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Bright spots as climate-smart marine spatial planning tools for conservation and blue growth

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Abstract

Marine spatial planning that addresses ocean climate-driven change ('climate-smart MSP') is a global aspiration to support economic growth, food security and ecosystem sustainability. Ocean climate change ('CC') modelling may become a key decision-support tool for MSP, but traditional modelling analysis and communication challenges prevent their broad uptake. We employed MSP-specific ocean climate modelling analyses to inform a real-life MSP process; addressing how nature conservation and fisheries could be adapted to CC. We found that the currently planned distribution of these activities may become unsustainable during the policy's implementation due to CC, leading to a shortfall in its sustainability and blue growth targets. Significant, climate-driven ecosystem-level shifts in ocean components underpinning designated sites and fishing activity were estimated, reflecting different magnitudes of shifts in benthic versus pelagic, and inshore versus offshore habitats. Supporting adaptation, we then identified: CC refugia (areas where the ecosystem remains within the boundaries of its present state); CC hotspots (where climate drives the ecosystem towards a new state, inconsistent with each sectors' present use distribution); and for the first time, identified bright spots (areas where oceanographic processes drive range expansion opportunities that may support sustainable growth in the medium term). We thus create the means to: identify where sector-relevant ecosystem change is attributable to CC; incorporate resilient delivery of conservation and sustainable ecosystem management aims into MSP; and to harness opportunities for blue growth where they exist. Capturing CC bright spots alongside refugia within protected areas may present important opportunities to meet sustainability targets while helping support the fishing sector in a changing climate. By capitalizing on the natural distribution of climate resilience within ocean ecosystems, such climate-adaptive spatial management strategies could be seen as nature-based solutions to limit the impact of CC on ocean ecosystems and dependent blue economy sectors, paving the way for climate-smart MSP.

KEYWORDS
adaptation, blue carbon, climate change, fisheries, marine protected area, marine spatial planning, mitigation, nature-based solutions

1 | INTRODUCTION

The cumulative pressures of an altered global climate system, enhanced harvesting of ocean resources, and increased use of coastal areas towards economic growth, have led to the deterioration of coastal and marine ecosystems worldwide (Bindoff et al., 2019; Halpern et al., 2012; Levin et al., 2020). Marine spatial planning (MSP) is a public process of analysing and allocating marine space to human activities to achieve ecological, economic and social objectives. Resulting plans regulate the sharing of marine space by different maritime industries and nature conservation, managing cross-sector trade-offs and outlining priorities, in harmony with within-sector policies and broader development and environmental goals (Ehler & Douvere, 2009). Designing MSP that addresses the effects of climate change ('climate-smart MSP') is a pressing, global ambition for ocean managers. It is seen as a key strategy to capitalize on, and adapt to, shifting living resource distributions; deliver effective marine conservation; promote sustainable, ecosystem-based management; reduce sectorial conflicts; promote poverty alleviation and food security in dependent communities; mitigate climate change ('CC'); and to protect life in a changing ocean for future generations (United Nations Sustainable Development Goals 1, 2, 13 and 14; Frazão Santos et al., 2020). With very few exceptions, however, climate-smart MSP remains a policy ambition without practical implementation. Marine ecological communities, and the ecosystems within which they exist, are the marine resources and natural capital that underpin the activities of key maritime sectors and the focus of marine conservation: all affected by MSP. It is recognized that marine communities strongly respond to many environmental conditions that are highly spatially and temporally dynamic, and increasingly variable, at almost any scale (Bates et al., 2018). This increased, climate-driven environmental variability, together with direct human pressures resulting from development, pollution and resource extraction (Frazão Santos et al., 2020; Queirós et al., 2016) expose marine ecosystems to a multiple stressor ocean (Bindoff et al., 2019). Climate-smart MSP must thus support effective strategies for the spatial management of those sectors reliant on wild species communities under CC, such as wild capture fisheries, farming, ecotourism, as well as for marine conservation. Only this path can support blue economic growth (Ehler & Douvere, 2009; IOC-UNESCO, 2018).

From an ecological perspective, designing effective climate-smart MSP thus requires an objective means to assess how ecosystem components relevant to each sector may respond to CC, including projections of climate exposure for ocean species and habitats, as well as their climate sensitivity (Bates et al., 2018; Rilov et al., 2019). Marine ecosystem-scaled CC modelling (physical–biogeochemical modelling, and species distribution modelling) has been identified as an important decision-support tool for MSP that can help meet this need. Indeed, it can enable the exploration of different spatial management scenarios under different climate futures, as well as their prioritization in time (Frazão Santos et al., 2020; Levin et al., 2020; Pınarbaşı et al., 2017; Queirós et al., 2016; Sarà et al., 2018). However, traditional ocean CC modelling analysis methods tend to focus on long-term climate impacts on individual ocean attributes separately, and those that focus on species and habitats often equate ocean warming alone to CC (Bates et al., 2018; Bindoff et al., 2019; Kapsenberg & Cyronak, 2019; Molinos et al., 2016; Pinsky et al., 2019; Wilson et al., 2020). More encompassing CC modelling analysis approaches, providing a more holistic view of marine ecosystems, are needed to inform the development of MSP that is effective in a multiple stressor ocean, and anchored in ecosystem-based management (Ehler & Douvere, 2009; Queirós et al., 2016). Specifically, climate-smart MSP would ideally be supported by evidence analyses: that consider how the whole ecosystem supporting each maritime sector affected by a plan is changing over time; that are well aligned with the implementation time-frame of each plan; and that consider how maritime sectors interact spatially. If co-designed with practitioners, such analyses could significantly improve our ability to identify where, when and how resources and natural capital changes are driven by climate change. Indeed, the requirement for MSP to be harmonized with national and sectorial CC adaptation strategies is now common place. So ideally, CC analysis supporting MSP development should offer guidance about how such CC driven changes can be managed and capitalized upon, and not simply identify what will be lost. The result would be evidence-based CC adaptation and mitigation strategies for MSP that could be supported by secondary policy mechanisms, such as climate adaptation and mitigation plans (Frazão Santos et al., 2020; Queirós et al., 2016). However, this is not yet how MSP is typically developed around the world (Frazão Santos et al., 2020). More frequently, without the evidence (or the ability) to discriminate whether projected future change in the resources and natural capital that underpin spatially managed maritime sectors are indeed driven by climate, planners and other decision-makers do not truly understand the effects of CC on managed systems. Thus far, climate-smart MSP remains, broadly, aspirational.

To help resolve this challenge, we present here a CC assessment commissioned to inform the MSP process in Ireland. Climate Change is an Overarching Marine Planning Policy in the Irish National Marine Planning Framework Consultation Draft ('draft NMPF', Irish Government, 2019a). We use this as a case-study to demonstrate how to inform ecosystem-based, climate-smart MSP design. We updated a well-established method of spatial meta-analysis of CC modelling evidence (Levin et al., 2020; Queirós et al., 2016; Wilson et al., 2020) to better fit with the MSP process, and applied it to modelling outputs and other spatial data resulting from various globally distributed research activities. Our method was designed specifically to respond to marine planners need to identify if any changes in the ecosystem underpinning each spatially managed area of activity are indeed driven by CC and, thus, whether climate-adaptive and mitigating strategies should be prioritized under a plan. Specifically, sub-sets of physical–biogeochemical and mechanistic species distribution modelling projections under different global emissions scenarios (i.e. projection of species exposure, and sensitivity, to CC respectively) were used here as inputs to MSP-specific analyses focused on the Irish fishing sector and marine nature conservation. These are key areas of interest for MSP in Ireland. The Irish Government, as others globally, is also interested in capitalizing on the role of the ocean as a nature-based solution to regulate the climate system (Hoegh-Guldberg, Caldeira, et al., 2019; Hoegh-Guldberg et al., 2019, Irish Government, 2019a). Therefore, a specific focus of our analyses was also the possibility to inform on how marine nature conservation areas can contribute to enhance the spatial management of habitats delivering carbon sequestration within the Irish EEZ. Interactions between these focal areas of interest and other maritime sectors considered in the NMPF draft were also explored, as climate change unfolds in the region. Sub-sets of modelling data were selected for analyses, representing: the marine resources and natural capital underpinning the Irish fishing sector; the species and habitats at the heart of Irish marine nature conservation mechanisms; and habitats with carbon sequestration potential addressed through the NMPF process. The joint, spatial distribution of climate resilience of these resources and natural capital within the region covered by the NMPF was then estimated, by applying spatial meta-analysis to each data sub-set. For each focal area of interest (fisheries, conservation and carbon sequestration) each analysis compared the present ecosystem state, when the MSP is being implemented, with that at the end of the MSP implementation period. This specific statistical modelling analysis method identifies if and where the climate signal may emerge (Hawkins & Sutton, 2012) within the Irish EEZ, during the timeline of implementation of the NMPF. Analyses of this type more traditionally focus on estimating the spatial distribution of the 'time of emergence', when an individual ecosystem property (e.g. temperature) enters a state that is outside of its natural historical variability. These are routinely used to identify when and where climate change has caused a significant change in the underlying environment (Bindoff et al., 2019). Our approach repackages this concept to better fit the MSP process. We estimate if and where a climate signal emerges in the ecosystem conditions, resources and natural capital underpinning each MSP focal area of interest, within the time-frame of implementation of a plan. Our statistical analyses method further identifies where ecosystem change may benefit the objectives of the plan, thus providing information on where sustainability and growth targets may be supported, beyond climate-driven losses. In this way, we aimed to inform the development of sector-specific spatial management strategies that could be prioritized within the Irish MSP process, to help deliver its aims of promoting CC adaptation and mitigation (Irish Government 2019a).

2 | MATERIALS AND METHODS

The analyses presented are based on research activities co-developed with MSP practitioners in various globally distributed research programmes and, more recently, a climate-change assessment commissioned to inform the MSP process in Ireland (Queirós et al., 2020). Below, we provide a description of the steps undertaken in, and principles guiding, this study. These steps cover the four stages of the study, including data gathering, analysis, outputs and interpretation. These steps are also represented schematically in Figure 1, and their numbering in the figure is referred to throughout, for guidance. Additional, technical recommendations around each of these steps can be found in Supplementary Information. All analyses and mapping were carried out using author-led R core scripts (R Core Team, 2020).

2.1 | Selection of focal MSP sectors

The starting point for this work was the NMPF Baseline Report (Irish Government, 2018) which identified the key issues for marine planning in Ireland. Specifically, the document provided a definition and analysis of the existing sectoral development and activities in Irish seas. Furthermore, it stated that the plan should consider climate change in both supporting adaptive actions (that limit the impact of CC) as well as mitigation (helping to curb CC). Indeed, climate change was recognized as a considerable threat to the marine environment that may modify effects of other pressures. Initial consultation with various agencies involved in the development of the NMPF draft (Irish Government 2019a) then helped us identify for which specific sectors covered by the plan, CC adaptation (and mitigation) strategies were to be developed, that our analysis was to inform. The fishing sector is a key, discrete sector within the NMPF. Nature conservation was also considered as a sector within the NMPF Baseline Report (Irish Government, 2018), although it is described in the current plan under the umbrella of overarching policies with environmental and ocean health objectives, which the plan is harmonized with. Indeed, Ireland's National Biodiversity Action Plan 2017–2021 has as one of its seven objectives 'Conserve and restore biodiversity and ecosystem services in the marine environment'. Furthermore, with the publication of the NMPF Consultation Draft in 2019, developments were now further required to consider carbon sequestering habitats in the coast and open ocean. Specifically, planning proposals must demonstrate that they will avoid, minimize or mitigate adverse impacts on those habitats (Irish Government

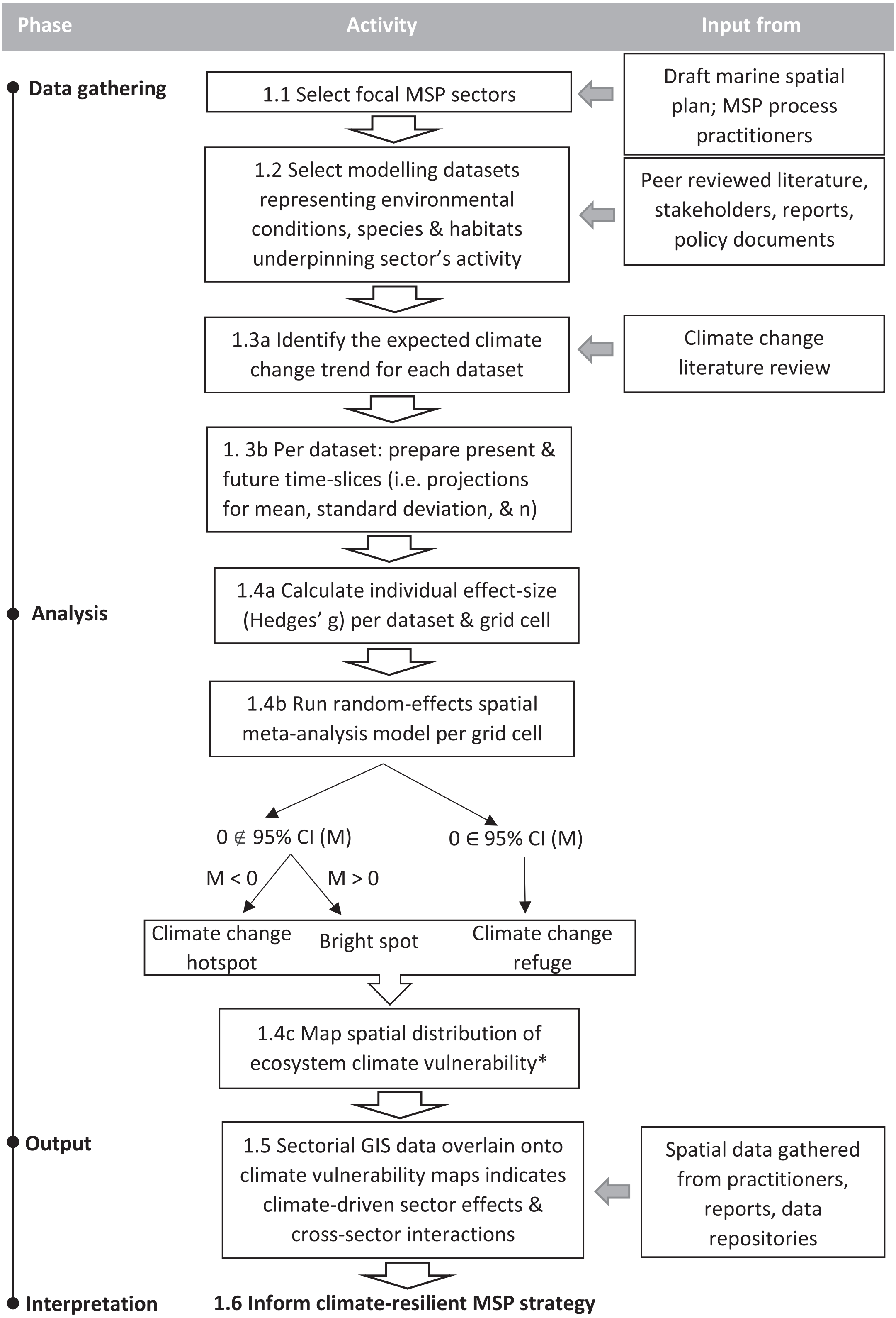

FIGURE 1 Schematic representation of the analytical approach employed, from data gathering, to advice. Please refer to Section 2. Further technical recommendations about each step of this approach are made in Supplementary Information

2019a). As a result of this consultation, we focused the analyses presented here on the spatial management of: the fishing sector; areas of interest to nature conservation in Irish waters; and carbon sequestering habitats (Figure 1, step 1.1). Additional analyses carried out for other MSP sectors of interest during this project can be found elsewhere (Queirós et al., 2020).

2.2 | Selection of modelled datasets for sectorial analyses

Modelled datasets were selected for analysis to best, and as comprehensively as possible, represent the ecosystem components (environmental and/or ecological) underpinning the activity of three focal sectors identified in 1.1 (Figure 1, 1.2). Dataset selection was a co-developed step of the analysis design, including input from the end-users to ensure our work as best as possible met their needs and priorities (Figure 1, 1.2). We analysed modelling projections covering the Irish Exclusive Economic Zone, comparing the present decade at the start of the NMPF implementation period (2011–2020) to the decade at the end of the implementation period (2040–2049). In this way, we assessed whether the NMPF draft could benefit from any adaptation measures that could best account for the effects of CC on the ecosystem underpinning each of the focal sectors of interest (fisheries, nature conservation, distribution of carbon sequestering habitats), in the period of implementation of the policy. The subsequent decade (2050–2059) was also compared to the present decade to enable horizon scanning, informing about the direction of travel for the managed system—of interest to the design of the next policy implementation stage. For the fishing sector analysis, we analysed species distribution modelling (SDM) projections for the species that compose the top 80% of Ireland's landings by value (LBV, 2013– 2017, Eurostat, consulted June 2019), as detailed in Table S1. While the majority of these are native species, Irish fishers have been quick to capitalize on new species which have been increasing in relative abundance in catches, as a result of range expansions into the Irish EEZ (Cheung et al., 2012). Four new species featured in the top 80% of Ireland's landings by value at the time of the study, and we were also able to include projections for one of those in our analyses: the common sole (0.5% LBV). However, sole abundance is expected to decrease in the long term (Table S1), given that the whole region is expected to experience a long-term decline in productivity (Table S2). Separate analyses were undertaken for pelagic versus benthic and demersal species of commercial interest (Figure 1, 1.4). In the marine nature conservation analyses, we included physical and biogeochemical modelling projections for known drivers of the distribution of species of conservation interest to Ireland, as well as mechanistic SDM projections for their prey (Table S2). This choice was justified based on the presently important absence of mechanistic SDM tools, or of end-to-end models, particularly including the species of the highest conservation interest to Ireland. As in most areas of the globe, a large proportion of these are marine megafauna, such as marine mammals, seabirds, sharks and rays, and a species of sea turtle (Table S3). This choice was seen as preferable to the use of projections for these species resulting from statistics-based modelling tools which can produce less well-constrained projections (Palacios et al., 2013; Silber et al., 2017). We also included in the nature conservation analyses datasets on winter and summer thermal front strength in the Irish EEZ, based on POLCOMS-ERSEM sea surface temperature projections (Miller et al., 2020; Table S2). The inclusion of these secondary modelling datasets was justified based on the close dependency of the spatial distribution of large marine megafauna of conservation interest to Ireland on these oceanographic features, as documented in detail in Table S3. All marine nature conservation datasets were analysed separately depending on whether they affect pelagic versus benthic and demersal species of conservation interest (Table S2). Furthermore, changes in carbon sequestration potential of seabed habitats were assessed, specifically, based on calculations (Figure 1, 1.4) using projections for 'bottom non-living organic carbon' (Table S2). In all analyses, we considered modelling projections forced by global greenhouse gas concentration scenarios (i.e. representative concentration pathways, 'RCPs', Van Vuuren et al., 2011) RCP4.5 and 8.5. 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 (Hausfather & Peters, 2020; IPCC, 2013; Schwalm et al., 2020). RCP4.5 assumes strong curbs in global emissions towards CC mitigation, from 2050 onwards, while emissions continue to rise steadily throughout the 21st century under RCP8.5.

The final selection of modelling projections for the marine environment, species and habitats (Figure 1, 1.3b) we analysed is hereafter referred to as 'datasets' (SI Tables S1 and S2). Specifically, for a given global emissions scenario, each dataset is a modelling output from a specific ecosystem-scaled 3D model, including projections for the present time slice (at the start of the NMPF implementation period) and the future time slice (2040–2049 and 2050–2059 were considered in separate analyses). Each dataset thus includes six matrices describing, for each grid cell of the model domain: (1) the mean of the modelled variable at the start of the MSP implementation period (e.g. sea surface temperature in 2011–2020; the abundance of a specific species of interest in 2011–2020; SI Tables S1 and S2); (2) the corresponding standard error; (3) the number of times the model outputs were sampled to estimate (1) and (2) (e.g. 120 for monthly model outputs over 10 years used to estimate (1) and (2)); (4) the mean of the modelled variable over the future period of interest (e.g. sea surface temperature in 2040–2049); (5) the standard deviation corresponding to (4); and (6) the number of times the model outputs were sampled to estimate (4) and (5) (as before). All projections analysed had a $0.1° \times 0.1°$ (longitude × latitude) horizontal resolution. Datasets from model setups employing a coarser grid (i.e. SS-DBEM, $0.5° \times 0.5°$ resolution, SI Tables S1 and S2) were projected onto the same grid as the most resolved model employed (POLCOMS-ERSEM, $0.1° \times 0.1°$ resolution) without further spatial processing. In this way, we were able to include all information contained in the most resolved models in subsequent analyses (Figure 1, 1.4). Marine climate model uncertainty is an aspect of interest to end-users of this type of work, and the focus of a productive research field, beyond the scope of this study (Lotze et al., 2019; Payne et al., 2015). All datasets analysed here derive from models with established track record in the region of the Irish EEZ, as illustrated by references provided in SI Tables S1 and S2. Further technical recommendations about data selection can be found in Supplementary Information, including dataset scale, resolution and scenario considerations.

2.3 | Reviewing CC evidence and preparing modelling datasets for analysis

Climate change literature was reviewed to identify the expected CC trend for each modelling dataset selected during the initial data scan described (Figure 1, 1.2-3). This is a necessary step to inform the design of the analysis algorithm, detailed in Section 2.4, below. All expected long-term CC trends in ocean variables, species and habitats considered as datasets in this study are documented alongside the corresponding modelling datasets, in SI Tables S1 and S2.

2.4 | Spatial meta-analysis of modelling datasets: Applying the CC attribution analysis algorithm

We assessed the climate resilience of the ecosystem underpinning each of our focal sectors of interest by building one spatial meta-analysis model per grid cell of the common model domain, per focal area of interest, scenario and time period of interest, to analyse the modelling datasets. Spatial meta-analysis of modelling data has two steps: first, we calculate the change in each dataset and grid cell during the MSP implementation period; then we bring all of those together to calculate the overall ecosystem-level change in each grid cell (Figure 1, 1.4a,b, Queirós et al., 2016). We refer to these two statistics as the individual effect and the summary effect, respectively, using common meta-analysis terminology (Borenstein et al., 2011). We calculated individual effects using the unbiased standardized mean difference estimator Hedges' *g* (Hedges, 1982). Hedges' *g* is centred around 0 and provides a means to compare all datasets on a common scale, being particularly useful when different types of variables need to be combined in one meta-analysis model (e.g. physical–biogeochemical variables, species distributions and habitat suitability datasets; Queirós et al., 2016). Given the diversity of datasets considered, we expected not one, but a family of possible individual-effect sizes per analysis. This attribute of the data justified the use of a random-effects meta-analysis model (Borenstein et al., 2011). Applying the latter requires the calculation of the variance of the individual effects as the sum of (i) the variance of Hedges' *g* for each dataset, and (ii) the variance between datasets, for each grid cell. The latter is known as τ^2, and is estimated using the DerSimonian–Laird method (1986; Borenstein et al., 2011). The resulting test statistic from the meta-analysis model in each grid cell, the summary effect, is typically referred to as '*M*', and is also centred around 0. The variance of *M* is used to calculate its confidence interval in each grid cell. The null hypothesis tested by each random-effects meta-analysis model is that *M* is 0, under a normal distribution (Borenstein et al., 2011).

The current application of this framework deviates from the previously published approach (Queirós et al., 2016) by specifically building the expected direction of climate change effects on each analysed modelled variable (Figure 1, 1.3) into the calculation of Hedges' *g* (and thus *M*) (Figure 1, 1.4). This step is important because not all individual datasets included in one analysis will vary in the same direction between the present and the future, as a result of CC. For instance: mean sea surface temperature will generally *increase* in the long term as a result of global warming; the abundance of a given species may be expected to *decrease* regionally through climate-driven loss of suitable habitats (e.g. Atlantic herring). We used the reviewed and documented expected trends in each analysed dataset resulting from climate change (Figure 1, 1.3) to determine the order in which time slices were fed into the calculation of Hedges' *g* (per dataset). That order is such that if the expected climate change trend is observed, Hedges' *g* will be negative, and positive otherwise. This specific analysis design (Figure 1, 1.4a) then allows for the calculation of a negative summary effect (*M*) in cells where, predominantly, individual effects are negative over the period of analysis, reflecting a climate-driven change in the ecosystem state. The calculation of the 95% confidence interval for *M* then allows for the estimation of the probability, under a normal distribution, that *M* is zero. In ecosystem terms, this approach therefore allows the determination of whether the system (described by the modelling layers analysed) remains (or not) within its range of variability in the 'reference period' (in this case, the present time slice, Hawkins & Sutton, 2012; Queirós et al., 2016). Three outcomes are then possible for each grid cell (Figure 1, 1.4b). First, if the confidence interval of *M* includes 0, we consider that the system remains, at the end of the MSP period, within the range of its variability in the present-time slice, and such areas are considered climate-resilient (i.e. climate change refuge, Figure 1, 1.4b). We employ the term 'climate-resilient' adopting the common definition of an ecosystem where function, regular patterns of biogeochemical cycling and of biomass production are maintained under stress (Irish Government 2019b). Identifying climate-resilient sites is especially important to the MSP process because these are sites where the distribution of the activities of each sector within a plan may be expected to continue to have the same effect it has at present, despite CC. For instance, those could include areas where sites designated for marine nature conservation may be expected to have the same broad efficacy as at present; where fished resources may continue to be exploited to similar levels. Climate-resilient sites ('CC refugia', Figure 1, 1.4b) therefore represent safe choices for the activity of spatially managed sectors within a plan around which each of our analysis is designed. Second, a negative *M* with a confidence interval that does not overlap 0 expresses a long-term, climate-driven change at the ecosystem level. This change can be interpreted as the emergence of the climate signal within the period of analysis (per Hawkins & Sutton, 2012), with the signal emerging at the ecosystem level. We term such sites as climate change hotspots (Figure 1, 1.4b). This approach thus presents a parallel to analyses used by the IPCC to estimate the time of emergence of the climate signal (IPCC, 2019). Third, cases where *M* is positive and its confidence interval also does not overlap 0 express a change in the ecosystem that is contrary to expected regional long-term mean CC trends. These are areas where regional processes may modify the expression of long-term CC trends over shorter time periods (e.g. the Atlantic Multi-decadal Oscillation, McCarthy et al., 2015). Such results are likely to be specific to the time-frame of analysis. However, these sites are also experiencing fast ecosystem change, and we coin their definition as 'CC bright spots': areas where species may find improved habitat conditions in the medium term, that may be seized upon within marine conservation strategies and sustainable fishing management. For analyses focused solely on SDMs (e.g. our fishing sector analysis), these are sites where abundances increase across species, and thus where reduced sensitivity to CC may be observed across the community. For analyses that focus entirely or partially on habitat conditions (e.g. the analysis focused on nature conservation), these sites are areas where exposure to CC is reduced over the time-frame of analysis. In the majority of cases, this will express improved habitat conditions (e.g. increased dissolved oxygen, increased food availability). However, where bright spots are identified, individual projection layers should be further scrutinized to determine how each individual effect used in the calculation relates to the habitat needs of specific species of interest.

For each focal sector of interest to MSP, scenario and time-frame, the spatial meta-analysis results were mapped in categorical form to reflect the distribution of: CC refugia (where the ecosystem underpinning each focal sector is resilient to CC); CC hotspots (climate-vulnerable sites, where a climate signal emerges); and CC bright spots (where there may be new opportunities for sustainable blue growth and conservation, Figure 1, 1.4c). The resulting figures thus condense complex climate-driven oceanographic and ecological processes into a format accessible to those less familiar with climate modelling, for example, in marine planning departments. Because climate change trends are part of the analysis design, we provide further methodological recommendations around this point as Supplementary Information.

2.5 | Overlay of sectorial GIS datasets

To the maps resulting from each spatial meta-analysis of modelling data, we overlaid the distribution of relevant uses (i.e. fishing effort distribution; designated sites under the Habitats and Birds Directives), as well as the distribution of other MSP sectors covered in the NMPF (Figure 1, 1.5). This step of the analysis provided an objective means to explore which sector-specific climate-adaptive measures could best be used to limit the effects of climate change on the ecosystem underpinning Irish fisheries, designated sites and carbon sequestering habitats, in the period of implementation of the NMPF. Cross-sectorial interactions were also explored that could serve as useful CC adaptation or mitigation strategies (including promoting carbon sequestration). By capitalizing on the natural, heterogeneous distribution of climate resilience within the ecosystem managed (Figure 1, 1.4c), climate-adaptive spatial management strategies based on this evidence may thus serve as nature-based solutions to limit the impact of climate change on the delivery of those aims (Seddon et al., 2021).

To this end, the best available sectorial GIS data were sourced at the start of the study (end of 2017), and updated in 2021. Specifically, to the best of our ability, all GIS datasets presented here are consistent with those used for Ireland's MSP process. Where they are not (given the timeline of this work relative to the development of the draft NMPF) this is now highlighted. GIS datasets on Special Areas of Conservation ('SACs') and Special Protection Areas ('SPAs') used are owned by the Irish National Parks and Wildlife Service. Data on aggregate extraction substrate and fishing effort distributions were provided by the Marine Institute and ABPmer, having been collated for the NMPF as part of activities within the European Maritime Fisheries Fund Operational Programme for 2014–2020. Plotted fishing data are for over 15 m vessels and includes beam, otter and pelagic trawling, Nephrops and scallop dredging, gill and seine netting, and longlining. GIS data on oil and gas platforms, undersea telecommunications cables, pipelines (active), offshore wind farms, sewage discharge points and capital and maintenance dredging points were retrieved from the EMODnet Human Activities data portal (https://www.emodnet-humanactivities.eu/view-data.php) and checked against the draft NMPF for consistency. It was noted that the wind farm data presented here includes those approved, planned and operational in the region, while the NMPF includes spatial data only on those currently in operation. It is also noted that the cables network shown in the maps presented here is a schematic representation of cabling routes, cf. what is shown in the NMPF. Further data on megafauna occurrences was gathered from the Dept. of Communications, Climate Action & Environment and the Dept. of Culture, Heritage and Gaeltacht's programme ObSERVE, and analysed in the preparation of this work.

3 | RESULTS

3.1 | Fishing sector

We found that a climate signal emerged in the distribution of species which underpin both pelagic and benthic/demersal fisheries by the 2040s, in both RCP4.5 and 8.5, and across the majority of the Irish EEZ (Figures 2 and 3; Figures S1 and S2). Many areas where fishing is currently concentrated are therefore likely to become CC hotspots (Figure 2). At these sites, the ecosystem may enter a state that is very different from that which is observed at present by the 2040s, resulting in the potential loss of abundance of species that are currently in the top 80% of LBV from coastal and shelf environments (Table S1; Figures 2 and 3). Although we also identified both CC refugia and bright spots for commercially valuable populations within the timeline of this analysis, these sites likely represent limited opportunities for the growth of the Irish fishing sector. The majority of these sites were identified either in nearshore areas that are already exploited by other habitat-degrading sectors (e.g. capital and maintenance dredging, E coast, Figure 2e), or in deeper offshore regions where fishing potential may be limited (Figure 2b). We were, however, able to identify some smaller CC refugia in areas already

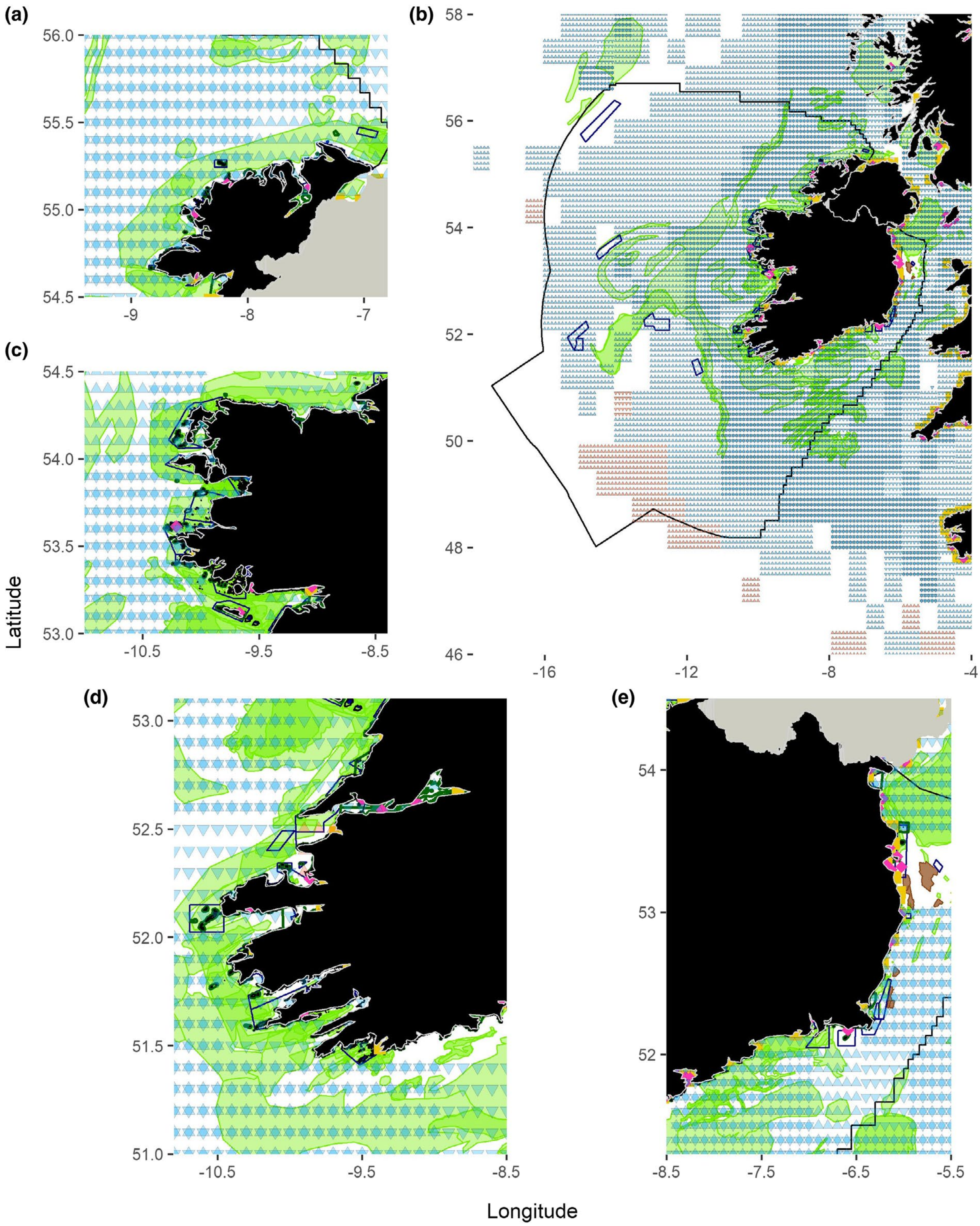

FIGURE 2 Vulnerabilities that arise from climate change for the spatial management of Irish pelagic and benthic/demersal fisheries in 2040–2049, under RCP8.5, given the distribution of other habitat-degrading spatially managed sectors. The colour of triangles denotes CC hotspots (blue) or bright spots (red) in the time period and scenario analysed, with no triangles denoting CC refugia. Upward triangles reflect results from the analysis of pelagic datasets, and inverted triangles indicate the results of benthic and demersal datasets. Overlapping triangles indicate where hotspots and/or bright spots occur in both pelagic and benthic/demersal analyses. Dark blue and dark green outlines indicate the locations of Special Areas of Conservation and Special Protection Areas respectively. Areas shaded in pale green are the locations of fishing grounds. Brown shading indicates areas that could be used for aggregate extraction. Yellow squares are areas of sewage inflow, and pink diamonds are areas where capital and maintenance dredging takes place

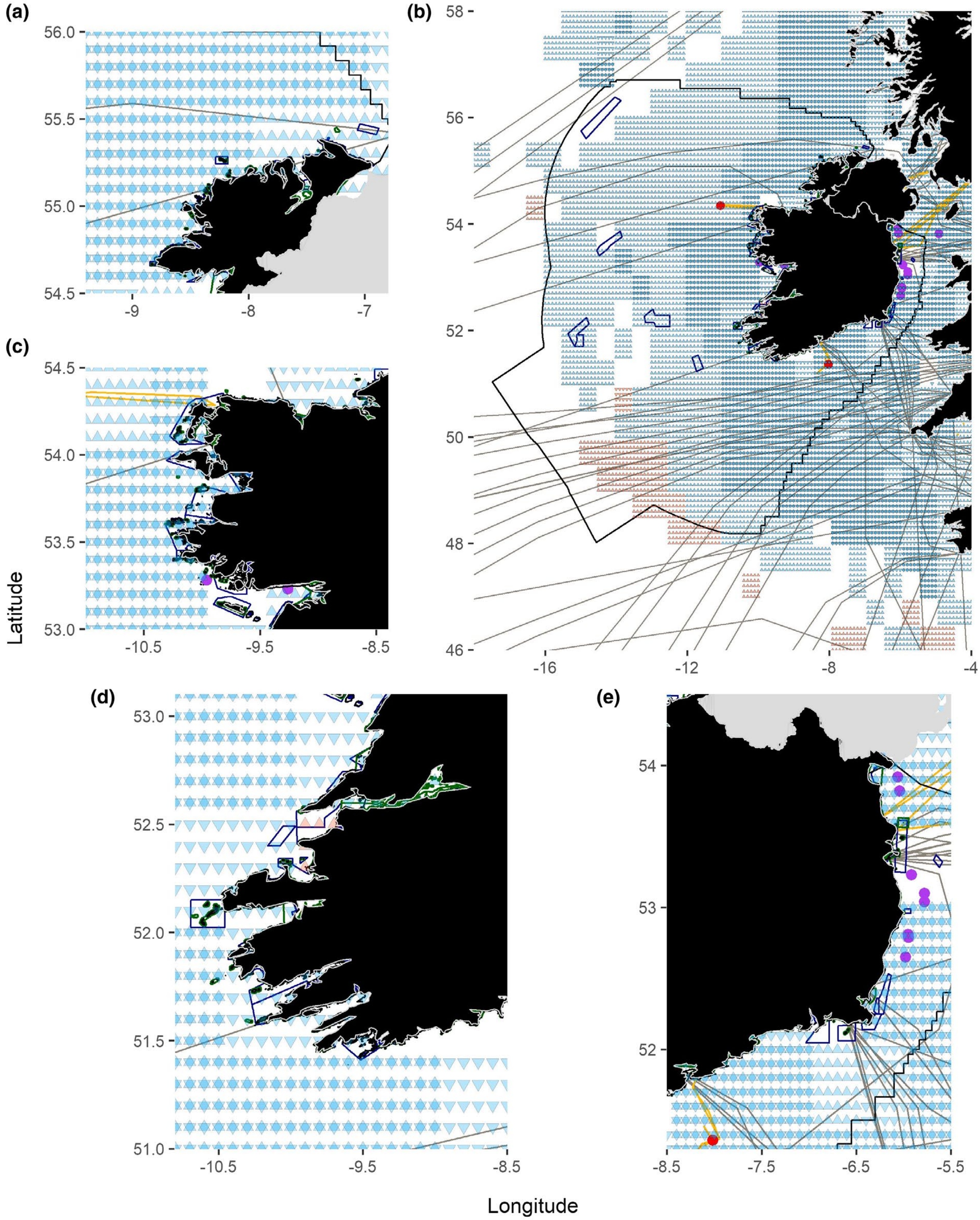

FIGURE 3 Opportunities that arise from climate change for the spatial management of Irish pelagic and benthic/demersal fisheries in 2040–2049, under RCP8.5, given the distribution of other sectors that limit destructive extractive practices. The colour of triangles denotes CC hotspots (blue) or bright spots (red) in the time period and scenario analysed, with no triangles denoting CC refugia. Upward triangles reflect results from the analysis of pelagic datasets, and inverted triangles indicate the results of benthic and demersal datasets. Overlapping triangles indicate where hotspots and/or bright spots occur simultaneously in pelagic and benthic/demersal analyses. Dark blue and dark green outlines indicate the locations of Special Areas of Conservation and Special Protection Areas respectively. Grey lines are the (schematic) locations of undersea cables, yellow lines are the locations of undersea pipelines. Purple circles are the locations of planned, approved, under construction or active offshore wind installations and red circles are oil and gas platforms

exploited by fishers and/or not currently of interest to other sectors (Figures 2c–e and 3c–e) which could support climate-resilient exploitation by fisheries in the future (e.g. some nearshore areas on the E and NW coasts of Ireland). Identified CC refugia were more extensive under RCP4.5, where species abundances were projected to be climate-resilient in nearshore areas off the N, NW and E coasts of Ireland, and further offshore in the Rockall Bank (Figures S1 and S2). Spatial co-management of these fisheries with other sectors may provide opportunities to support the broader sustainability of commercially important species. For instance, we identified both CC refugia and bright spots in some regions where destructive practices are already restricted, such as in SACs, around one wind farm (e.g. Figure 3e), and in areas harbouring pipelines and cables (e.g. Figure 3b). However, horizon scanning into the subsequent decade (the 2050s), indicated that the Irish fishing sector is likely to continue to face challenges as species abundances remain vulnerable to CC under both RCP considered. Indeed, losses of species abundances from coastal and shelf habitats were particularly pronounced under RCP8.5 in that decade (Figures S3 and S4). While there were still widespread losses in abundances across species in the 2050s under RCP4.5, we identified several nearshore areas around the Irish coast that appeared to serve as CC refugia (Figures S5 and S6) including areas where fishing already occurs (e.g. around the N, W and SW coast). As in the 2040s, some of the climate-resilient sites identified by the 2050s also occur where existing infrastructure (e.g. one wind farm on the E coast, SACs on the N and NW coasts) may provide habitat protection from other destructive practices, such as capital and maintenance dredging or aggregate extraction. CC bright spots occurred in deep offshore areas.

3.2 | Marine nature conservation

We found that the degree of CC experienced by the Irish EEZ during the NMPF's implementation period will largely determine whether its current network of SACs and Special Protection Areas (SPAs) network will continue to be effective, especially in coastal and shelf areas (RCP 8.5, Figures 4 and 5, c.f. RCP4.5 Figures S7 and S8). By the 2040s, under RCP8.5 (Figure 4) and with few exceptions (Figure 4a,d,e) the majority of benthic species and habitats underpinning those protected areas (Tables S2 and S3) will be part of ecosystems that have been significantly and negatively forced by CC into a state that is outside of their current natural variability. However, some refugia were identified and in several of these restricted uses of the seabed are already enforced, offering some protection from destructive practices (such as areas currently harbouring pipelines and energy infrastructure, Figure 5a–e). In many cases, in CC hotspots within SACs, SPAs and in surrounding habitats, the effects of climate may be compounded by other types of habitat degradation, such as fishing activity, sewage inflow and dredging (e.g. many coastal areas, Figure 4b). CC refugia within SACs and SPAs also often occurred where those negative pressures co-occur (Figure 4e). In parallel, refugia and bright spots unaffected by other sectors reducing habitat condition occurred predominantly offshore (Figure 5b). Indeed, no bright spots for benthic species and habitats occurred within existing SACs or SPAs under RCP8.5 in the 2040s; they occurred in deep offshore areas to the SW, benefitting from some protection against destructive uses of the seabed by the presence of underwater cables (Figure 5). In contrast to benthic species and habitats, pelagic habitats within SACs and SPAs were found to be resistant to CC by the 2040s under RCP8.5, almost without exception (Figures 4 and 5). For instance, the distribution of surface thermal fronts underpins the temporal occurrence of high biodiversity patches, seasonally attracting large migratory megafauna of conservation value such as seabirds, marine mammals, sharks and turtles (Table S3). The timing and location of these features is well established at present within the Irish EEZ, and was found to vary in explored future scenarios (Figures S9–S12) but this did not correspond to CC hotspots in the analysis of pelagic species and habitats (Figures 4 and 5). The nature conservation analysis focusing further into the 2050s (Figures S13 and S14), produced very similar results, and marked differences between decades were only really observed in NW coastal habitats (Figures S13c and S14c). In contrast to RCP8.5, in the 2040s and the 2050s, most Irish SACs and SPAs were identified as resilient to the lower degree of CC expressed by RCP4.5, and would be expected to be underpinned by ecosystems similar to those we see today (Figures S7, S8, S15 and S16). Under the more optimistic RCP4.5, and in stark contrast to RCP8.5, most of Ireland's marine SACs and SPAs would represent CC refugia, and some would host bright spots (Figure S16b).

3.2.1 | Conservation of carbon sequestering seabed habitats

The Irish Government is interested in enhancing the delivery of carbon sequestration as a climate regulating service, through conservation actions delineated within the NMPF (Irish Government 2019a). We therefore further assessed modelling datasets indicating the availability of organic carbon input to the seabed as a potential indicator for seabed carbon sequestration. Areas where organic carbon may be accumulating on the seabed appeared to change under the effect of climate pressure on the marine environment by the 2040s under RCP8.5 (Figure 6). Specifically, organic carbon availability to bottom waters appeared to increase in coastal and shelf environments in all scenarios and time-frames analysed (Figure 6; Figures S17–S19), consistent with the expectation of increased water column stratification (Table S1). Projections for changes in deeper waters offshore were more variable. A clear decrease in carbon availability on the seabed was estimated by the 2040s under RCP8.5 (Figure 6). Only minimal changes were evident by the 2050s, relative to the present under RCP8.5 (Figure S17), or under the lower emissions scenario RCP4.5 in either time-frame (Figures S18 and S19). Areas on the west coast of Ireland which are already recognized as important carbon storing habitats (e.g. Mayo and Galway; Fernández

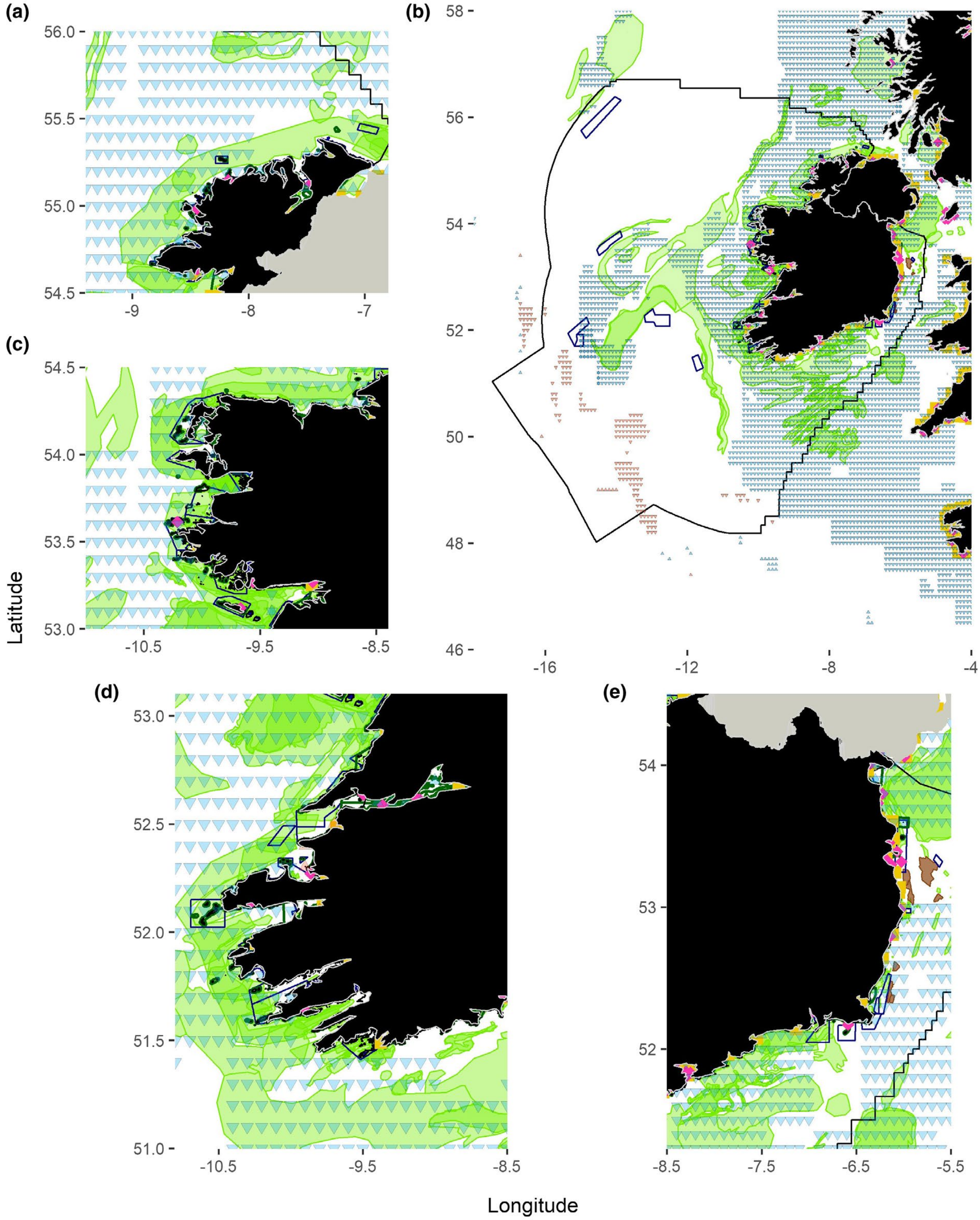

FIGURE 4 Vulnerabilities that arise from climate change for the spatial management of Irish marine conservation sites in 2040–2049, under RCP8.5, given the distribution of habitat-degrading, spatially managed sectors. The colour of triangles denotes CC hotspots (blue) or bright spots (red) in the time period and scenario analysed, with no triangles denoting CC refugia. Upward triangles reflect results from the analysis of pelagic datasets, and inverted triangles indicate the results of benthic and demersal datasets. Overlapping triangles indicate where hotspots and/or bright spots occur in both pelagic and benthic/demersal analyses. Dark blue and dark green outlines indicate the locations of Special Areas of Conservation and Special Protection Areas respectively. Areas shaded in pale green are the locations of fishing grounds. Brown shading indicates areas that could be used for aggregate extraction. Yellow squares are areas of sewage inflow, and pink diamonds are areas where capital and maintenance dredging takes place

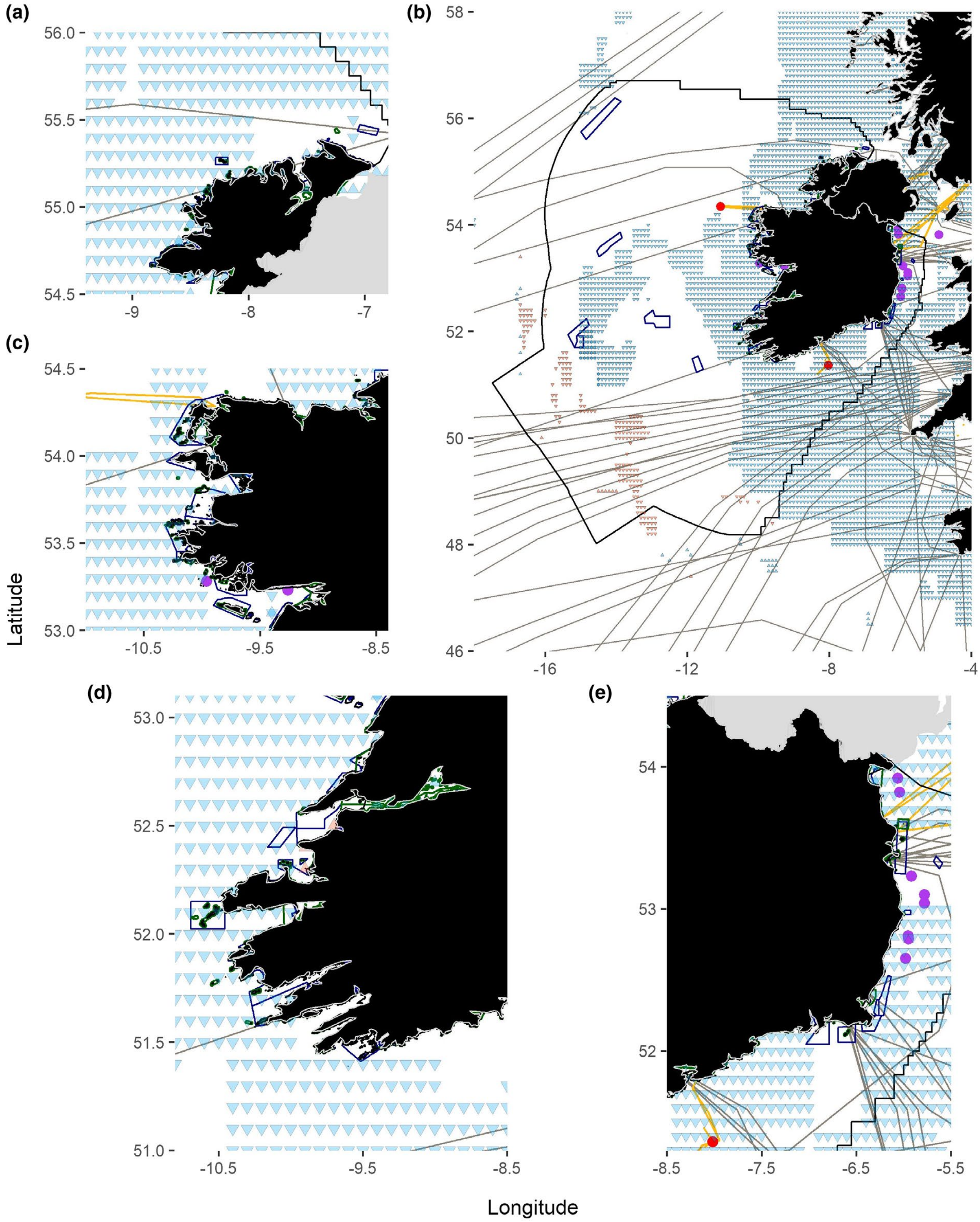

FIGURE 5 Opportunities that arise from climate change for the spatial management of Irish marine conservation sites in 2040–2049, under RCP8.5, given the distribution of other sectors that limit destructive extractive practices. The colour of triangles denotes CC hotspots (blue) or bright spots (red) in the time period and scenario analysed, with no triangles denoting CC refugia. Upward triangles reflect results from the analysis of pelagic datasets, and inverted triangles indicate the results of benthic and demersal datasets. Overlapping triangles indicate where hotspots and/or bright spots occur simultaneously in pelagic and benthic/demersal analyses. Dark blue and dark green outlines indicate the locations of Special Areas of Conservation and Special Protection Areas respectively. Grey lines are the (schematic) locations of undersea cables, yellow lines are the locations of undersea pipelines. Purple circles are the locations of planned, approved, under construction or active offshore wind installations and red circles are oil and gas platforms

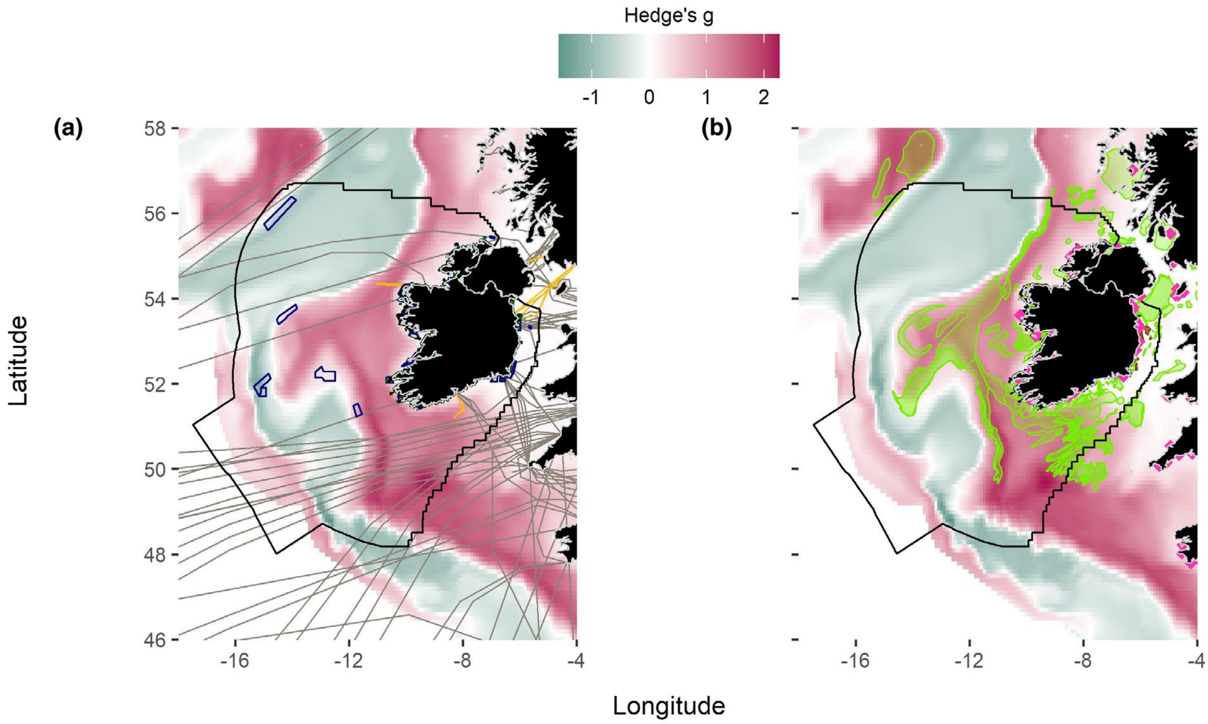

FIGURE 6 Climate-driven changes in the distribution of areas potentially accumulating organic carbon on the seabed, between 2011–2020 and 2040–2049, based on the calculation of Hedges' *g* (Section 2), under RCP8.5. The background colour green indicates areas where organic carbon accumulation decreases by 2040–2049, given the basin-scale expectation of decreased productivity and increased stratification, while pink indicates the opposite trend (increased supply of organic carbon for potential carbon sequestration on the seabed). (a) areas of the seabed where, due to already existing infrastructure or restrictions, activities that perturb the ability of the seabed to store carbon may already be limited, such as I SACs and SPAs (dark blue and dark green lines respectively), undersea cables (grey) and pipelines (yellow). (b) areas where activities from sectors that will negatively affect the ability of the seabed to store carbon take place, including benthic/demersal fisheries (pale green shading), potential sites for aggregate extraction (brown shading), and ongoing capital and maintenance dredging (pink diamonds)

et al., 2019) may experience an increase in the availability of organic carbon in the coming decades (Figure 6).

4 | DISCUSSION

4.1 | Bright spots and climate-smart MSP

The analyses undertaken in this study highlight that, as in other regions of the globe, CC presents important challenges to delivery of sustainability objectives enshrined in Ireland's MSP policy (Irish Government 2019a). Therefore, without CC adaptation strategies, Ireland may not realize its blue growth ambitions (Irish Government, 2017). Alongside the identification of areas that represent CC hotspots and refugia for the fishing sector and marine nature conservation, we have also identified (few) bright spots where there may be increased abundance of species targeted by fisheries, and where conditions for protected species and habitats may be improved within the NMPF implementation time-frame (2040). The growing challenge of climate impacts to both fisheries and marine nature conservation has been widely recognized, as has the need to identify climate refugia, and to address the role of new species within managed areas (Johnson & Kenchington, 2019; Levin et al., 2020; Pinsky et al., 2020; Queirós et al., 2016; Rilov et al., 2020; Wilson et al., 2020). However, the potential importance of bright spots, as defined here, has not yet been raised. We argue that in their identification lie opportunities for blue growth and effective conservation, in an ocean rapidly changing under the pressure of an altered climate system, which is redistributing species. In contrast to CC refugia, bright spots are also areas changing rapidly over time. But unlike in CC hotspots, these changes do not mirror long-term, mean global CC trends. Climate cycles and basin-scale oceanographic processes, such as the Atlantic Multidecadal Oscillation (AMO; McCarthy et al., 2015) and a changing Atlantic Meridional Overturning Circulation (AMOC; McCarthy et al., 2017), modify the regional expression of climate trends (Bindoff et al., 2019). These can cause significant departure from expected long-term (century-scaled) mean CC signals within the short and medium term (years to decades): those scales most relevant to ocean policies. Among the many competing interests that lead to MSP implementation, planning is guided by specific political contexts, and political cycles are very rarely sensitive to the need for pre-emptive management of changes that will take place in the long term (Frazão Santos et al., 2020; Pınarbaşı et al., 2017). Projections for physical–biogeochemical variables included in our analyses, such as seabed temperature and dissolved oxygen concentration among others, exhibited significant departure from the expected mean long-term trends by the 2040s, in the SW areas of the Irish EEZ. These changes are consistent with expected medium-term effects of a cooling AMO phase (i.e. cooling and dissolved oxygen increase in bottom waters; detailed in Queirós et al., 2020). Such effects would have affected the results from the analyses of those datasets (included in the marine conservation analyses), as well as the results of analyses of SDM projections for models that use these and other affected physical–biogeochemical variable projections as input (included in the fisheries and conservation analyses). We argue that recognizing the occurrence of CC bright spots is therefore the opportunity to comprehensively quantify the full range of changes in ocean ecosystems underpinning the activity of sectors affected by MSP, at scales required for the implementation of spatial plans. Effective and sustainable management of CC bright spots, alongside refugia and hotspots, may thus provide a needed route to identify adaptive measures that can help deliver blue growth compatible with sustainability targets, and the realization of climate-smart MSP. Our approach to the analysis of ocean climate modelling may thus represent an important decision-support tool with global application. Accordingly, we provide below specific recommendations for the management of these sites in the Irish EEZ that are transferable to other regions of the world, where the delivery of conservation goals is being balanced alongside blue growth within MSP. Furthermore, we provide technical recommendations for future uses of our analysis approach as Supporting Information.

4.2 | Climate-smart MSP for Irish fisheries and marine nature conservation

Our fishing sector analyses indicate that climate-driven impacts on the species currently underpinning 80% of Ireland's LBV will be vast and pervasive, but a limited number of CC refugia and bright spots for these populations were identified in regions currently targeted by fisheries. Bright spots identified further offshore could drive the displacement of fishing effort to those new areas in future in the absence of other management measures, with the potential to cause important first effects with negative ecological impacts on previously undisturbed habitats (Foden et al., 2011). This may lead to new interactions with other sectors that will require consideration. The exploitation of these offshore sites would come with additional fuel and other costs, and may therefore be limited to fishers able to stay at sea for longer periods. In all fishing sector analyses, climate-resilient sites emerged frequently where other existing infrastructure can provide habitat protection from destructive practices, such as an area around a wind farm in the East coast, and offshore seabed sites harbouring cables and pipelines. Supporting blue growth could be seen to require allowing some level of co-location, allowing some degree of access to these sites by fishers (Agardy, 2010; Stelzenmüller et al., 2021). Conversely, protecting such CC refugia and bright spots, by bringing them within an MPA network, could still benefit catches in the wider region already exploited by fishers, because of the potential positive impacts of spill-over upon the wider populations' reproductive output (Beukers-Stewart et al., 2005). This strategy could thus represent a win-win scenario for MSP, helping to meet fisheries sustainability targets without the need to allow fishing in new sites. Indeed, including CC refugia and bright spots identified in the fishing sector analyses within conservation mechanisms would be well aligned with the ambition to protect nature for biodiversity and man's sake. That is, such a strategy could serve as nature-based solution limiting the impact of climate change on both exploited populations and the associated fishing sector, a stance at the heart of recent environmental policies such as the European Green Deal (European Commission, 2019). The decision on whether to allow access to these sites (as opportunities to support the Irish fishing sector) or to protect them (supporting the sector with perhaps less immediate gains, but at the same time ensuring the sustainability of exploited species) would be a trade-off to be considered by Irish policy makers. Such decisions are likely to be entirely specific to individual marine spatial plans and the ecological, social and economic objectives they are intended to balance (Ehler & Douvere, 2009).

In parallel, planning policies for marine aggregates and mining within the NMPF frame them as future sources of 'sustainable minerals' to meet long-term market demands. Similarly, expanding Offshore Renewable Energy is a priority identified within the NMPF, supporting Ireland's decarbonization journey (Irish Government 2019a). Within the Irish EEZ, as in other areas of the world, these different maritime sectors also compete for spatial access to resources. CC refugia and bright spots for fisheries identified in onshore and offshore areas harbouring potentially important aggregate, mining or wind resources may thus necessitate the consideration of impacts across sectors other than those currently outlined within the NMPF, which are based on the present distribution of these sectors. Specifically, the identification of bright spots and refugia raises the necessity to further balance which specific sustainability targets the plan may prioritize (ocean health, decarbonization and sustainable minerals), and where (Levin et al., 2020).

Similar challenges and opportunities emerge for the spatial management of CC bright sports and refugia identified in our marine nature conservation analyses. For Ireland's network of marine and coastal sites of conservation interest, it was the uncertainty between compared emissions scenarios that was most striking, underscoring the critical importance of emission reductions in determining if the current network is climate-resilient. Our analyses provide important evidence that may thus be used to inform the implementation of Ireland's Biodiversity CC Sectoral Adaptation Plan, with which the NMPF could be harmonized as part of the National Adaptation Framework (Irish Government 2019a). Interestingly, benthic and demersal species and habitats of conservation interest appeared more vulnerable to CC than pelagic ones, in all conservation analyses. This potentially greater climate sensitivity of the benthic compartment may reflect both important change in habitat conditions, and strong negative responses of benthic species to these. Increased stratification of the water column resulting from increased warming of the sea-surface and reduced salinity is expected to reduce connectivity between the surface and the seabed, driving deoxygenating conditions on the seabed, loss of nutrient exchange between the seafloor and the surface, and other habitat altering conditions (IPCC, 2019). In parallel, many seabed species have limited ability to track climate-driven changes in habitat distributions due to limited movement and dispersal ability (Hiddink et al., 2015). This is exacerbated by individual-level trade-offs between energetically costly stress response pathways triggered by environmental change and processes supporting dispersal potential (Calosi et al., 2013; Queirós et al., 2015). Such impacts likely further affect important benthic–pelagic coupling processes mediated by benthic communities, indicating that CC may in this way indirectly affect broader ocean functioning in the region (Snelgrove et al., 2018).

The comparatively greater CC resilience estimated for pelagic species and habitats may be primarily explained by the larger variability of modelling layers analysed, as pelagic habitats are spatially more dynamic by nature. However, changes in the distribution of important pelagic foraging areas, such as the location of surface thermal fronts, were also identified. The analyses presented could, in this case: (1) be used in conjunction with megafauna tracking data to further inform the design of climate-adaptive management measures to protect important foraging sites, as Irish waters change in the coming decades; (2) help avoid conflicts that may arise for species dependent on those sites, given the distribution of other maritime sectors; and (3) help identify climate-resilient corridors that may be targeted for dynamic protection to ensure pelagic species can continue to access seasonally important foraging areas, given that large pelagic foraging activity is affected by environmental change (Block et al., 2011; Vedor et al., 2021). At present, only 2.7% of Irish marine waters are MPAs. As a European Union member state, Ireland must deliver on its ambition to extend MPA coverage to 30% of its waters, as outlined in EU's 2030 Biodiversity Strategy. This analysis could aid the identification of potential locations for future MPAs. CC bright spots and refugia identified under the higher emissions scenario provide safer bets to help meet this target, irrespective of emissions trajectories beyond 2050 (RCP4.5 cf. RCP8.5; International Union for Conservation of Nature, 2016; Van Vuuren et al., 2011). Protecting those sites is thus also a potential nature-based solution for marine conservation, contributing to limit the impacts of CC on Ireland's marine biodiversity and associated economic sectors, building on its natural distribution of resilience to climate change (Figure 1, 1.4c, IUCN, 2020). Equally, areas of the seabed that may most effectively serve as carbon sinks under climate-driven shifting patterns of ecosystem functioning identified here can help realize the ambition to use the Irish EEZ to mitigate climate change (Irish Government 2019a). Limiting extractive seabed uses in those sites, by bringing them under some degree of protection, thus also serves as a nature-based solution for climate change (Hale et al., 2017, Irish Government 2019a). All of these proposed measures could help to deliver on the NMPF objective of supporting the implementation of Ireland's National Mitigation Plan and its Climate Action and Low Carbon Development Act (2015), as well as potentially support Ireland's voluntary Nationally Determined Contributions under the Paris Accord (Gallo et al., 2017; Hoegh-Guldberg, Caldeira, et al., 2019; Queirós et al., 2019). Such important examples highlight how the types of analyses presented here can support the implementation of ecosystem-based management principles that are expected to guide MSP policies (Ehler & Douvere, 2009); the design of climate-resilient MPA networks (Wilson et al., 2020); and that of other CC adaptive and mitigating ocean management practices that should be part of climate-smart MSP. These analyses, linking climate to the spatial management of resources and biodiversity, therefore have broad applicability globally (Tittensor et al., 2019).

4.3 | Communicating climate modelling analyses in support of climate-smart MSP development

A global effort is underway to improve the uptake of CC evidence within MSP processes, including the design of MPAs, but examples of this remain rare (Rilov et al., 2019; Tittensor et al., 2019; Wilson et al., 2020). Large stumbling blocks continue to include the unsuitability of traditional CC evidence analyses relative to the requirements of MSP processes, including how to use often complex CC evidence in support of necessary consultations with diverse pools of stakeholders towards decision-making (Queirós et al., 2016). For instance, knowing that ocean warming may increase by a specified value by 2060 is not sufficient to inform the decision of whether or not to designate an area for marine conservation or grant an aquaculture license application. This is because the ocean resources and natural capital underpinning each affected sector involve much broader sets of conditions within an ecosystem, changing simultaneously. In parallel, potentially limited CC literacy within departments developing MSP, and indeed a lack of fit-for-purpose mechanisms required for uptake of this evidence within planning processes remain major challenges, despite climate-smart MSP policy aspirations (Craig, 2012; Ehler & Douvere, 2009; Frazão Santos et al., 2020; Gissi et al., 2019). These challenges are compounded for MSP affecting the management of apex species, highly migratory species, and species and habitats in the deep sea. Indeed, these species and resources occur in extensive areas where regulatory hurdles are far more complex and due-process mechanisms are lacking or underdeveloped (Levin et al., 2020; Popova et al., 2019). The analyses and methods presented here, using the Irish case-study, demonstrate how current challenges of integrating CC evidence into MSP dialogues can be effectively resolved. It provides a means to consider highly detailed CC modelling projections about the ecosystem that underpins each affected sector in a categorical, mapped format that is amenable to management scenario exploration in an MSP, multi-sectorial, co-location context. The outputs of our analyses provide a simple means to answer questions sought after by planners: where the ecosystem supporting specific spatially managed sectors is resilient to CC in the period of implementation of a plan; where it is vulnerable to CC; and where new opportunities for expansion of the activity of a sector emerge within the time-frame of the plan's implementation. The ability to identify CC bright spots, alongside refugia, is potentially especially attractive to managers because it meets the common aspiration of identifying what can be done, instead of just identifying what will be lost. Analysis tools such as these could therefore be invaluable in helping to bridge communication challenges between those that best understand the effects of CC on the marine environment and those responsible for spatial planning and the design of marine policy (Frazão Santos et al., 2020; Pınarbaşı et al., 2017; Queirós et al., 2016). Offering positive solutions is another important step forward towards effective decision-support tools for climate-smart MSP design (Pınarbaşı et al., 2017). Importantly, the consideration of the time-frame of the plan in the specific design of modelling data analyses, as done here, is an essential aspect of potential interest to planners. With few exceptions (e.g. Levin et al., 2019), a traditional mismatch in temporal scales between typical ocean policies (a few decades) and long-term CC analyses contributes to the often-held perspective that climate effects on the marine environment are a future concern that cannot or need not be addressed by ocean managers (Lubchenco & Grorud-Colvert, 2015). The nature-based solutions we propose here are not an alternative to the need to slow the pace of climate change. And yet, the pervasive effects of CC on ocean species and habitats make the implementation of climate-smart MSP an urgent necessity, especially for marine conservation (Bindoff et al., 2019). Identifying bright spots may provide opportunities to reap benefits for marine conservation as part of sustainable blue growth. This opportunity can be seized upon under the growing momentum to use the next decade to support sustainable ocean management through the International (UN) Decade of Ocean Science for Sustainable Development (IOC-UNESCO, 2018; Ryabinin et al., 2019).

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

All modelling datasets used in this publication are available via the COPERNICUS Climate Data Store or otherwise available on request from the authors. All Geographical Information System datasets used expressing the distribution of maritime industries and marine nature conservation areas are publicly available via the Marine Institute (Ireland) and the European Marine Observation and Data Network (EMODnet). Please refer to the main text for guidance.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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