribution	<i>Micromesistius poutassou</i>	Abundance	Pelagic megafauna	SS-DBEM
Species distribution	<i>Scomber scombrus</i>	Abundance	Pelagic megafauna	SS-DBEM
Species distribution	<i>Sprattus sprattus</i>	Abundance	Pelagic megafauna	SS-DBEM
Physical-biogeochemical	Bottom dissolved oxygen	mmol m <sup>-3</sup>	Benthic megafauna	POLCOMS-ERSEM
Physical-biogeochemical	Bottom non-living organic carbon	Kg C m <sup>-3</sup>	Benthic megafauna	POLCOMS-ERSEM
Physical-biogeochemical	Bottom sea water potential temperature	scalar	Benthic megafauna	POLCOMS-ERSEM
Physical-biogeochemical	Bottom sea water salinity	PSU	Benthic megafauna	POLCOMS-ERSEM
Physical-biogeochemical	Net primary production	Kg C m <sup>-3</sup> s <sup>-1</sup>	Benthic megafauna	POLCOMS-ERSEM
Habitat suitability	<i>Cancer pagurus</i>	habitat suitability	Benthic megafauna	DEB
Species distribution	<i>Crangon crangon</i>	habitat suitability	Benthic megafauna	SS-DBEM
Species distribution	<i>Gadus morhua</i>	abundance	Benthic megafauna	SS-DBEM
Species distribution	<i>Loligo forbesii</i>	abundance	Benthic megafauna	SS-DBEM
Species distribution	<i>Mytilus edulis</i>	abundance	Benthic megafauna	SS-DBEM
Species distribution	<i>Pleuronectes platessa</i>	abundance	Benthic megafauna	SS-DBEM
Species distribution	<i>Pollachius virens</i>	abundance	Benthic megafauna	SS-DBEM
Species distribution	<i>Solea Solea</i>	abundance	Benthic megafauna	SS-DBEM
Species distribution	<i>Clupea harengus</i>	abundance	Forage fish	SS-DBEM
Species distribution	<i>Sardina pilchardus</i>	abundance	Forage fish	SS-DBEM
Species distribution	<i>Sprattus sprattus</i>	abundance	Forage fish	SS-DBEM

w	Institute	Scenario	Time period	Predicted outcome	Source
Miller et al. 2020-	PML	RCP4.5; RCP 8.5	2006-2098	Increased	IPCC (2019)
Queiros et al 2023	PML	RCP4.5; RCP 8.5	2006-2098	Increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Increased	IPCC (2019)
Sailley et al. 2020	PML	RCP 4.5 MSY 6; RCP8.5 MSY 8	2006-2099	Decrease due to decreased productivity. Though proportional increase in catch.	IPCC (2022); Townhill, Couce et al. (2023)
Fernandes et al. 2017-	PML/AZTI	RCP2.6; RCP8.5	2006-2098	Decreased	Pinnegar, Wright et al. (2020), IPCC (2022)
Fernandes et al. 2017-	PML/AZTI	RCP2.6; RCP8.5	2006-2098	Decreased	IPCC (2022); Townhill, Couce et al. (2023)
Sailley et al. 2020	PML	RCP 4.5 MSY 6;	2006-2098	Decreased	IPCC (2022); Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP8.5 MSY 8	2006-2098	Decreased	IPCC (2022); Pinnegar, Wright et al. (2020)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased, decreased productivity	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	increased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Kay et al. 2020	PML	RCP4.5; RCP 8.5	2006-2099	Decreased	IPCC (2019)
Queiros et al. 2023	PML	RCP4.5; RCP 8.5	2006-2098	Decreased	Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP 4.5 MSY 6; RCP8.5 MSY 8	2006-2098	Decreased	Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP 4.5 MSY 6; RCP8.5 MSY 8	2006-2098	Decreased	Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP 4.5 MSY 6; RCP8.5 MSY 8	2006-2098	Decrease due to decreased productivity. Though proportional increase in catch.	IPCC (2022); Pinnegar, Wright et al. (2020)
Fernandes et al. 2017-	AZTI	RCP 2.6; RCP8.5	2006-2098	Decreased	Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP 4.5 MSY 6; RCP8.5 MSY 8	2006-2098	Decreased	Pinnegar, Wright et al. (2020)
Fernandes et al. 2017-	AZTI	RCP 2.6; RCP8.5	2006-2098	Decreased	Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP 4.5 MSY 6; RCP8.5 MSY 8	2006-2098	Decreased	Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP8.5 MSY 8	2006-2098	Decreased	IPCC (2022); Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP8.5 MSY 8	2006-2098	Decreased	IPCC (2022); Pinnegar, Wright et al. (2020)
Sailley et al. 2020	PML	RCP8.5 MSY 8	2006-2098	Decreased	IPCC (2022); Pinnegar, Wright et al. (2020)



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**A2 Temporal and spatial resolution of analyses**

We co-designed analyses with the ambition to provide the best ocean climate change evidence for the Irish National Marine Planning Framework areas, in the format that best suited the needs of our end-users. To this end, we focused on contrasting the current state of Irish coastal and marine habitats used by the groups of species considered in this chapter, with those of these ecosystems in the short-, medium and long-term. 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 km<sup>2</sup>). 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 in subsequent sections. 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 2, above (Queirós, Talbot et al. 2021).

**A3 Other spatial data used**

The results from the climate modelling analyses were then interpreted in the context of the current distributions of SACs, SPAs and the one MPA in Ireland, as well as new areas proposed for siting of MPAs in the Revitalising Our Seas report. The overlay of modelling data with this GIS information allowed us to identify opportunities for the location of new MPAs, or expansion of existing MPAs, into areas harbouring climate change refugia. GIS datasets are detailed in Table A2, p.23

**A4 Summary plots and shapefile creation**

To facilitate the use of information contained in this chapter, we created summary plots that summarise 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 across NMPFa. The former are provided as part of this report. The shapefiles containing the GIS information used to construct these plots is also made available with the chapter.

Given climate change creates wide distributions of climate change hotspots across much of the EEZ in most analyses, we restricted the analyses leading to the creation of these summary plots to the period between 2026-2069, covering the year immediately after the period used as the present in all analyses (2006-2025), extending beyond the mid-century. To this end, we further processed the outputs of all species groups analyses, in both climate change scenarios (detailed in Annex 2). 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 species 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, and exported as shapefiles.

Table A2: GIS datasets and sources

Spatial dataset	Data provider	Available at
Special Areas of Conservation	National Parks and Wildlife Service	<a href="https://www.npws.ie/maps-and-data/designated-site-data/download-boundary-data">https://www.npws.ie/maps-and-data/designated-site-data/download-boundary-data</a>
Special Protection Area	National Parks and Wildlife Service	<a href="https://www.npws.ie/maps-and-data/designated-site-data/download-boundary-data">https://www.npws.ie/maps-and-data/designated-site-data/download-boundary-data</a>
National Marine Planning Framework Area	Department of Housing, Local Government and Heritage	<a href="https://atlas.marine.ie/#?c=53.9108;-15.9082;6">https://atlas.marine.ie/#?c=53.9108;-15.9082;6</a>
EEZ	Department of Communications, Climate Action and the Environment	<a href="http://atlas.marine.ie/midata/AdministrativeUnits/MaritimeBoundary_Exclusive_Economic_Zone.shapezip.zip">http://atlas.marine.ie/midata/AdministrativeUnits/MaritimeBoundary_Exclusive_Economic_Zone.shapezip.zip</a>
Inshore fishing distribution	Irish Marine Institute	<a href="https://atlas.marine.ie/#?c=53.9108;-15.9082;6">https://atlas.marine.ie/#?c=53.9108;-15.9082;6</a>
Offshore fishing distribution	Global Fishing Watch	<a href="https://globalfishingwatch.org/data-download/datasets/public-fishing-effort">https://globalfishingwatch.org/data-download/datasets/public-fishing-effort</a>
Offshore oil and gas authorisations	Department of Communications, Climate Action and the Environment	<a href="http://atlas.marine.ie/midata/EnergyResourcesExploration/Current_Authorisations.shapezip.zip">http://atlas.marine.ie/midata/EnergyResourcesExploration/Current_Authorisations.shapezip.zip</a>
Offshore oil and gas infrastructure	Department of Communications, Climate Action and the Environment	<a href="http://atlas.marine.ie/midata/EnergyResourcesExploration/Exploration_Wells_Irish_Offshore.shapezip.zip">http://atlas.marine.ie/midata/EnergyResourcesExploration/Exploration_Wells_Irish_Offshore.shapezip.zip</a>
Marine artificial light at night	Fabio Falchi	By request
Telecommunications cables	EMODnet Human Activities data portal	<a href="https://emodnet.ec.europa.eu/geoviewer/">https://emodnet.ec.europa.eu/geoviewer/</a>
Aggregate extraction	EMODnet Human Activities data portal	<a href="https://emodnet.ec.europa.eu/geoviewer/">https://emodnet.ec.europa.eu/geoviewer/</a>
Capital and maintenance dredging	EMODnet Human Activities data portal	<a href="https://emodnet.ec.europa.eu/geoviewer/">https://emodnet.ec.europa.eu/geoviewer/</a>
Dredge spoil dumping	EMODnet Human Activities data portal	<a href="https://emodnet.ec.europa.eu/geoviewer/">https://emodnet.ec.europa.eu/geoviewer/</a>
Pipelines	EMODnet Human Activities data portal	<a href="https://emodnet.ec.europa.eu/geoviewer/">https://emodnet.ec.europa.eu/geoviewer/</a>
Windfarms	EMODnet Human Activities data portal	<a href="https://emodnet.ec.europa.eu/geoviewer/">https://emodnet.ec.europa.eu/geoviewer/</a>

The overlay of modelling data with this GIS information allowed us to identify opportunities for the location of new MPAs, or expansion of existing MPAs, into areas harbouring climate change refugia. GIS datasets are detailed in Table A2

## A5 Annex 1 References

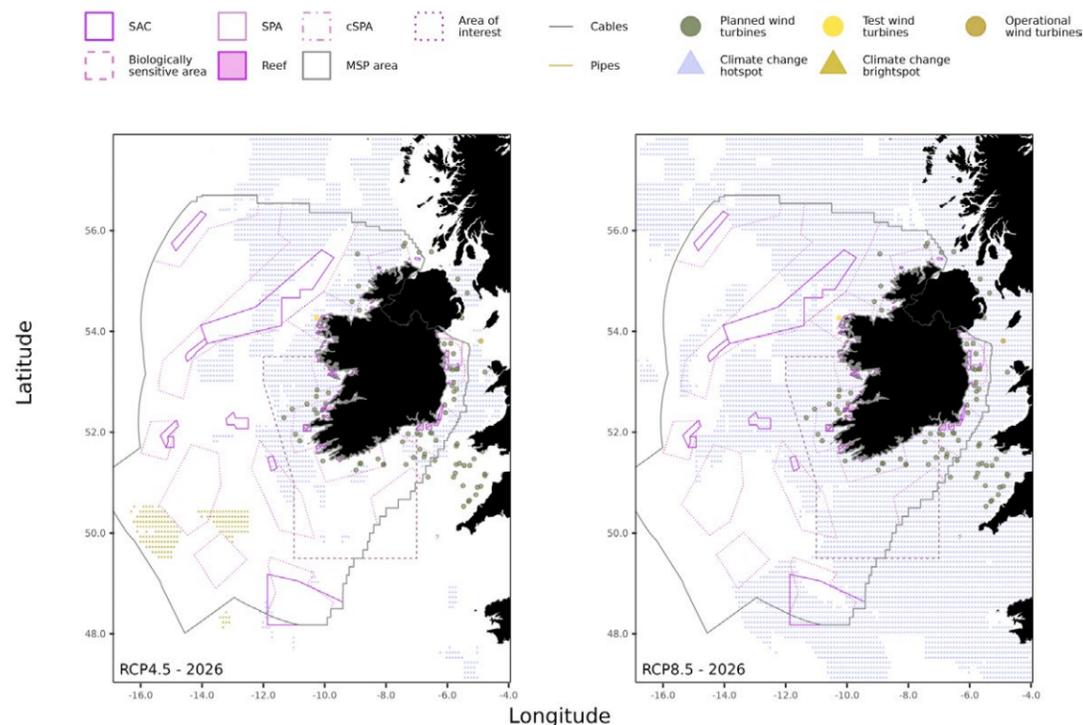
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# Annex 2

## Supplementary figures

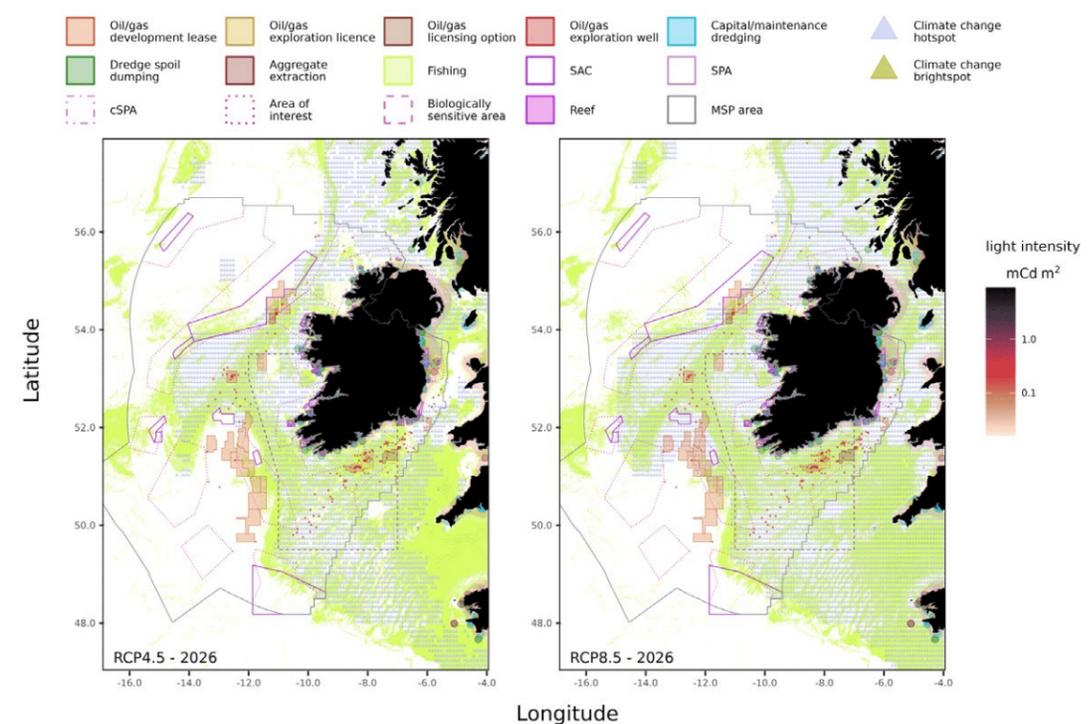
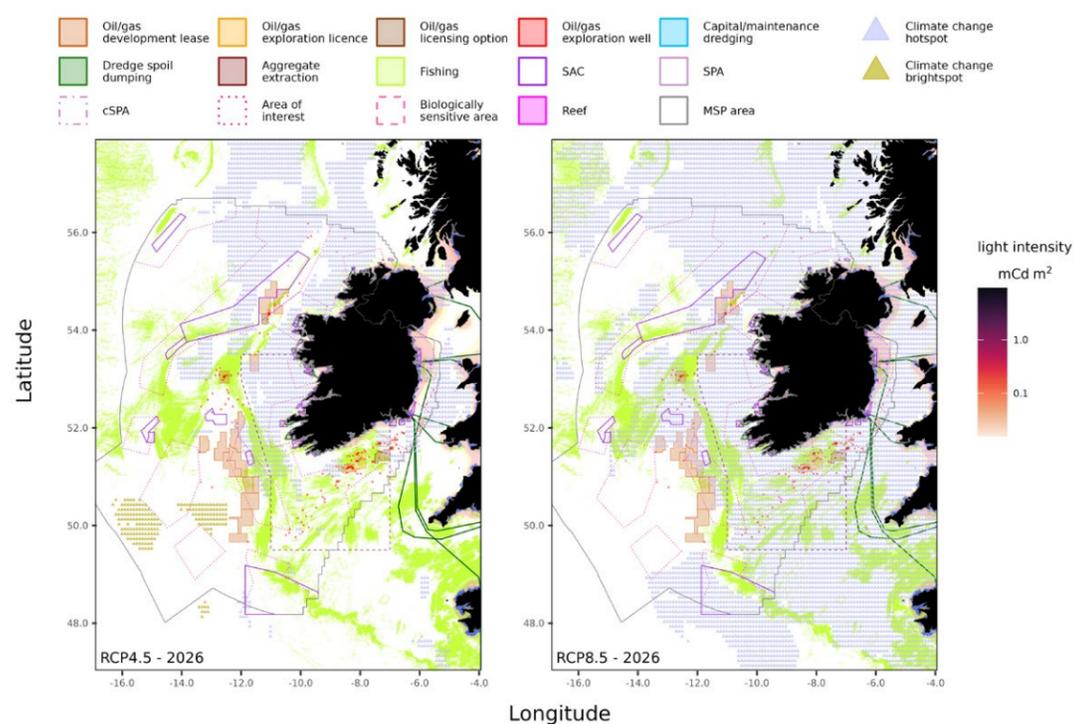
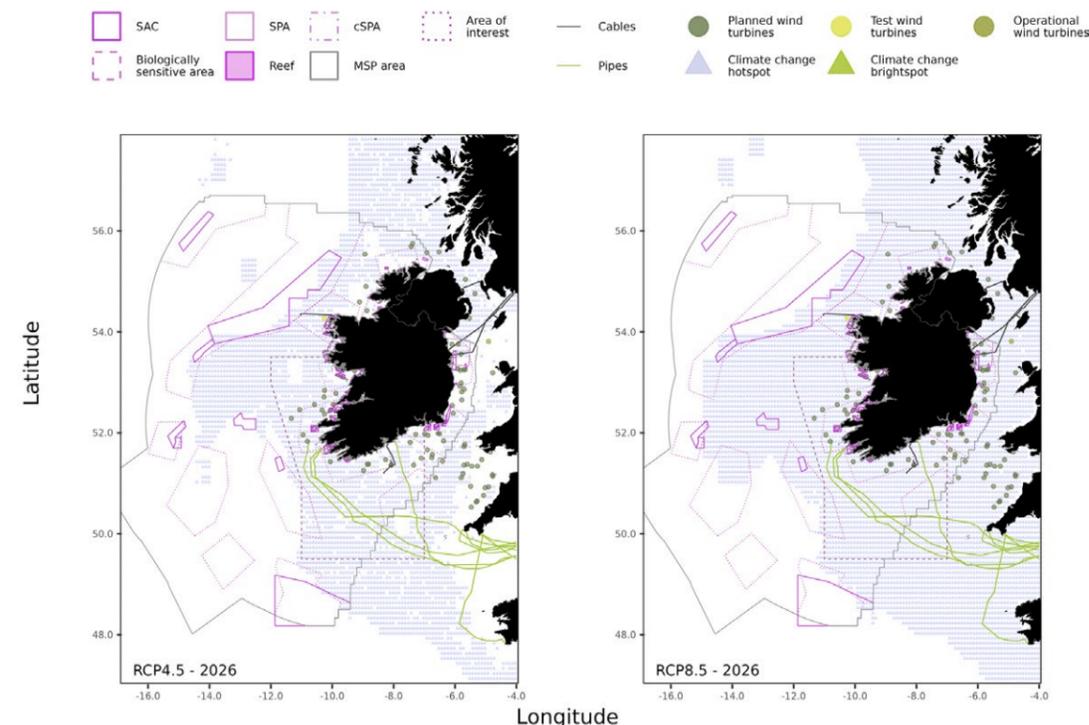
**Figure A1:** Climate change resilience maps for habitats (environment and prey) required by pelagic megafauna in Irish waters, against the distribution of the existing Natura 2000 network (top), and other human pressures and maritime sectors (bottom). Animations run through the 21<sup>st</sup> century, contrasting the present 20 year period (2006-2025) with all subsequent 20 year periods, the first year of each indicated in the bottom left corner of each map.

Left: Projections under RCP4.5. Right: Projections under RCP8.5. Climate change refugia (white) are widespread in the SW of the Irish EEZ, where some bright spots (yellow) also occur temporarily under RCP 4.5. Climate change hotspots (purple) dominate the rest of the EEZ, enclosing all inshore waters. Underlying modelling datasets are detailed in Annex 1 Table A1. The grey line is the boundary of the marine planning area.



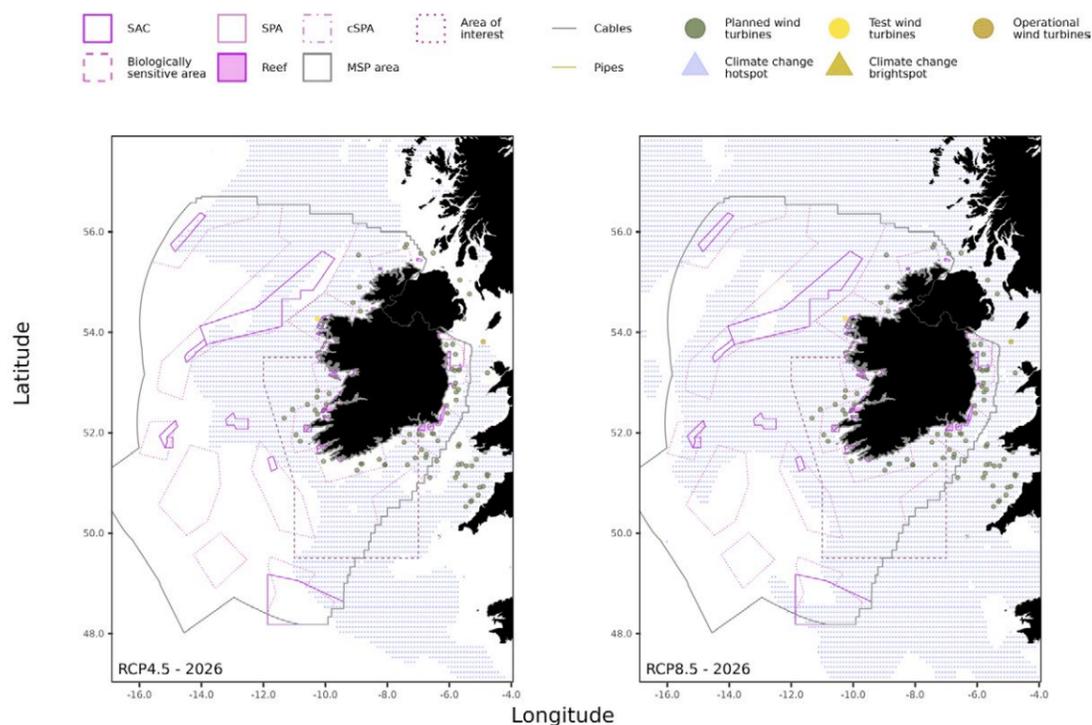
**Figure A2:** Climate change resilience maps for habitats (environment and prey) required by benthic megafauna in Irish waters, against the distribution of the existing Natura 2000 network (top), and other human pressures and maritime sectors (bottom). Animations run through the 21<sup>st</sup> century, contrasting the present 20 year period (2006-2025) with all subsequent 20 year periods, the first year of each indicated in the bottom left corner of each map.

Left: Projections under RCP4.5. Right: Projections under RCP8.5. Climate change refugia (white) are widespread in western, offshore areas, and are dotted around inshore waters. Climate change hotspots (purple) dominate the rest of the EEZ. Underlying modelling datasets are detailed in Annex 1 Table A1. The grey line is the boundary of the marine planning area.



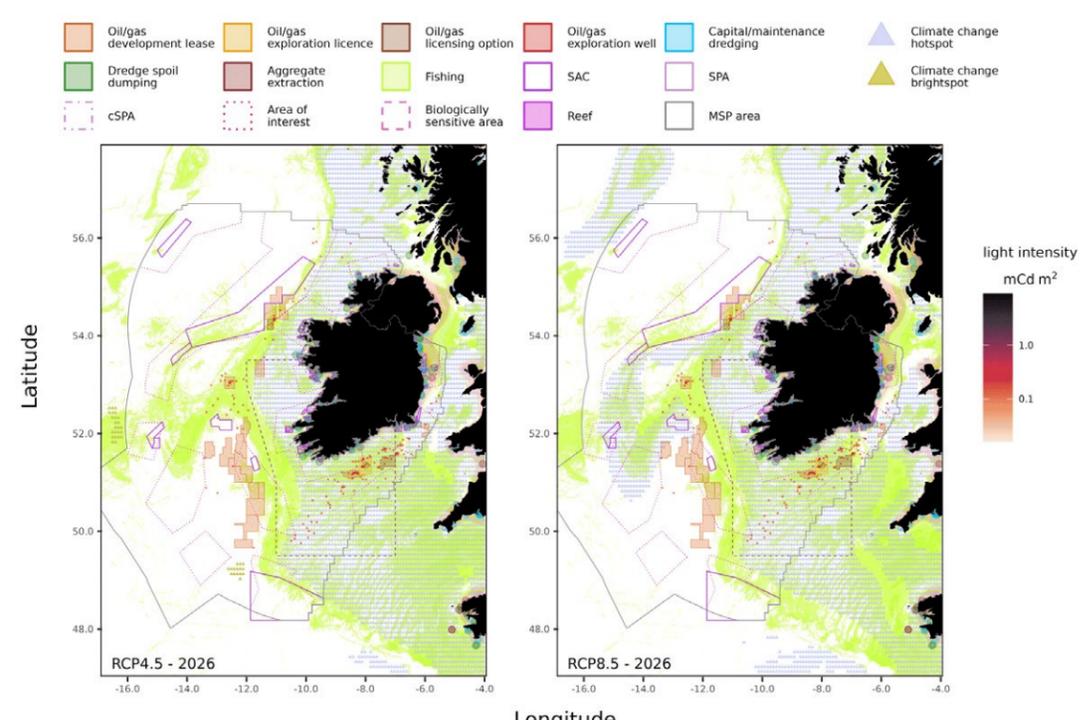
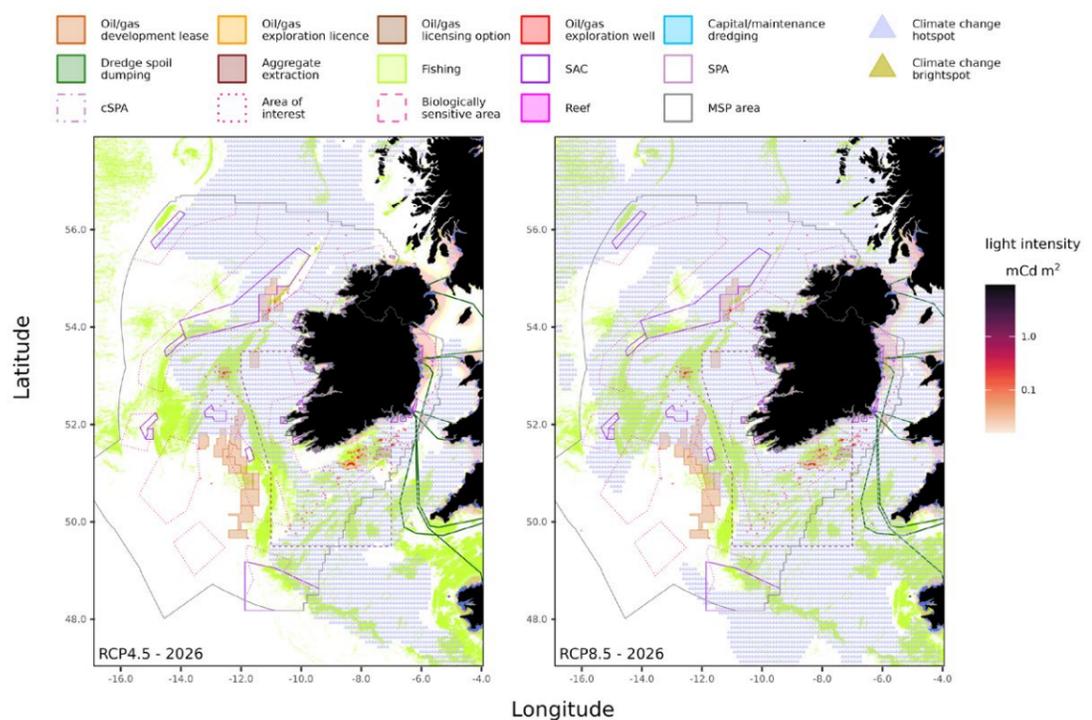
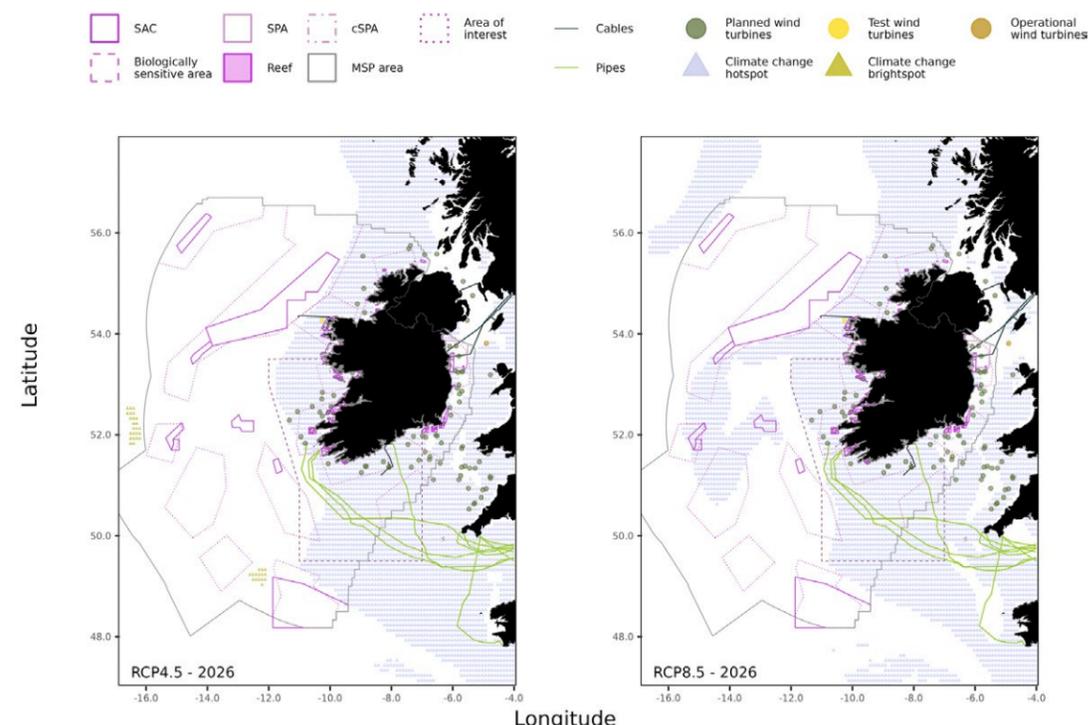
**Figure A3:** Climate change resilience maps for pelagic species (other than megafauna) in Irish waters, against the distribution of the existing Natura 2000 network (top), and other human pressures and maritime sectors (bottom). Animations run through the 21<sup>st</sup> century, contrasting the present 20 year period (2006-2025) with all subsequent 20 year periods, the first year of each indicated in the bottom left corner of each map.

Left: Projections under RCP4.5. Right: Projections under RCP8.5. Climate change refugia (white) are widespread in the SW of the Irish EEZ, especially under RCP 4.5. Climate change hotspots (purple) dominate the rest of the EEZ, enclosing all inshore waters. Underlying modelling datasets are detailed in Annex 1 Table A1. The grey line is the boundary of the marine planning area.



**Figure A4:** Climate change resilience maps for benthic species (other than megafauna) in Irish waters, against the distribution of the existing Natura 2000 network (top), and other human pressures and maritime sectors (bottom). Animations run through the 21<sup>st</sup> century, contrasting the present 20 year period (2006-2025) with all subsequent 20 year periods, the first year of each indicated in the bottom left corner

of each map. Left: Projections under RCP4.5. Right: Projections under RCP8.5. Climate change refugia (white) are widespread in the SW of the Irish EEZ, especially under RCP 4.5. Climate change hotspots (purple) dominate the rest of the EEZ, enclosing all inshore waters. Underlying modelling datasets are detailed in Annex 1 Table A1. The grey line is the boundary of the marine planning area.





At Fair Seas, we seek to protect, conserve and restore Ireland's unique marine environment. Our ambition is to see Ireland become a world leader in marine protection, giving our species, habitats and coastal communities the opportunity to thrive.

Fair Seas aims to build a movement of ocean stewardship across Ireland that energises and empowers people, to advocate for ambitious and robust legislation, provide impartial scientific data and research, and propose a network of effective well-managed marine protected areas.

The Fair Seas campaign is led by a coalition of Ireland's leading environmental non-governmental organisations and networks.



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