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Welsh National Marine Plan Storyline

Narrative of marine (spatial) planning scenarios explored in the MSPACE project

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Section A: The MSPACE project

MSPACE is a £1.7m, 4 year (2021-2025), highly integrated, multidisciplinary project, conceptualised to drive forward the capability of the four UK Nations in designing and implementing climate-smart marine spatial plans (MSP). The project is funded by UKRI under the UK Government's Strategic Priorities Fund. The projects team brings together natural and social scientists, planning practitioners and industry representatives from across the UK Nations, and global experts in ocean sustainability and climate change. The main ambition of the project is to support the delivery of marine planning that addresses the causes and impacts of climate change (i.e. mitigation and adaptation) in a way that is economically feasible and socially acceptable, supporting people and nature for future generations.

We first delivered an Early Warning System (EWS) report, infographic and summary for policy makers, which analyses state-of-the-art climate modelling projections and identified opportunities for climate-smart spatial management of UK marine conservation, fisheries and aquaculture. These are based on the identification of areas of our marine waters with different degrees of sensitivity to ongoing climate change. We then mapped the governance structured around four case-study marine plans across the UK nations, and the preferences of its stakeholders on marine space.

We are now co-developing with our stakeholders 4 alternative possible spatial management scenarios for each case-study (Section D, East of England Inshore and Offshore, Northern Ireland, Scotland (Orkney Islands) and Wales), as follows:

1. The first scenario represents the current marine plan for a region (*Business-as-Usual Scenario*).
2. The second is a climate-smart scenario that uses the information made available in the MSPACE EWS to prioritise changes in spatial uses to include the specific use of areas identified in the EWS report as having low sensitivity to climate change (i.e. climate change refugia) to maximise environmental and economic goals for marine conservation (*Conservation Scenario*).
3. The third is the same as the second, except designed to maximise environmental and economic goals for fisheries and aquaculture (*Food Provision Scenario*).
4. A fourth scenario takes elements from the other three scenarios to maximise environmental and economic goals for the region (*Compromise Scenario*).

Project recommendations for each case-study region are based on the Compromise Scenario. In the last year of the project (2024-2025), we convert the co-produced decision support system created by MSPACE into a web-based, artificial intelligence assisted tool, and test its application with our project partners towards the delivery of climate-ready spatial management policies across the UK nations.

Section B: Regional context

The Welsh marine plan area consists of approximately 32,000 km^2 of sea, with 2,120 km of coastline. The Welsh National Marine Plan (WNMP) covers both the Welsh inshore region (from mean high water spring tides out to 12 nm) and offshore region (beyond 12 nm). The plan area is adjacent to two English marine planning regions, the North-West and South-West marine plan areas. The plan area also shares boundaries with Northern Ireland, the Isle of Man and Republic of Ireland.

The plan area is used by several industrial and environmental sectors. Key sectors include:

- Marine renewables, especially offshore wind (OWE)
- Shipping
- Aggregate extraction
- Dredging and disposal
- Fishing
- Aquaculture
- Tourism and recreation
- Marine protected areas (MPAs)

The WNMP was published in 2019 and is currently in the second monitoring period (2022-2025). The marine plan area supports the shared UK vision of energy security, net zero, economic growth, environmental sustainability and human wellbeing. It also plays a role in the UK's ability to mitigate and adapt to climate change and will experience the continued development of the renewable energy sector and associated cabling. The UK Government has pledged to protect at least 30% of land and sea for nature by 2030. The WNMP area is of significant ecological importance, and include MPA designations for seabirds, marine mammals, and several benthic habitat types.

The WNMP includes 13 strategic objectives, supported by further general and sector-specific policies and objectives. Sector specific aims include:

- Fisheries: To support and safeguard a sustainable, diversified and profitable fishing sector including promoting sustainable capture fisheries and optimising the economic value of fish caught as a supply of sustainable protein.
- Aquaculture: To facilitate the development of sustainable aquaculture, including innovative fin/shellfish and marine algal businesses.
- Renewable energy: To contribute significantly to the decarbonisation of the economy and to develop Wales as an exemplar of marine renewable energy technology.
- Oil and gas: The Welsh Government's policy objective is to avoid further extraction and consumption of fossil fuels, including shale gas, coal bed methane and underground coal gasification.
- Tourism: To contribute to sustainable development by protecting and promoting access to the coast and improving the quality of the visitor experience thereby increasing Wales' reputation as a world class sustainable marine tourism and recreation destination.

The WNMP also contains explicit objectives for climate change adaptation and mitigation (objective 8), and to realise sustainably the potential of renewable energy (objective 3). These objectives are supported by plan specific policies:

- SOC-10: Supports proposals that minimise climate change by avoiding, minimising or mitigating greenhouse gas emissions
- SOC-11: Supports proposals that demonstrate resilience to climate change by considering the impacts of climate change and incorporating appropriate adaptation measures
- ENV-01: Supports proposals that avoid, minimise or mitigate negative impacts on marine ecosystems, in order to increase the resilience of marine ecosystems and the benefits they provide.

To determine stakeholder preferences for the use of marine space in Wales and thereby inform the development of the MSPACE climate-smart spatial management scenarios presented in this document (Sections D.4 – D.6), we used direct survey techniques during remote 1-2-1 interviews conducted from July 2022 through April 2023 (Reinhardt & Danahey Janin, 2025). We gave stakeholders a values questionnaire which asked participants which are active in either conservation, fisheries or aquaculture, to give a numerical value from 0-100 on several criteria associated with marine space. The number given was explicitly meant to represent the value, or level of importance, that the specific element of the marine space represented to them in their professional capacity. We sought this information as these sectors are seen as key stakeholders to the planning process in Wales. As each participant filled out their ratings, a member of the research team engaged them in conversation to elicit complementary information on why and how they valued these elements at the levels indicated.

The original selection of elements of the marine space to rank was based on the World Bank's "Roles Oceans and Coasts Play in Human's Lives" (p. 2) (*Biodiversity and Ecosystem Services in Marine Spatial Planning: Supporting biodiversity and healthy ecosystem services in oceans and coasts*, 2022), augmented by insights gleaned from other sources(IPBES, 2022; Newton & Elliott, 2016; Strickland-Munro et al., 2015). This list included: leisure and recreation; food provision; identity, culture, and heritage; conservation designations; tourism; governance; biodiversity; learning and research; biosecurity; water quality; economy; health; and transportation and shipping. Once interviews began, participants were given the opportunity to name additional elements they found important about the marine space. Some respondents also chose not to rate elements about which they felt they had no professional opinion/remit. If another element of the marine space was mentioned 3 or more times by respondents, it was added to the questionnaire. As a result, only a portion of respondents rated these additional fields: climate change; energy.

With respect to the WNMP area, we spoke with respondents in the sectors of aquaculture, conservation, fisheries, and regulation/government. The self-identification of these sectors among respondents is represented in Table B.1.

Table B.1 Respondents' self-identification of sectors in which they work or have a professional interest

Wales - Sectors	Freq.	Percent
Aquaculture	2	28.57
Aquaculture, Conservation, Fisheries	1	14.29
Conservation	4	57.14
Total	7	100

The indicative value rankings of criteria by participants speaking about the Wales are summarised in Table B.2. On average, respondents rated biodiversity and climate change highest.

Table B.2 Means, Standard Errors, and Confidence Intervals for ratings of elements of the marine space, as rated by respondents

Wales	Obs	Mean	Std. Dev.	95% Conf	Interval
Biodiversity	7	96.14286	6.890297	89.7704	102.5153
Biosecurity	7	72.57143	27.53093	47.10956	98.0333
Climate change	3	83.33333	28.86751	11.62245	155.0442
Conservation designation	7	81.28571	31.11652	52.50773	110.0637
Economy	7	77.85714	23.06822	56.5226	99.19169
Energy	3	76.66667	7.637626	57.69375	95.63958
Food provision	7	70.14286	18.8894	52.67307	87.61264
Governance	6	84.66667	31.91656	51.17229	118.1610
Health	6	89.5	12.06234	76.84135	102.1586
Identity/culture/heritage	7	83.14286	14.90446	69.35853	96.92718
Learning and research	7	86	18.61003	68.78859	103.2114
Leisure/recreation	7	83.85714	12.8767	71.94818	95.76611
Tourism	7	71.57143	26.96824	46.62997	96.51289
Transport and shipping	7	69.57143	25.24452	46.22414	92.91871
Water quality	7	95.71429	7.867958	88.43764	102.9909

Section C: Projected impacts of climate change in the Welsh National Marine Plan area

C.1 Glossary

Annex 1 habitats and species: Habitat types and species which occur in the UK and for which SACs and SPAs have been designated (see below for specific definitions of SAC and SPA).

Biologically relevant artificial light (critical depth): The depth to which artificial light of an irradiance that elicits biological responses in marine organisms penetrates.

Bright spot: a site where multiple habitat conditions for a given set of species is improved in the short and mid-term, entering a new ecosystem state beyond its natural variability (*sensu* Hawkins & Sutton, 2012; Queirós et al., 2021) , but where this state is defined by trends that are inconsistent with mean expected 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.

Climate change hotspot: a site where a climate signal emerges. That is, a site where climate pressures drive an ecosystem into a new ecosystem state, beyond its natural variability (*sensu* Hawkins & Sutton, 2012; Queirós et al., 2021).

Climate change refuge: a site that remains climate-resilient within a given period of analysis.

Climate change resilience of habitats: the ability of a habitat to remain within a current or reference ecosystem state, within the boundaries of its natural variability, despite climate change pressures. In this report, focused on the detection of the emergence of climate signals within UK marine waters, their species and habitats, we define resilience as the absence of the emergence of a climate signal, when climate pressures drive an ecosystem into a new ecosystem state, beyond its natural variability (*sensu* Hawkins & Sutton, 2012; Queirós et al., 2021).

Climate services: Seabed habitat conditions potentially promoting carbon sequestration.

Designated feature: The habitat(s) or species for which a conservation area in Wales is designated.

Feature of Conservation Interest (FOCI) list: Marine features that are particularly threatened, rare, or declining species and habitats. They were chosen to focus the process used to identify Marine Conservation Zones in Wales, and are listed in Annex 1 of Carr et al. (2016).

Intervention: Theoretical spatial management measures simulated in each climate-smart scenario. These represent potential easy-wins that could be delivered or encouraged through marine planning, to improve climate change adaptation or mitigation potential for each of the MSPACE focal sectors.

Marine Conservation Zone (MCZ): MPA designated under legal order made by Defra under section 116(1) of the Marine and Coastal Access Act 2009 (MCAA).

Marine Protected Area (MPA): The purpose of an MPA is to protect and recover rare, threatened and important habitats and species from damage caused by human activities. In this document, MPA is used as a catch-all term to denote any designated conservation site in the plan area. In practice, there are a number of different MPA designations (SAC, SPA, MCZ, see this glossary for the different types present in the planning area), which are created under specific, and different, pieces of legislation.

Nationally determined contributions: Commitments that countries make to reduce their greenhouse gas emissions as part of climate change mitigation. These commitments include the necessary policies and measures for achieving the global targets set out in the Paris Agreement.

Priority area: An area identified within a climate change refuge for a given sector, which represents either climate resilient sectoral activity (when the priority area is already used by a sector) or an opportunity to expand into a new area (when the priority area is not currently used by the sector)

Scenario: Theoretical situation which represents possible alternative futures for the EMP area. Scenarios vary in ambition to act on climate change evidence (as presented in the MSPACE EWS) and on the prioritisation of outcomes for specific sectors.

Seafloor aquaculture: For the purposes of this document, seafloor aquaculture is any cultivated production of species that occurs on the seabed (e.g. seabed production of mussels, trestle culture of oysters).

Special Area of Conservation - SAC: MPAs put in place to protect habitats and species listed in Annexes I and II of Council Directive 92/43/EEC (the Habitats Regulations).

Special Protection Area - SPA: SPAs referred to in this document are all SPAs “with marine components”. These sites are MPAs that protect bird species listed in the Birds Directive (2009/147/EC) as Annex I or as regularly occurring migratory species, that are dependent on the marine environment for all or part of their life-cycle, where these species are found in association with intertidal or subtidal habitats within the site.

Water column aquaculture: For the purposes of this document, water column aquaculture is any cultivated production of species that occurs in the water column (e.g. rope grown mussels or seaweed, salmon cages)

C.2: MSPACE Early Warning System: summary of results for Welsh waters

The development of scenarios in MSPACE begins with an assessment of climate-driven changes in the UK EEZ. Here, we summarise first the findings of an assessment carried out by the project to identify key challenges and opportunities emerging from climate change for the spatial management of UK seas. Specifically, the MSPACE Early Warning System ("EWS", Queirós et al. 2024) was co-produced with the UK Marine Climate Change Impacts Partnership, key agencies with statutory responsibility for planning across the UK nations, and key representatives of maritime sectors. In that report, climate change modelling datasets were analysed as a means to explore the potential to deliver climate-smart spatial management strategies for marine planning across the UK EEZ; that is, strategies that could promote climate change adaptation of marine sectors (including marine conservation) as well as climate change mitigation. The work focused specifically on identifying the location of areas which exhibit long-term sensitivity to climate change (climate change hotspots) and those more resilient to climate change (climate change refugia and bright spots). This was done through analyses designed specifically to estimate climate effects on marine conservation, fisheries and aquaculture, interpreted within the context of the broader UK blue economy. In the Early Warning System, we focused on identifying areas that fell into each of those three categories consistently over the 21st century, in both emissions trajectories considered (RCP4.5 and RCP8.5). RCP4.5 (the "slowly declining emissions" scenario) assumes strong curbs in global emissions toward climate change mitigation, from 2050 onwards, leading to a mean global warming by the end of the century of ~2.4 °C. Contrastingly, emissions continue to rise steadily throughout the 21st century under RCP8.5 (the "growing emissions" scenario), leading to mean global warming ~4.3°C. The two scenarios correspond to a mean warming of UK sea surface temperature of about 1°C and 2°C by the end of the 21st century, respectively, in the physical modelling dataset used. The EWS report is supported by a technical report that provides an assessment of the confidence that can be placed in the modelling datasets used as inputs, in terms of their ability to replicate real life observations. Those analyses are provided in Kay et al. 2024, which is Annex 1 of the EWS report. Annex 2 of the report provided evidence on the current seabed status of the UK EEZ, based on an estimate of the effects of bottom contact fisheries and aggregate extraction. In the EWS, we also explored how climate change effects relate to the distribution of those other pressures on seabed habitats, and that cumulative assessment can be found in the main report here.

What follows is a summary of the key findings outlined in the EWS report which are relevant to the Welsh National Marine Plan. When considering the locations of **long-term climate change hotspots and refugia with high agreement between emissions scenarios**, we found that Welsh waters are projected to be sensitive to climate change impacts, with limited areas emerging as long-term climate change refugia for the three focal sectors (capture fisheries, aquaculture and marine conservation), **under the two emissions trajectories we considered**.

C.2.1 Climate change impacts on marine species and habitats in Welsh waters

Considering the MPA network across Welsh waters with a focus on biodiversity, it is likely that the designated habitat features and their associated species located inside current conservation sites may not continue to function in the same way in the future as climate

change unfolds across the region. This is due to the extensive distribution of climate change hotspots for benthic and pelagic habitats, and benthic and pelagic megafauna, throughout the planning area (Figure C.1).

A long-term climate change refuge for benthic habitats was identified in the Irish Sea, towards the edge of the offshore sector of the marine planning area (Figure C.2). This refuge covers the location of an unprotected area of an OSPAR threatened and declining habitat (sea pens and burrowing megafauna), which has been assessed as being highly disturbed by bottom contacting demersal fishing gears (Annex 2, Queirós et al., 2024), and the broad-scale habitat "offshore circalittoral sand", which is moderately disturbed by demersal fishing gears (Annex 2, Queirós et al., 2024). While the OSPAR habitat appears on the MPA features list for Wales, the circalittoral sand as a habitat does not (Carr et al., 2016).

When we considered seabed habitat conditions potentially promoting carbon sequestration (Queirós et al. 2024; Supplementary Information Table S3), we found that refugia for such "climate services" (Benyon et al., 2020; Flavell et al., 2020) emerged across the majority of the planning area (Figure C.2), including some areas that have been identified as having high carbon sequestration potential, such as Carmarthen Bay (Robbins et al., 2022). Climate services refugia could help deliver climate change mitigation if evidence substantiates their potential and legislation is introduced that allows the designation of MPAs for the protection of carbon stocks.

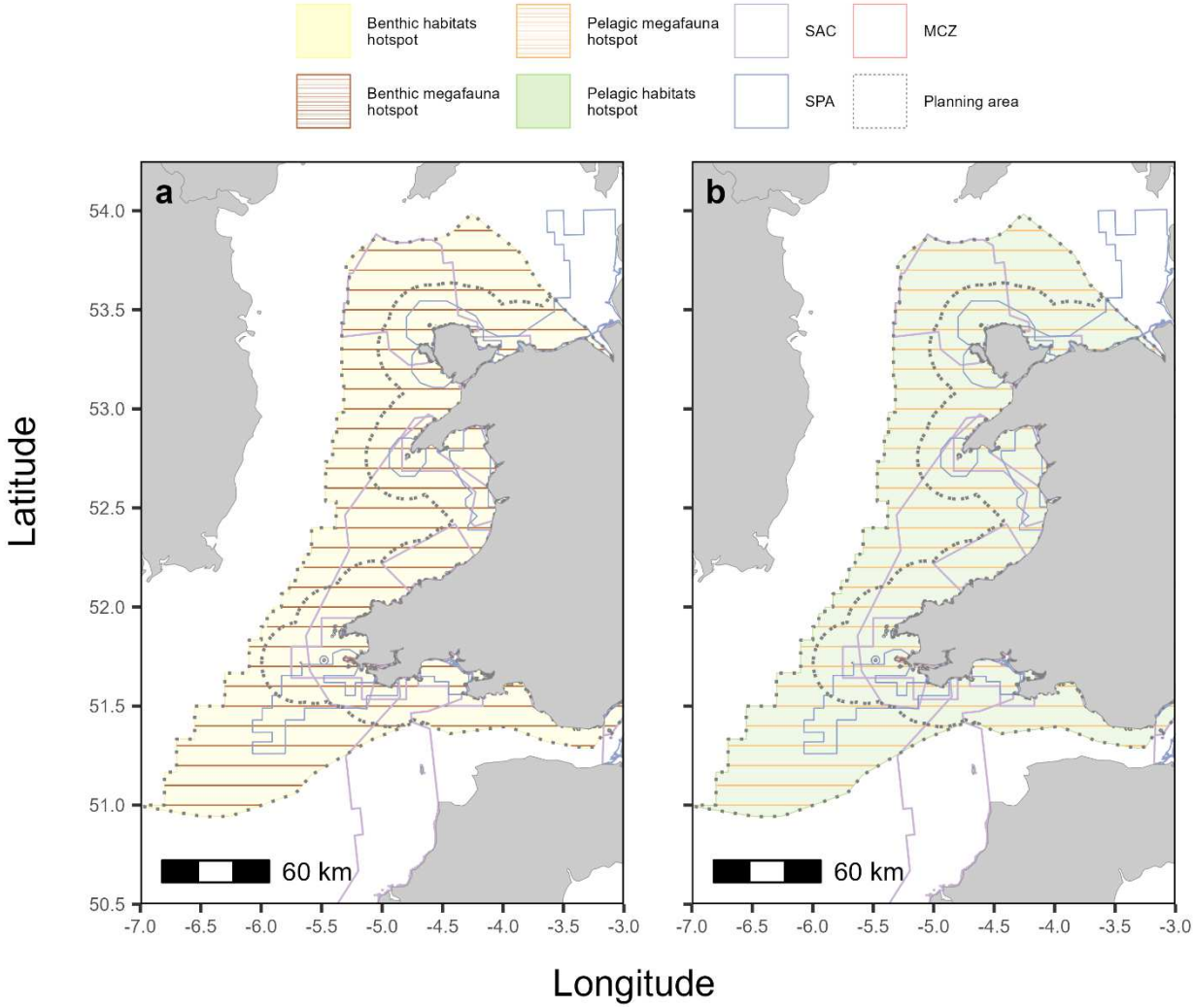

Figure C.1: Locations of climate change hotspots relevant to the conservation of benthic habitats and megafauna (a) and pelagic habitats and megafauna (b) where there is high agreement between the two emissions scenarios (RCP4.5 and RCP8.5) considered in the MSPACE EWS.

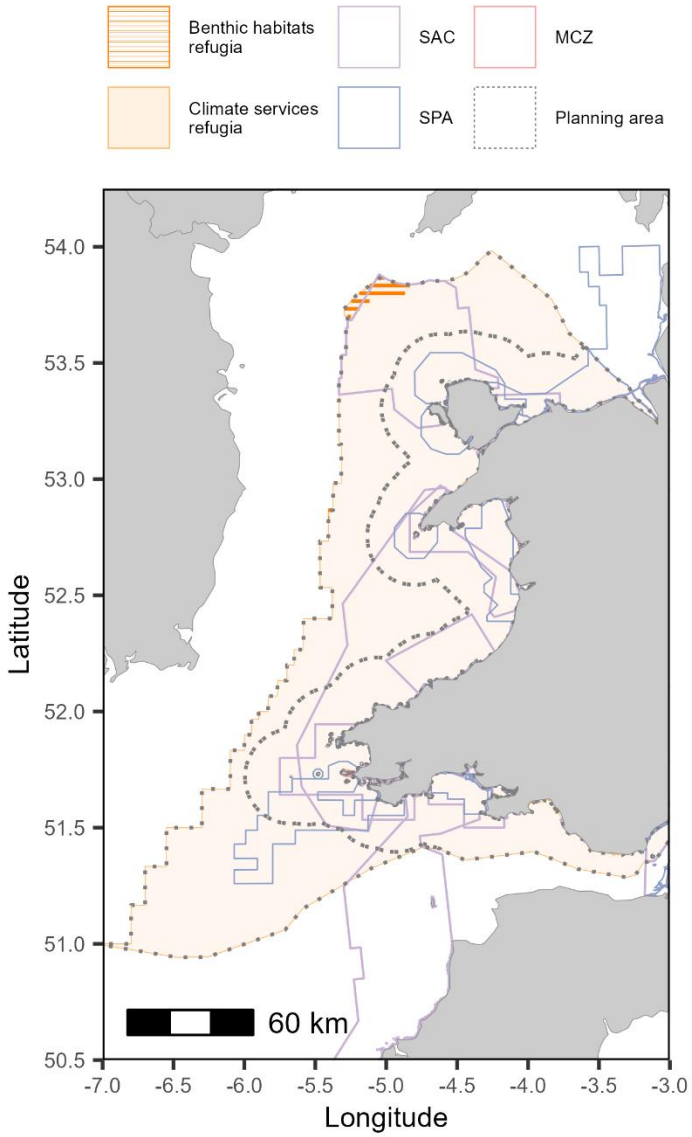

Figure C.2: Locations of climate change refugia relevant to marine conservation. The only refugia identified where there is high agreement between the two emissions scenarios (RCP4.5 and RCP8.5) considered in the MSPACE EWS were for climate services and benthic habitats, with no refugia present for benthic megafauna, or pelagic habitats and megafauna.

C.2.2. Climate change impacts on marine fisheries and aquaculture in the Welsh waters

Based on the EWS analyses, we find that some demersal (finfish and shellfish) and pelagic capture fisheries and seafloor and water column aquaculture (based on the current UK target species, Queirós, 2023; Supplementary Information Table S4) could be particularly vulnerable to climate change in Welsh waters, as hotspots for these sectors cover the majority of the planning area (Figure C.3). This is based on projected decreases in abundances of brown shrimp (*Crangon crangon*) and the edible crab (*Cancer pagurus*) which comprise a minority of Welsh fisheries landings). However, it is worth noting, that this analysis did not include modelling data for other key species which comprise the majority of Welsh landings such as whelk (*Buccinum undatum*), lobster (*Homarus gammarus*) or king

scallop (*Pecten maximus*), as it was not available to us at the time of analysis. Demersal finfish species such as Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and plaice (*Pleuronectes platessa*) are also projected to decline in Welsh waters. Similarly, conditions for the production of important aquaculture species such as mussel (*Mytilus edulis*) are projected to be less favourable in the future.

A refuge for pelagic fisheries was identified to the north of Anglesey, with abundances of species such as Atlantic horse mackerel (*Trachurus trachurus*) projected to remain stable in the future in this area (Figure C.4). Contrastingly, abundances of mackerel (S*comber scombrus*) are projected to decline. We note here however, that at present, there is no Welsh pelagic fleet (NRW, personal communication, Feb. 2025).

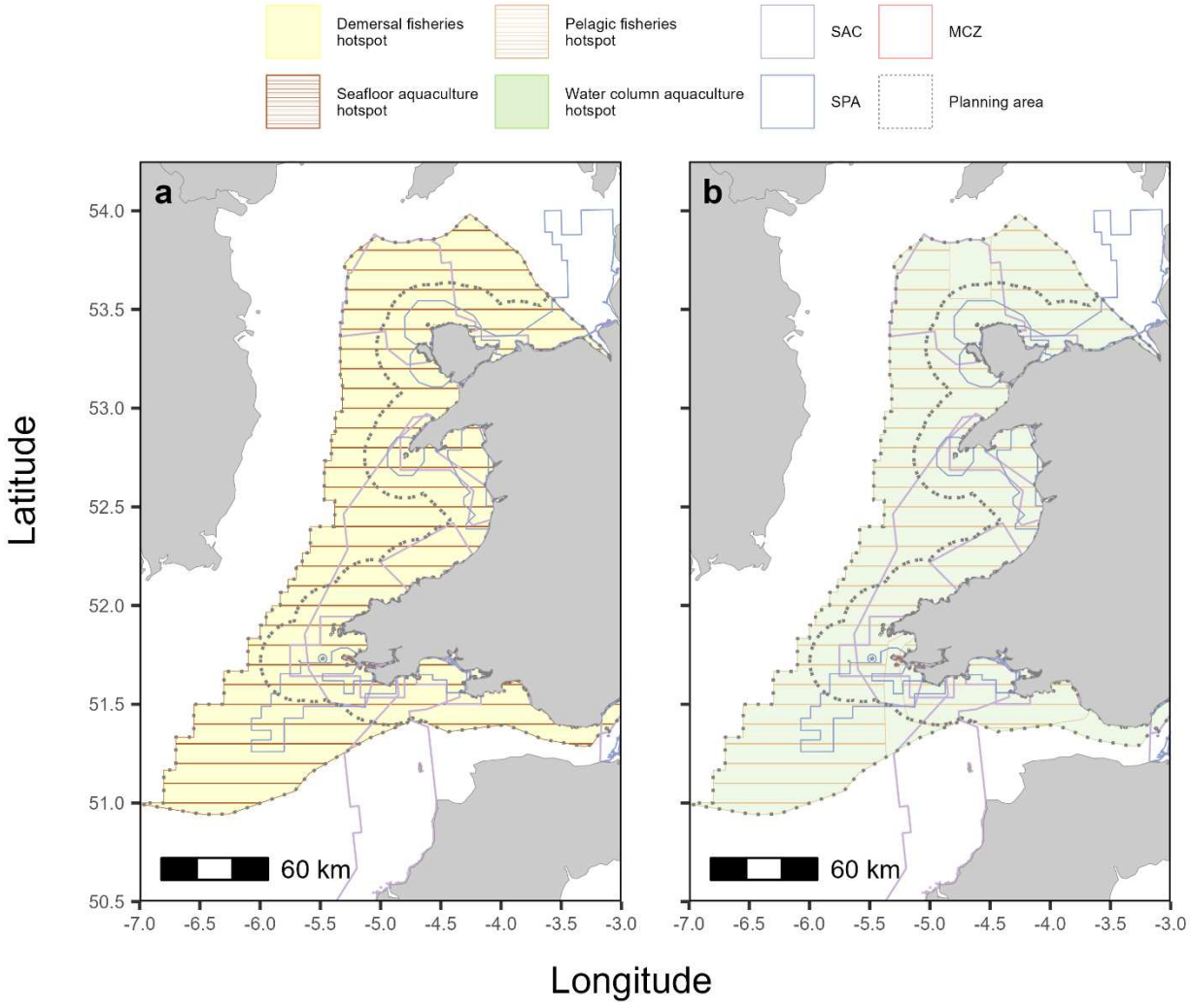

Figure C.3: Locations of climate change hotspots relevant to the sustainability of demersal (finish and shellfish) capture fisheries and seafloor aquaculture (a) and pelagic capture fisheries and water column aquaculture (b) where there is high agreement between the two emissions scenarios (RCP4.5 and RCP8.5) considered in the MSPACE EWS.

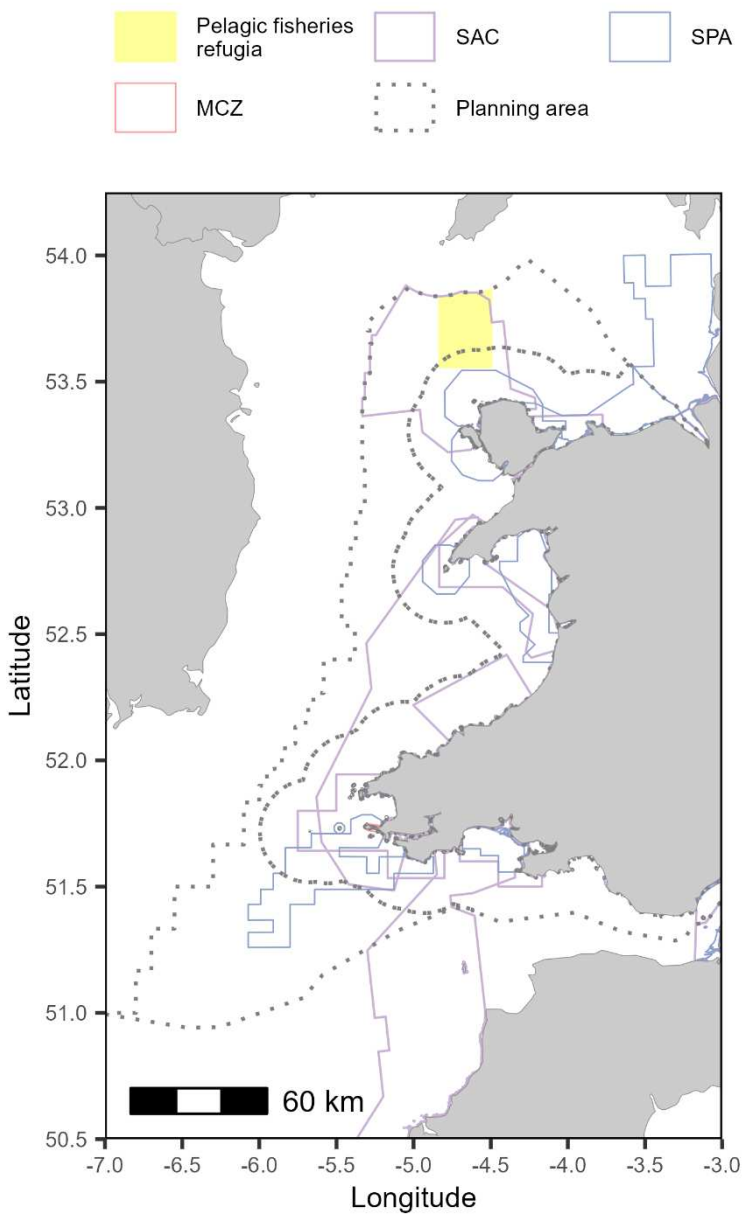

Figure C.4: Location of climate change refugia relevant to the sustainability of pelagic fisheries (there were no other fisheries or aquaculture refugia present in the Welsh planning area, see main text for details), where there is high agreement between the two emissions scenarios (RCP4.5 and RCP8.5) considered in the MSPACE EWS.

Overall, evidence uncovered in the EWS indicated that there is variability between emissions scenarios, leaving less room for the development of no-regrets decisions with regard to planning, that is, decisions based on findings that would hold across the range of future greenhouse gas emissions simulated by RCP4.5 and RCP8.5. For this reason, in Section D below, **we consider EWS evidence for long-term climate change refugia emerging only under the moderate emissions trajectory RCP4.5,** as this is a likely outcome if current climate action plans are implemented, and nationally determined contributions are achieved (United Nations Environment Programme, 2024; Wang et al., 2023)

Section D: The MSPACE management scenarios for the Welsh National Marine Plan area

D.1 Scenario overview

We now outline four scenarios, representing possible alternative futures for Welsh waters. Scenarios vary in ambition to act on climate change evidence (as presented in the MSPACE Early Warning System) and on the prioritisation of outcomes for specific sectors. These scenarios therefore represent *alternative, hypothetical ways* through which the potential for climate change adaptation and mitigation of marine wildlife and sectors in Welsh waters could be encouraged through planning actions. They are expected to lead to different ecological, social and economic outcomes for the region, based on climate change impacts and opportunities. These scenarios build on formulations described in Annex 1, as follows:

1. **The Business-as-Usual scenario**: represents a possible future for Welsh waters which does not provide marine planning policies that act on climate change evidence as presented in the EWS, and simply estimates the modelled effects of climate change on the region and its associated economic impacts, considering the current distribution of human uses and conservation areas.

Additionally, three climate-smart scenarios then prioritise outcomes for specific sectors, and propose spatial interventions that promote climate change adaptation and mitigation, based on specific uses of identified climate change refugia for those sectors:

2. **The Conservation Scenario:** prioritises climate change adaptation for the conservation sector (i.e. marine conservation and restoration), and the protection of areas delivering potential for resilient, nature-based climate services toward climate change mitigation. The interventions considered aim to avoid, minimise or mitigate the impacts of activities which could negatively affect the climate change adaptation potential of 1) habitats and species of high conservation value in Welsh waters where they occur in climate change refugia, and 2) areas which at present hold important carbon stocks and which are projected to have climate resilient seabed carbon sequestration potential in the future (e.g. areas which may provide future "climate services").
3. **The Food Provision Scenario:** prioritises climate change adaptation for the fishing and aquaculture sectors. The spatial interventions outlined in this scenario aim to support and safeguard climate-resilient fisheries and to facilitate the development of climate-resilient aquaculture in the Welsh waters, by prioritising the access of these sectors where their resources occur in climate change refugia.
4. **The Compromise Scenario:** aims to promote a balance of improved outcomes for the conservation and food provision sectors, with a view for what other priorities stakeholders hold for the region with regard to other sectors of economic activity (Section B). The interventions considered aim to support climate-resilient fisheries, facilitate the development of climate-resilient aquaculture and seek to avoid, minimise or mitigate the impacts of activities which could negatively affect habitats and species of conservation interest in Welsh waters. These aims are supported by prioritising access to areas of climate change refugia for each sector, or by prioritising conservation objectives where designated conservation areas overlap

with climate change refugia. It is expected that the Compromise Scenario may meet a broader set of objectives with regard to stakeholders in Wales.

D.2 Scenario co-development methodology

D.2.1. Spatial data interrogation

The methodology for scenario co-development is summarised in the diagram below (Figure D.2.1). First, GIS datasets showing the locations of climate change refugia and hotspots relevant to each of the four spatial management scenarios, produced as part of the MSPACE EWS, were overlaid with spatial distributions of designated conservation sites and human activities (e.g. locations of planned and operational offshore renewable energy structures, locations of aquaculture infrastructure etc.). This allowed us to estimate how current sectoral activities overlap with climate change hotspots, and thus where each focal sector may become unsustainable without additional climate change adaptation measures (e.g. an MCZ designated for benthic features located in a projected hotspot for benthic habitats). The same analyses also allowed us to identify how areas used at present by a given sector overlap with identified climate change refugia (or bright spots) for that sector, leading to potentially climate-resilient sectoral activity or growth into the future (e.g. currently fished areas located within projected climate change refugia for fisheries). These areas of overlap between marine activities and correspondent refugia (or bright spots) were termed "priority areas" for each sector in each spatial management scenario (Figure D.2.1, 1). The set of interventions developed in each climate-smart scenario are seen to represent potential easy-wins that could be delivered or encouraged through marine planning, to improve climate change adaptation or mitigation potential for that (those) sector(s) (Figure D.2.1, 2). Proposed interventions also take into account the values that previously surveyed stakeholders in the region were found to place on the marine environment (Reinhardt & Danahey Janin, 2025). Interventions take into account the potential for co-location of activities, where possible. All climate-smart scenarios (i.e. all but the Business-as-Usual Scenario) therefore propose a set of interventions to this end (Figure D.2.1).

Co-developed interventions in each scenario also consider possible conflicts between sectors. For example, where a demersal fisheries refuge was identified in an area where demersal fisheries occur, the scenario may simulate that planning (and associated governance mechanisms) thereafter avoid, minimise or mitigate any proposed activity that limits access of demersal fishers to that site, as a means to help safeguard the climate-resilience of that sector. That may cause a knock-on effect for another sector which currently uses that identified priority area, which may lose access in the scenario if activities are not compatible (e.g. aggregate extraction and benthic fisheries). Priority areas identified within scenarios, underpinning simulated interventions, also include climate change refugia that might provide opportunities for sectoral expansion in the future into areas where there is not currently activity for that sector, against a backdrop of climate change impacts elsewhere. For instance, areas that were identified as climate refugia for seafloor aquaculture which do not harbour aquaculture facilities at present were flagged as priority areas for industry development.

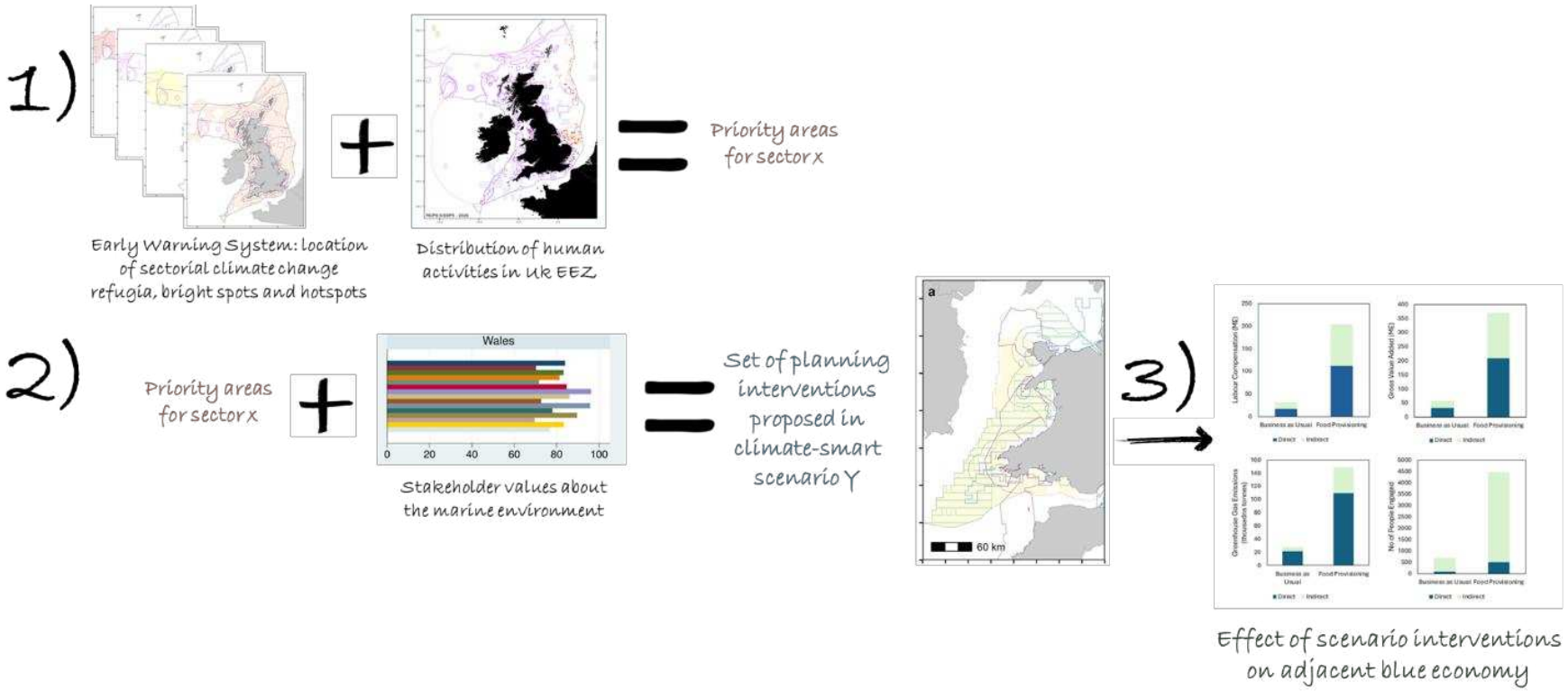

Figure D.2.1: Schematic representation of climate-smart scenario development.

It is important to note that areas that are identified as climate refugia, and subsequently priority areas for some sectors, can be climate change hotspots for others and vice versa, as all climate change sensitivity analyses were carried out for each individual sector in the MSPACE EWS (please see Section C). Once priority areas for each sector had been identified, and hypothetical spatial management interventions developed, we were then able to calculate the possible effect of these interventions on other sectors within each scenario. For example, if a priority area for aquaculture were to be developed in the future, but the area is fished at present, how much area (in Km^2) could be lost to fisheries due to the development of the site? Additionally, it is possible that area lost to one sector due to the development of new activities by another would be strongly impacted by climate change effects regardless (e.g. area would be lost to climate change even without losses due to the development of other sectors), and these effects of climate change on cross-sector interactions are accounted for in our economic estimates (Figure D.2.1 3; Annex I). In this way, we attempt to identify possible conflicts and trade-offs between sectors, while also considering the overall climate effect on each MSPACE focal sector in the planning area. Once the spatial effect of each management scenario had been calculated (e.g. the area in Km^2 identified as priority areas or area lost for each sector), it was then possible to model the economic effect of each scenario (Figure D.2.1 3).

D.2.2. Economic analysis

The economic modelling carried out in MSPACE is aimed at translating the spatial interventions simulated in co-developed scenarios into economic metrics, to help end-users explore how climate action interventions outlined in scenarios affect the adjacent blue economy. This work aims specifically to fill a perceived data gap, and supports end-users in the development of evidence-based approaches that promote a better understanding of the economic feasibility of climate change adaptation and mitigation strategies through marine planning and associated governance mechanisms.

The economic modelling method deployed is termed Input-Output modelling and focuses on how changes to the input (or resource) used by a given sector (e.g. changes in wild capture fisheries catch) affect economic metrics for that sector, as well as other sectors within that economic structure, both directly and indirectly (Roca Florido et al., 2025). Based on data availability emerging from extensive data searches at the UK and devolved nation level and co-development with stakeholders, the economic model has 17 marine focussed sectors (Table A1, Annex 2) and 62 general sectors. The primary driver of economic effects (direct and indirect) are the changes in resource (space) available to marine conservation, fisheries and aquaculture simulated in scenarios, as these are sectors reliant on the marine environmental conditions more directly, that are explored in the Early Warning System report. The marine focussed sectors are particularly explicit on fisheries and aquaculture which represent 9 of the 17 sectors (Roca Florido et al., 2025, Table A1, Annex 2). Whilst the renewable sector in particular is seen as a key sector in Wales, we did not estimate the effects of climate change on the future activity of that sector due to a lack of available modelling data at the start of the project, and no scenarios simulate changes to the area available to this sector. Hence, all estimates presented exclude the background effect of a growing renewable sector in Wales, since the outputs of that sector are not affected by individual scenarios, whilst analyses presented here focus on scenario comparison.

The economic model necessitates linear assumptions between resource availability to a sector and the particular area within the marine plan: for instance, for demersal fisheries, the catch of the sector is scaled linearly to the area where the fishery is known to occur, whilst we recognise that, in reality, total catch will vary across the area where the fishery is active (based on analysed fisheries statistics, MMO, 2018). Specifically, we assume that catch is equally distributed across the plan area accessible to a given fleet segment, at the resolution of ICES statistical rectangles (30nm x 30nm; 0.5°lat x 1°lon); i.e. we assume that a 95% loss of area in a statistical rectangle to a climate change hotspot equates to a 95% loss in catch for that rectangle. We make a similar assumption for aquaculture, e.g. that a 10% loss of area currently used for aquaculture equates to a 10% decrease in production. This simplification is a necessary step to enable the translation of proposed scenario interventions without adding too much complexity to analysis that would prevent the application of this approach to data poorer areas across the UK EEZ. As standard, the input-output table captures the value of all landings at ports in Wales, regardless of where the fish are caught. Therefore, the table is adjusted to account for the fact that the scenarios only cover fish species caught within the Wales planning area. Logbook data from MMO suggests that ~70% of Welsh landings by value are demersal and benthic species caught within Welsh waters, and ~5% of landings are pelagic species caught within Welsh waters. Output values for the relevant fishing fleets are therefore scaled in our analyses such that we do not account for catches from outside of the Welsh planning area landed within Welsh ports. The methodology employed is described in detail in Roca Florido et al. (2025).

For each economic scenario, we used input-output modelling to estimate the impacts on labour compensation, gross value added (GVA), greenhouse gas (GHG) emissions, and employment across all sectors of the Welsh blue economy. These estimates capture both the direct and indirect effects resulting from simulated changes in the area of activity (i.e. resource use) of the fisheries, aquaculture, and/or marine conservation sectors, based on detailed marine sectoral mapping presented in Roca Florido et al. (2025). Specifically, for each sector, we estimate labour compensation as the total cost of employment to an employer, including wages, overtime, pension contributions, employers national insurance contributions and other costs associated with employment. We also estimate the Gross Value Added (GVA), that is, labour compensation plus gross operating surplus plus taxes less subsides. Furthermore, we estimate greenhouse gas emissions of carbon dioxide, methane, nitrous oxide, hydro-fluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride in carbon equivalent resulting linearly from changes in activity of each sector, based on those direct and indirect effects. We also estimated, per sector, the number of persons engaged in the sector as the number of people employed, whether full or part time.

D.3. Business-as-Usual scenario

This scenario estimated the effects of climate change within Welsh waters if no additional climate-smart spatial management measures are implemented or encouraged via marine planning. Therefore, ***no spatial interventions are simulated*** as part of this scenario, and as such, it represents the status-quo.

D3.1 Ecological outcomes under Business as Usual

D.3.1a Spatial analysis of ecological outcomes of climate change for species and habitats of conservation value

Five different analyses were undertaken in order to establish the effect of climate change on marine conservation objectives in Welsh waters under RCP4.5, as described in Chapter 3.1 of Queirós et al. 2024. Analyses focussed on those modelled variables that describe benthic and pelagic habitats (Queirós et al. 2024; Supplementary Information Table S3), habitats and prey of value to benthic and pelagic megafauna (Queirós et al. 2024; Supplementary Information Table S3), and climate services (e.g. the carbon sequestration potential of benthic habitats). A full list of pelagic and benthic megafauna species of conservation importance can be found in Supplementary Information Table S6 in Queirós et al. (2024). The variables selected in the pelagic and benthic megafauna analyses therefore reflected environmental drivers of these species distributions and key prey species on which they are dependant. Within the Wales planning area, climate change hotspots (hereafter, "hotspots") identified in those analyses are extensive, even under RCP4.5 (Table D.3.1). Hotspots for pelagic habitats, pelagic megafauna and benthic habitats cover a significant part of the planning area. Hotspots for benthic megafauna are also present but are predominantly located in St George's Channel and Cardigan Bay (Figure D.3.1, below). It is therefore possible that any habitat features and their associated species communities within designated conservation areas that overlap with hotspots may function differently in the future, as climate change unfolds across the region.

Some climate change refugia were also identified (Figure D.3.2). When we considered seabed habitat conditions potentially promoting carbon sequestration (Queirós et al. 2024; Supplementary Information Table S3), we found that refugia for climate services (Benyon et al., 2020; Flavell et al., 2020) cover the majority of the planning area. It should be noted however, that observational data available for the validation of the numerical modelling data used for the analyses of carbon sequestration potential of marine sediments is sparse, and that we therefore have low confidence in the climate services analysis results (Annex 1, Queirós et al., 2024).

Table D.3.1: Summary of the expected climate change effects on Welsh waters in the Business as Usual Scenario, and their potential ecological and economic effects.

Climate change impact	Potential ecological effects	Expected economic effects
Conservation: • Widespread climate change hotspots for benthic habitats, pelagic	**Conservation:** • Designated habitat and species features and their associated	Relative to economic effects of fisheries and aquaculture in Welsh Marine Plan Area:

habitats and pelagic megafauna • Climate change refugia for benthic megafauna cover the northern and southern parts of the planning area • Widespread climate change refugia for climate services	communities inside MPAs may not continue to function in the same way in the future • Climate services refugia may be useful for climate change mitigation in areas where they overlap seabed with high sedimentary organic carbon levels	• ~75% reduction in Labour compensation and Gross Value Added • ~70% reduction in employment • ~80% reduction in GHG emissions
Fisheries: • Widespread climate change hotspots for demersal and benthic fisheries • Widespread climate change refugia for pelagic fisheries	**Fisheries:** • Abundances of traditional key demersal species likely to decline in demersal fisheries hotspots • Abundances of pelagic species likely to remain resilient in pelagic fisheries refugia	
Aquaculture: • Widespread climate change hotspots for seafloor and water column aquaculture • Climate change refuge for seafloor aquaculture north of Anglesey	**Aquaculture:** • Potential for sectoral expansion into refugia for seafloor aquaculture	

Focussing on biodiversity conservation, two benthic habitats refugia are identified to the north of Anglesey (Figure D.3.2). In these areas, the benthic ecosystem is expected to remain functional comparable to the present day under the RCP4.5 emissions trajectory. These benthic habitat refugia occur across the OSPAR threatened and declining habitat sea pens and burrowing megafauna (assessed as being highly disturbed by bottom contacting fishing gears (Annex 2, Queirós et al., 2024)), the broadscale habitat type “offshore circalittoral sand” (assessed as being moderately disturbed by bottom contacting fishing gears (Annex 2, Queirós et al., 2024)), and the broad scale habitat “offshore circalittoral coarse sediment” (Annex 2, Figure A.1). However, it should be noted that none of the habitats within the identified benthic habitats refugia occur within MPAs currently designated for benthic habitats. Refugia for benthic megafauna were also identified in waters around Anglesey, in Cardigan Bay and around the SW coast and the Bristol Channel (Figure D.3.2). This suggests that habitat and prey conditions supporting benthic megafauna populations in Welsh waters may be climate resilient under the RCP4.5 emissions trajectory.

Finally, the identified refugia also appear to be largely unaffected by man-made stressors such as artificial light at night (ALAN), a pervasive pressure which has been shown to interfere with a number of life history processes in marine organisms (Marangoni et al., 2022 and references therein). Looking at Welsh MPAs more broadly, while there is some evidence of ALAN pollution in the (data from Smyth et al., 2024, Figure D.3.3)(data from Smyth et al., 2024, Figure D.3.3), which may disorient seabirds (particularly fledglings) as they move between the colony and offshore foraging grounds, possibly leading to strandings or collision(Gjerdrum et al., 2021; Ronconi et al., 2015)(Gjerdrum et al., 2021; Ronconi et al., 2015), the majority of the current MPA network does not overlap with incidences of ALAN pollution, suggesting that features of conservation interest within the network are not exposed to biologically relevant levels of artificial light.

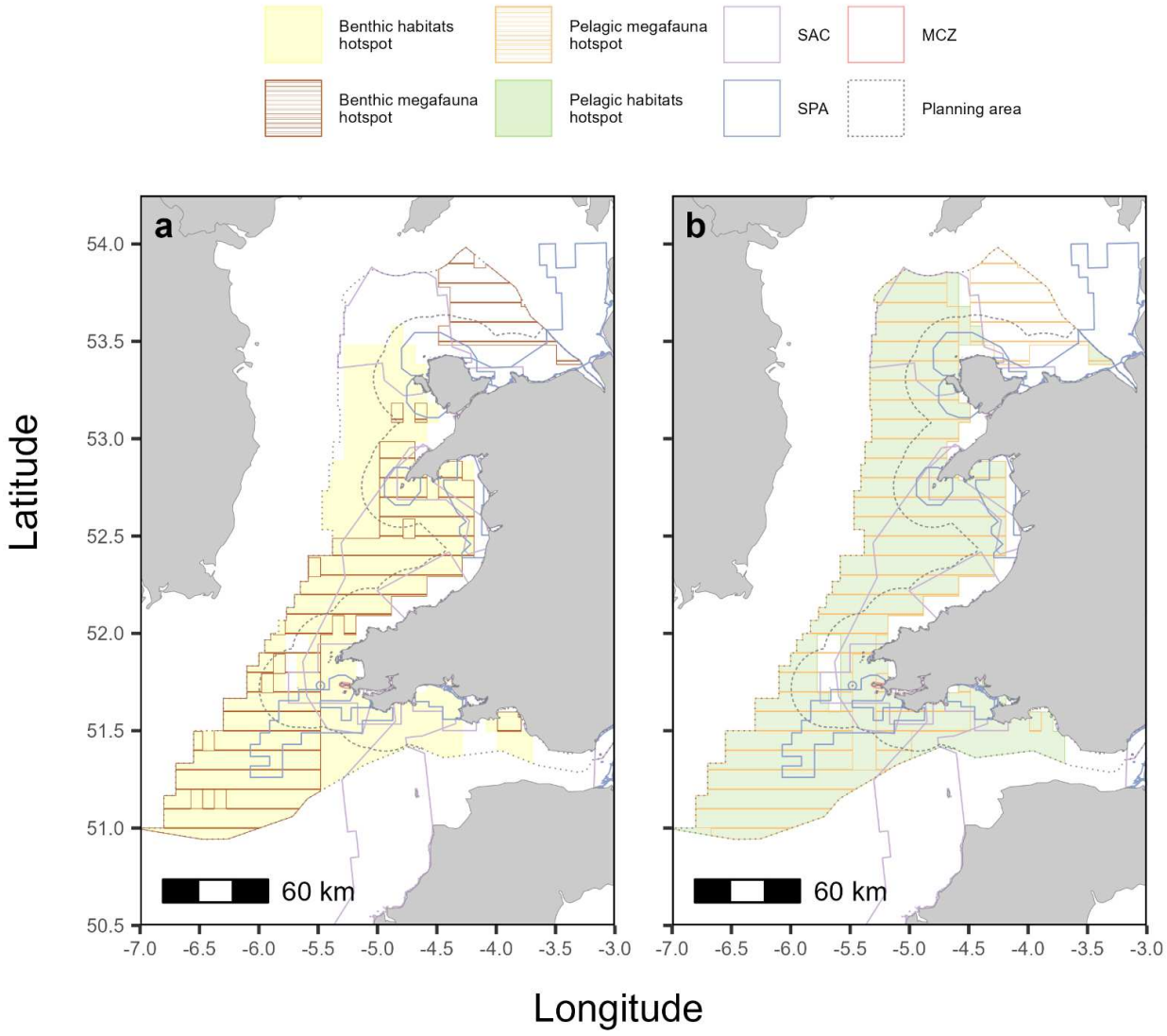

Figure D.3.1: Locations of conservation hotspots in the Wales marine planning area under the RCP4.5 emissions scenario. Benthic habitats and benthic megafauna hotspots (a), pelagic habitats and pelagic megafauna hotspots (b). Those conservation areas which fall within climate change hotspots may not continue to function in the same way in the future, as climate change unfolds across the region.

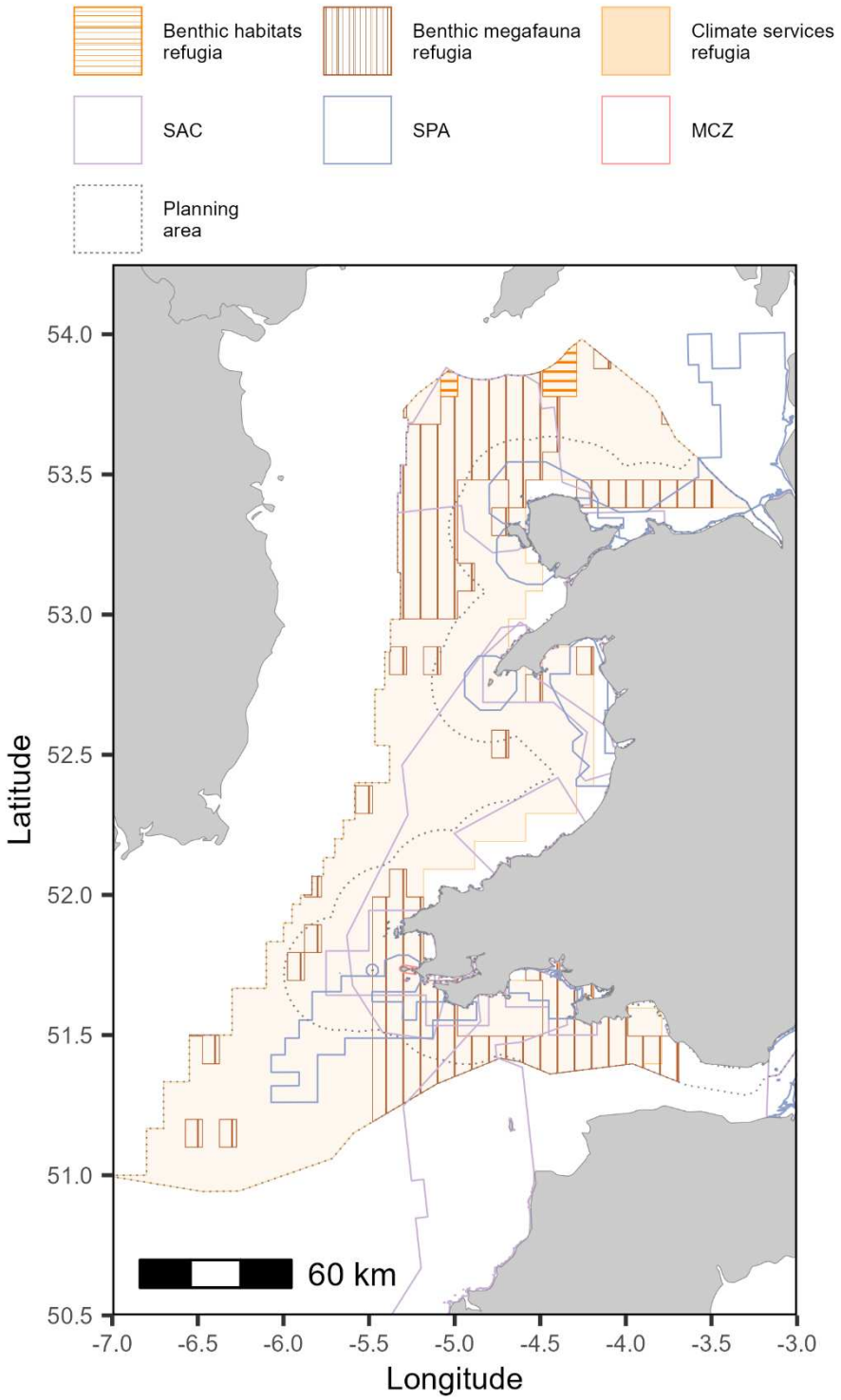

Figure D.3.2: Locations of conservation refugia in the Wales marine planning area under the RCP4.5 emissions scenario (benthic habitats, benthic megafauna and climate services refugia). Conservation areas which overlap with refugia will continue to be effective and deliver services into the future under the RCP4.5 emissions trajectory.

D.3.1b Spatial analysis of ecological outcomes of climate change for species and habitats of value to fisheries and aquaculture

Four analyses were undertaken to establish the effects of climate change on demersal (finfish and shellfish) and pelagic capture fisheries and seabed and water column aquaculture production (collectively termed hereafter as "food provision", Table D.3.1). For capture fisheries, analyses focussed on distribution modelling of species representing the top landings by value landed by international and UK registered vessels in the UK only (EWS report Supplementary Information Table S4). For aquaculture, we considered species distribution modelling for key UK aquaculture species (sugar kelp (*Saccharina latissimi*), blue mussel (*Mytilus edulis*) and salmon (*Salmo salar*)), and a range of modelled environmental data to represent key drivers of species distributions.

Identified food provision climate change hotspots cover a large part of the planning area; water column aquaculture climate change hotspots encompass the whole of the planning area, and demersal fisheries and seafloor aquaculture climate change hotspots cover a significant part of Welsh waters (Figure D.3.3). Therefore, demersal capture fisheries may see some losses in the future as abundances of shellfish species which comprise a minority of Welsh fisheries landings decrease, such as brown shrimp (*Crangon crangon*) and edible crab (*Cancer pagurus*). However, it is worth noting, that the analysis did not include modelling data for other key species which comprise the majority of Welsh landings such as whelk (*Buccinum undatum*), lobster (*Homarus gammarus*) or king scallop (*Pecten maximus*), as it was not available to us at the time of analysis. Demersal finfish species such as Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and plaice (*Pleuronectes platessa*) are also projected to decline in Welsh waters, although abundances of hake (*Merluccius merluccius*) are projected to increase in the region, which may provide an opportunity for catch diversification.

Similarly, conditions for the production of important seafloor aquaculture species such as mussel (*Mytilus edulis*) are projected to be less favourable in the future across much of the Wales planning area, apart from north Wales. Two climate change refugia for seafloor aquaculture in offshore waters north of Anglesey were identified, although we recognise that development of these sites by the industry may be challenging due their exposed location, distance from shore and water depth. The majority of the planning area is a refuge for pelagic fisheries, suggesting that abundances of species such as horse mackerel (*Trachurus trachurus*) may remain comparable to the present day into the future (Figure D.3.4), although we note that at present, Wales does not have a pelagic fishing fleet (NRW, personal communication, Feb 2025).

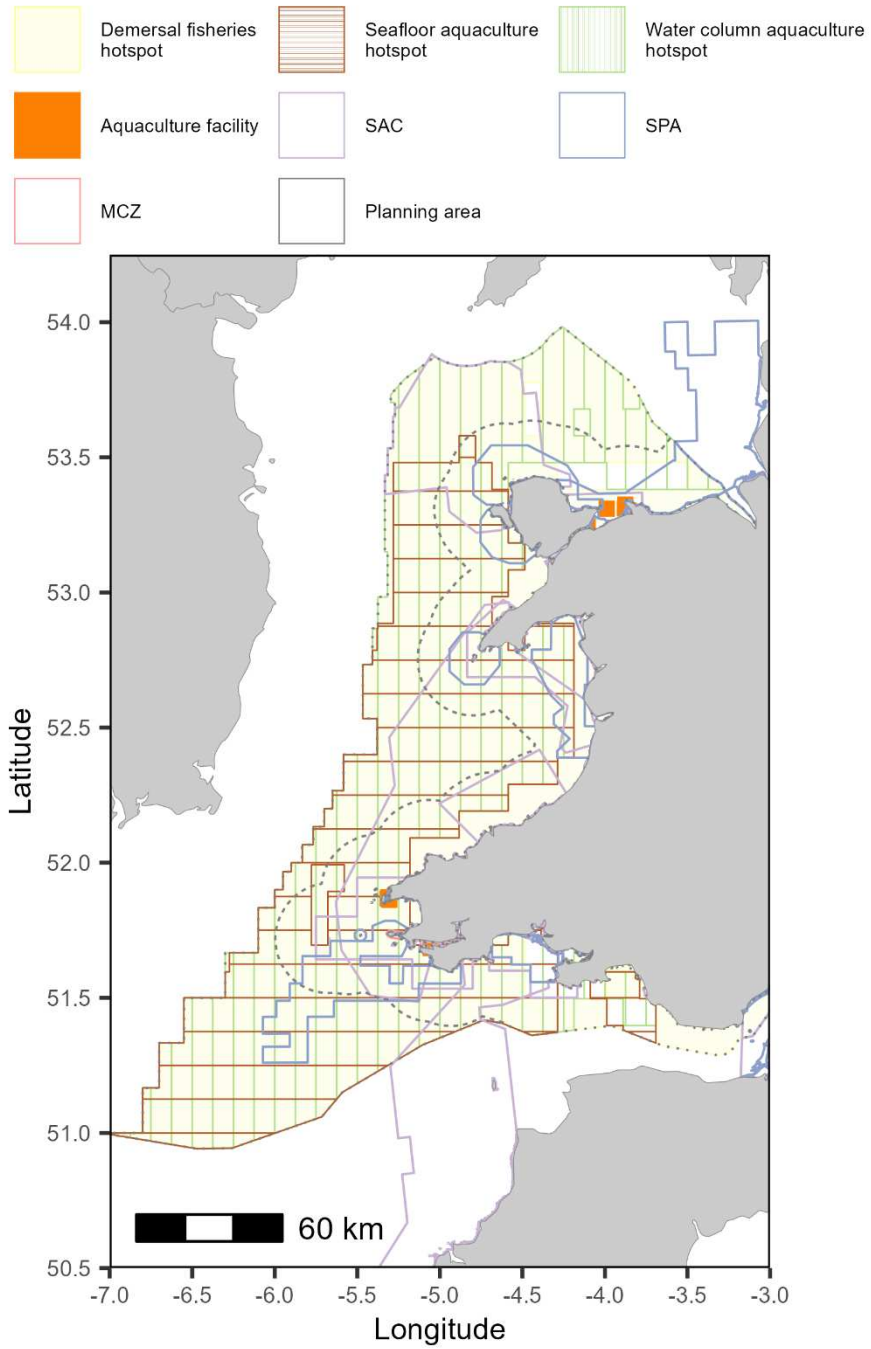

Figure D.3.3: Locations of food provision (fisheries and aquaculture) hotspots in the Wales marine planning area under the RCP 4.5 emissions scenario. Demersal (finfish and shellfish) fisheries may see losses in hotspot areas in the future as key commercial species abundances decline, while environmental conditions may challenge the expansion of seafloor and water column aquaculture due to widespread hotspots for those sectors.

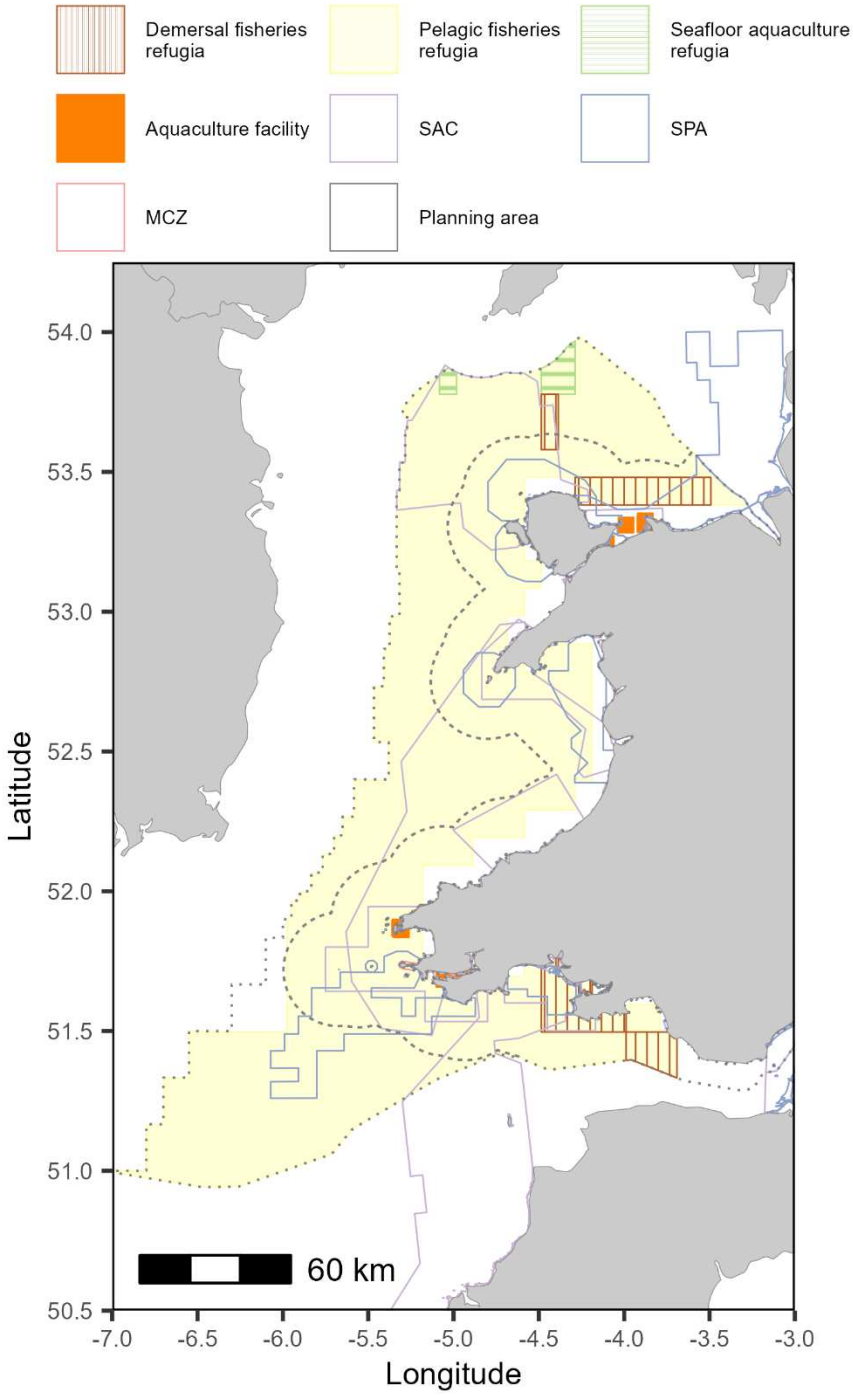

Figure D.3.4: Locations of food provision (fisheries and aquaculture) refugia in the Wales marine planning area under the RCP4.5 emissions scenario. Abundances of pelagic fish species in the region may be climate resilient in the future, as evidenced by a large refuge covering the majority of the planning area, although we note that there is currently no pelagic fleet in Wales. There are also refugia for seafloor aquaculture to the north of Anglesey.

D3.2 Economic outcomes for the adjacent blue economy of the Welsh region

The Business as Usual Scenario represents a significant loss to the marine economy in Wales. We estimate that the hotspot areas represent approximately a loss of around 95% of area available to be fished for the demersal fleets within the Welsh marine plan area. In this and all other scenarios

we assume that catch is equally distributed across the plan area accessible to a given fleet segment, at the resolution of ICES statistical rectangles (30nm x 30nm; 0.5°lat x 1°lon); i.e. we assume that a 95% loss of area in a statistical rectangle to a climate change hotspot equates to a 95% loss in catch for that rectangle. Together, losses to the fishing fleet translate to reductions of around 75% in labour compensation and gross value added, around a 70% reduction in number of people employed and approximately 80% reduction in carbon emissions (Figure D.3.5) relative to those currently associated with fishing and aquaculture in the Welsh Marine Plan Areas before climate effects. The biggest reductions across all impact variables tend to be in the fishing fleet segments and aquaculture (direct effects) themselves, though other sectors also face substantial losses, notably wholesale and retail trade and repair and maintenance of machinery (indirect effects).

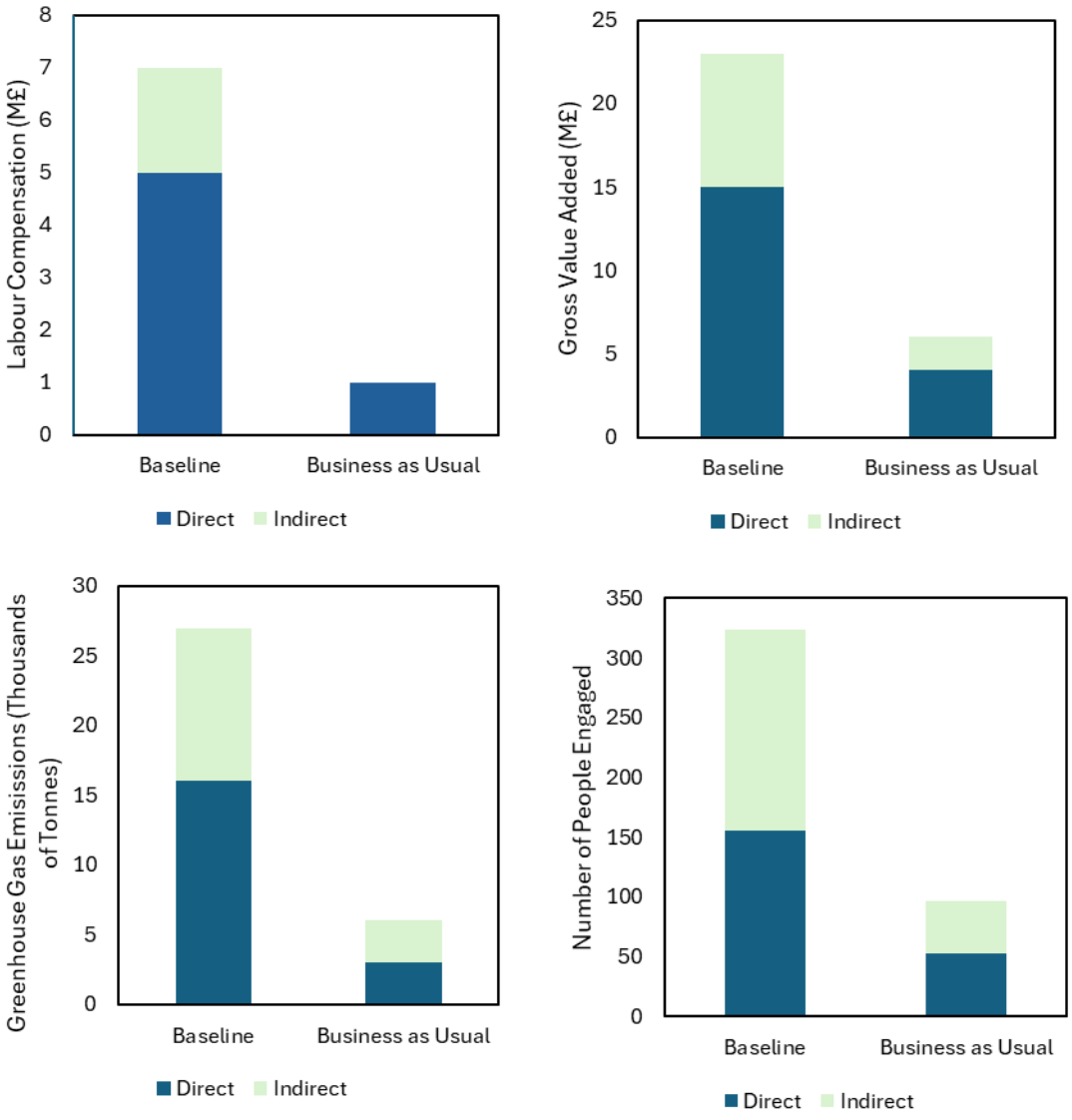

Figure D.3.5: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Business as Usual Scenario.

D.4.The Conservation Scenario

D.4.1 Spatial interventions maximising ecological outcomes under the Conservation scenario

In this *hypothetical scenario*, we simulate spatial interventions that:

1. aim to avoid, minimise or mitigate the impacts of activities which could negatively affect the climate change resilience or adaptation potential of habitats and species of conservation interest in Welsh waters. Simulated interventions are located in climate change refugia for benthic habitats or megafauna.
2. aim to avoid, minimise or mitigate the impacts of activities which could negatively affect the future provision of climate services (e.g. carbon sequestration) providing possible climate change mitigation. Simulated interventions are located in climate change refugia for climate services.

The Conservation Scenario spatial interventions C1, C2 and C3 described below have the purpose of avoiding, minimising or mitigating the impacts of activities which could negatively affect benthic megafauna species, benthic habitats of conservation interest and the future provision of climate services (respectively) in Welsh waters (Table D.4.1). In this hypothetical planning scenario, we simulate that these aims could be supported by changes to fisheries management legislation by Welsh Government to possibly reduce access to identified priority areas for conservation to mobile demersal gears where it is still permitted at present, and additional legislation that might allow 1) current MPAs to be managed more flexibly – e.g. with a whole site approach to management, rather than for designated features specifically and 2) for a new MPA designation to allow sites to be designated for the protection of organic carbon stores.

Intervention C1: Avoid, minimise or mitigate activities which could be incompatible with the conservation of priority areas in identified benthic megafauna refugia in Carmarthen Bay, Llŷn Peninsula and Sarnau and North Anglesey Marine SACs. We identified several priority areas for conservation which reflect the locations of long-term (2026-2069) climate change refugia for benthic megafauna under RCP4.5 (Figure D.4.1, Table D.4.1). The benthic megafauna found at the locations include a number of elasmobranch species (Annex 2, Figure A.3), considered as species of principal importance for the purpose of maintaining and enhancing biodiversity in Wales ("Environment (Wales) Act," 2016). We note however, that at present, it is not possible to protect these species in their own right within any Welsh SACs. Changes to legislation maybe be required to allow the Welsh SACs identified to be managed at the whole site level, rather than for their specifically designated features, or for new legislation to be introduced that allows MCZs to be designated for elasmobranchs identified in Section 7 of the Environment (Wales) Act, 2016 .

Intervention C2: Avoid, minimise or mitigate activities which could be incompatible with the conservation of a priority area in identified benthic habitats refugia in the North Anglesey Marine SAC. The area at the northern edge of the Wales planning area has been identified as a priority area for conservation for benthic habitats, due to the presence of a climate change refuge (Figure D.4.1, Table D.4.1). This area contains the OSPAR threatened and declining habitat (sea pens and burrowing megafauna) and the broad scale habitat offshore circalittoral sand. There is a second climate change refuge for benthic habitats in the Welsh offshore area, just outside the eastern boundary of the North Anglesey Marine SAC, which contains the habitat type circalittoral coarse sediment (Annex 2, Figure A.1). This

habitat is not on the MCZ FOCI list, therefore, we do not identify it here specifically as a priority area. It is not possible to protect these habitats in their own right within the North Anglesey Marine SAC as it is designated for the Annex II species harbour porpoise (*Phocoena phocoena*) only. A new MCZ for the habitats or changes to legislation maybe be required to allow the SAC identified to be managed at the whole site level, rather than for their specifically designated features.

Intervention C3: Avoid, minimise or mitigate activities which could be incompatible with the conservation of a priority area for climate services identified within Carmarthen Bay SAC. This area has been identified as a priority area for climate services where carbon sequestration in the fully marine part of the SAC (e.g. outside the estuaries) is estimated at between 100-150 tonnes yr^{-1}, and it falls within a refuge for climate services (Figure D.4.1, Table D.4.1). Please note that we exclude the estuary from any intervention simulated here as our modelling data, on which the identification of refugia was based, does not include estuarine or intertidal areas.

Table D.4.1: Summary of spatial interventions C1 - C3 proposed in the planning Conservation Scenario, and the potential ecological and economic effects of those interventions. Each intervention represents a possible mechanism by which **the impacts of activities which could negatively affect habitats and species of conservation interest in Welsh waters could be avoided, minimised or mitigated**. Full descriptions of each intervention, and the reasoning behind them, can be found in the main text.

Spatial intervention	Potential ecological effects	Expected economic effects
C1: Avoid, minimise or mitigate activities which could be incompatible with the priority area or conservation in identified benthic megafauna refugia in Carmarthen Bay, Llŷn Peninsula and Sarnau and North Anglesey Marine SACs	C1: Avoiding, minimising or mitigating the impacts of demersal trawls on several elasmobranch species of conservation interest could maximise the effectiveness of the identified climate change refuge in promoting the climate change resilience of these species.	Relative to economic effects of Business as Usual: • ~1% reduction in Labour compensation and Gross Value Added • ~1% reduction in employment • ~1% reduction in GHG emissions
C2: Avoid, minimise or mitigate activities which could be incompatible with the conservation of a priority area for benthic habitats refugia in the North Anglesey Marine SAC.	C2: Avoiding, minimising or mitigating negative impacts on habitat features could maximise the effectiveness of the identified priority area in promoting the climate change resilience of benthic habitats.	
C3: Avoid, minimise or mitigate activities which could be incompatible with the conservation of a priority area for climate services identified within Carmarthen Bay SAC.	C3: Avoiding, minimising or mitigating negative impacts on the seabed in areas where sediment has a high carbon sequestration potential may limit direct carbon release and degradation (avoided emissions) from disturbed sediment.	

D.4.2. Potential benefits of proposed spatial management measures

All of the simulated spatial management interventions listed above could result in the potential exclusion of vessels fishing with mobile demersal gears from those priority areas in which fishing occurs at present (we recognise that restrictions on certain gear types e.g. scallop dredges are already enforced in a number of Welsh MPAs inside 12nm). The proposed priority areas harbour refugia for benthic megafauna, and many shark, skate and ray populations exploiting these areas are considered vulnerable to fishing pressure due to their slow growth, late maturity and low fecundity (Rindorf et al., 2020). Minimising targeted fishing or bycatch of these species in fisheries could therefore be desirable in a scenario that maximises outcomes for priority areas in refugia. We recognise that using these priority areas to benefit elasmobranch species of conservation interest would require a change in the way that MPAs in Wales are designated and managed, perhaps applying a "whole-site" approach to management (e.g. managing a site by considering the integrity of a site as a whole, not just where designated features are present) in addition to the current "feature-based" approach. Evidence suggests that whole-site approaches to management increase functional redundancy in both sessile and mobile taxa when compared to feature-based approaches, perhaps indicating higher community resilience (Davies et al., 2022). Consequently, they have been advocated as a more effective management method for conservation targets (Rees et al., 2020; Solandt et al., 2020). In the case of the priority area identified for climate services in Carmarthen Bay, it is possible that intervention C3 may limit direct carbon release and degradation (avoided emissions) from disturbed sediment. Although we acknowledge that 1) it is unproven that protecting seafloor sediments from disturbance improves carbon storage or sequestration potential, and 2) climate change driven increases in storminess may cause more natural sediment overturning; the protection of marine carbon sinks may represent a sensible precautionary policy (Epstein et al., 2022; Epstein & Roberts, 2022; Jankowska et al., 2022), particularly given the current interest in the carbon storage and climate change mitigation potential of UK MPAs (Burrows et al., 2024). However, this intervention would require additional legislation that allowed sites to be designated for the protection of organic carbon stores.

The MSPACE project was designed to inform the spatial management of marine space, and as such we focus on spatial measures which may contribute to climate adaptation and mitigation in Welsh waters. However, we recognise that there may be technical measures that can support interventions C1-C3, by reducing the impact of mobile bottom contacting gears on benthic habitats and sediments. Seabed impact changes resulting from measures such as gear switches (from mobile to static gears) and gear modifications (e.g. changes in the design of otter boards or trawl sweep lengths, lighter gears) have been, and continue to be, investigated and trialled globally (Arjona et al., 2019; Bromhall, 2022; Linnane et al., 2007). The level of impact reduction is likely to be dependent on habitat type in fishing grounds, gear type and configuration, and vessel size, power and towing speed, so consultation and collaboration with fishers and other stakeholders will be critical in order to find the best approach(es) for Wales. Beyond any possible benefits to seabed habitats from the implementation of such measures (Szostek et al., 2022), there is also some indication that gear modifications can reduce fuel consumption and greenhouse gas emissions, and improve gear selectivity (Arjona et al., 2019; van Marlen et al., 2014), which may encourage

uptake by the industry. However, the economic cost to fishers to modify or switch gears is likely to be non-trivial, and further incentives will likely be needed.

D.4.3. Tourism, recreation and heritage

While there are a number of wrecks in the Welsh planning area, the identified priority areas overlap with only one of these (Annex 2, Figure A.3), a 19th Century merchant vessel in the Llŷn Peninsula and Sarnau SAC, which is designated as a historic wreck under the Protection of Wrecks Act 1973, and so already benefits from legal protection. Anchorages for yachting would be unaffected by the interventions simulated here for priority areas.

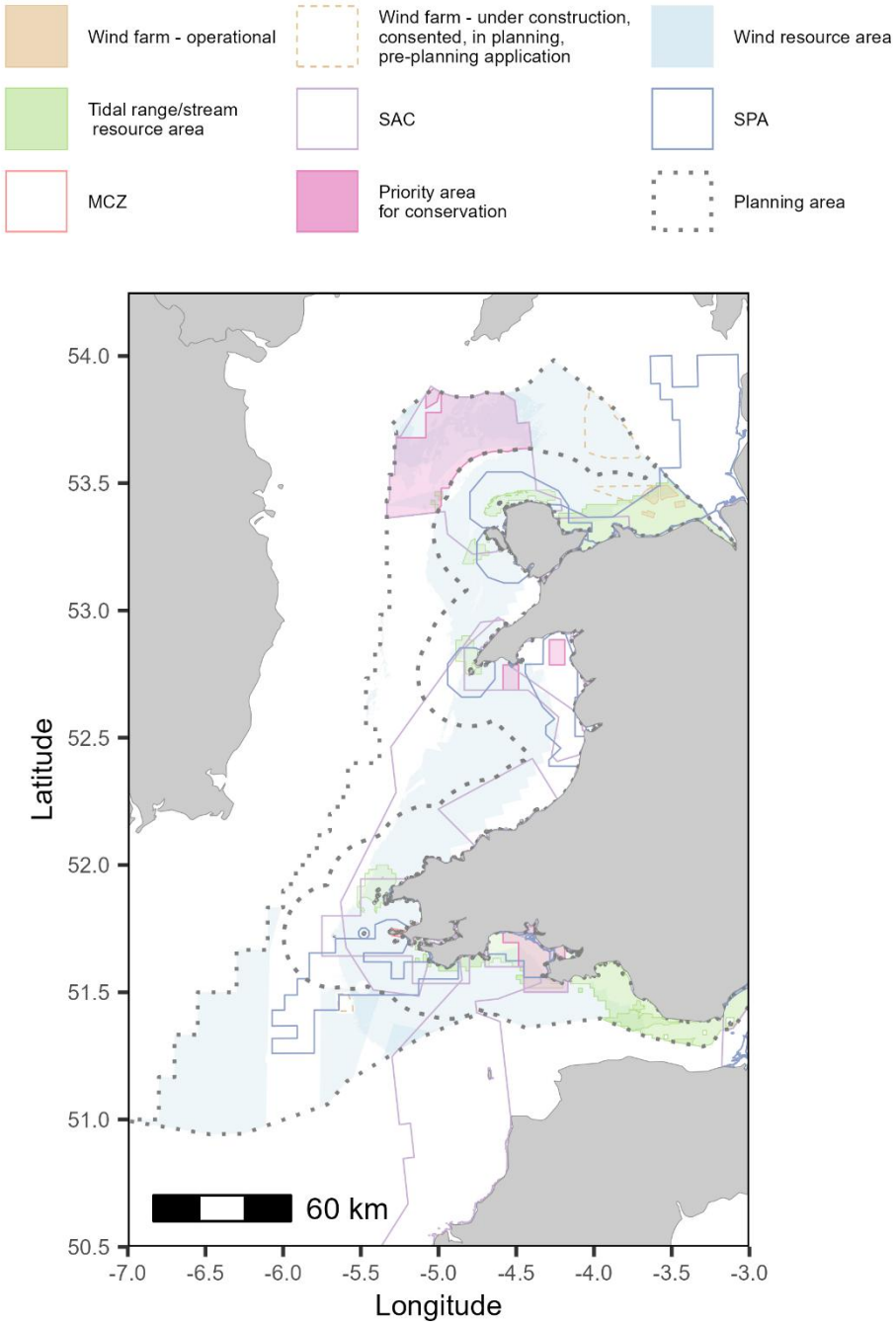

Figure D.4.1: Conservation scenario. Pink shaded areas are priority areas for conservation identified for benthic megafauna, climate services and benthic habitats .

D4.4 Economic outcomes for the adjacent blue economy of the Welsh region

In the Conservation Scenario we see further reductions in all impact variables relative to the Business as Usual Scenario (Figure D.4.2). There is an approximately 1% reduction in all impact variables relative to Business as Usual. Given uncertainties in the economic modelling, there is effectively no difference between the two scenarios. The small difference is because of the very large reductions due to climate change in BAU. These comprise around 95% of area available to the fishing fleets. In comparison, simulated additional closures for conservation reasons are marginal.

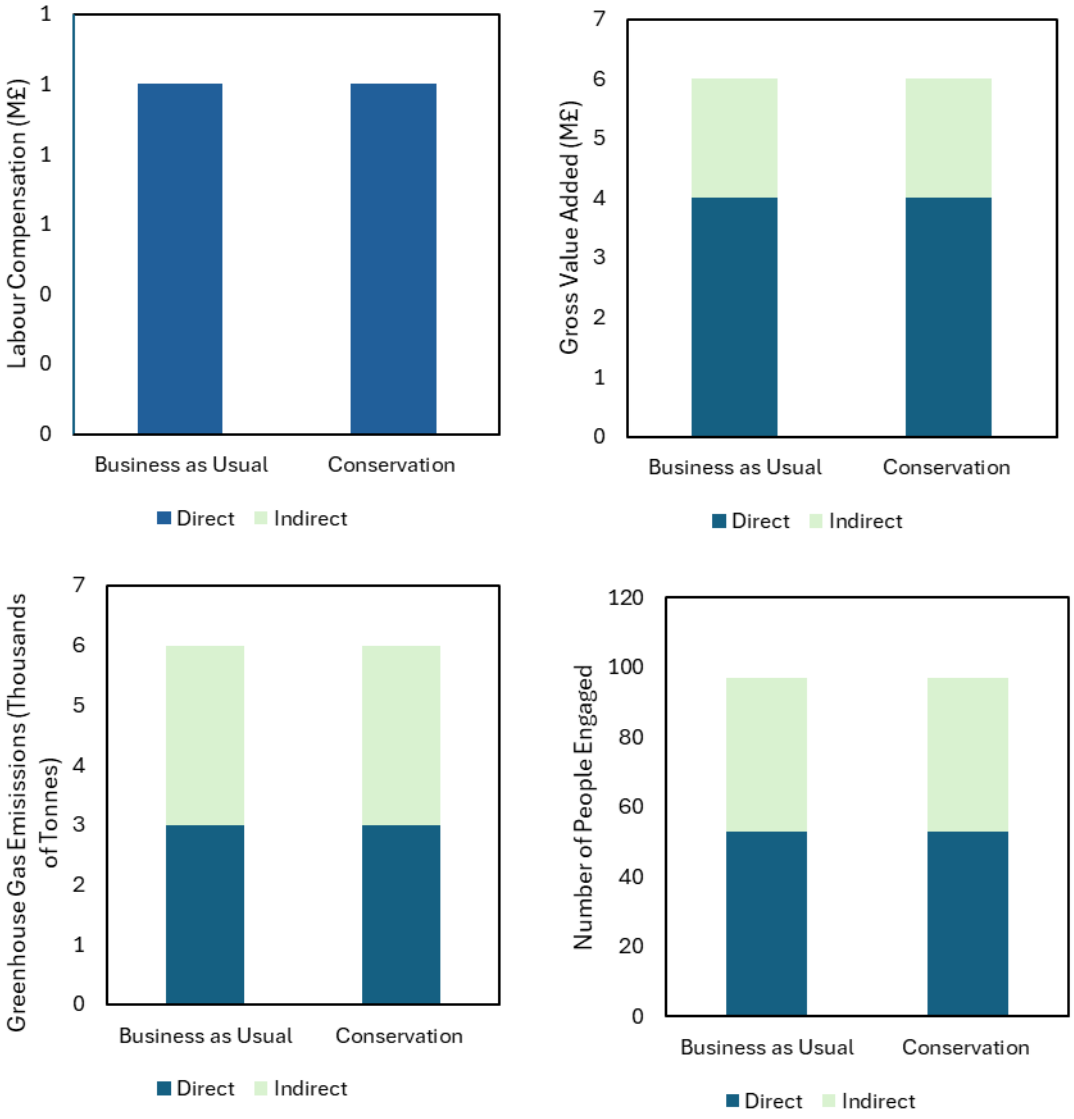

Figure D.4.2: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Conservation Scenario, as compared to the Business as Usual Scenario

D.5. The Food Provision Scenario

D5.1 Spatial interventions maximising outcomes under the food provision scenario

In this *hypothetical scenario*, we propose spatial interventions that:

1. aim to support and safeguard climate-resilient fisheries in Welsh waters. Simulated interventions are located in climate change refugia for demersal and pelagic fisheries.
2. aim to facilitate the development of climate-resilient aquaculture in Welsh waters. Simulated interventions are located in climate change refugia for seafloor aquaculture.

The spatial interventions FP1 and FP2 below have the purpose of supporting and safeguarding climate resilient capture fisheries and facilitating the development of climate resilient aquaculture in Welsh waters in the face of climate change impacts in the region (Table D.5.1). In this hypothetical planning scenario, we simulate that these aims would be further supported by Welsh planning and licensing authorities considering the locations of identified priority areas for fisheries and aquaculture when evaluating applications for development of marine space by other industries and sectors.

Intervention FP1: a) Avoid, minimise or mitigate proposals that are incompatible with access for demersal (finfish and shellfish) fisheries in those areas identified as demersal fisheries priority areas, located in refugia for the sector. b) Avoid, minimise or mitigate proposals that may be incompatible with access by the pelagic fleet to areas identified as pelagic fisheries priority areas, located in refugia for the sector. We identify priority areas for capture fisheries based on the locations of climate change refugia for the sector. Priority areas for demersal fisheries (which in the EWS analyses included both shellfish and finfish) are shown in Figure D.5.1. These areas include parts of the Bristol Channel, which overlap partially with areas that have provided high catches to the Welsh demersal fleet in the past (Wales Marine Planning Portal, accessed Oct 2024) and areas north and east of Anglesey. At the present time, shellfish such as crab, lobster, shrimp, scallop and whelk represent the majority of Welsh capture fisheries landings, and there are also targeted fisheries for plaice and sole (Uberoi et al., 2022). While modelling for European lobster (*Homarus gammarus*), king scallop (*Pecten maximus*) and common whelk (*Buccinum undatum*) was not available to us, our analysis suggests that abundances of species such as plaice (*Pleuronectes platessa*) and sole (*Solea solea*) will decline in all of Welsh waters. This perhaps indicates that the Welsh demersal fleet may have to diversify in order to remain sustainable. For example, hake (*Merluccius merluccius*) is projected to increase in abundance all around the Welsh coast, while pollock/saithe (*Pollachius virens*) is projected to increase to the south-west of the planning area; both species could represent opportunities for the sector in the future. We also recognise that shifting species distributions may result in new species entering Welsh waters, and these species could prove to be commercially valuable. While the modelling used for this analysis did not include any “new” species, so we cannot state what might be become available to the demersal fleet in the future, it is possible that there may be opportunities for the sector outside of the identified priority areas, even in the face of climate driven losses of currently exploited species as new species move north to warmer waters.

Based on analyses in the MSPACE Early Warning System, all of Welsh waters emerge as a climate change refuge for pelagic fisheries (Figure D.5.1). Abundances of species such as European sardine/pilchard (*Sardina pilchardus*) and Atlantic horse mackerel (*Trachurus trachurus*) are projected to remain stable even in the face of climate pressures. It is important to note that, at present, there is no Welsh pelagic fleet (NRW, personal communication, Feb. 2025); in the future however, it is possible that a pelagic fishery could be supported in Welsh waters.

Intervention FP2: Avoid, minimise or mitigate proposals for activities that could limit the development of seafloor aquaculture in priority areas for this sector. A refuge for seafloor aquaculture was identified in the offshore area to the north of Anglesey (Figure D.5.1) where it may be possible to support aquaculture in the region in the long-term, despite broader climate change pressures. Although the site identified is <50m deep, we recognise that whilst offshore *pelagic* aquaculture is commonplace in Europe and growing in the UK, developing *seabed* aquaculture facilities in deeper and more exposed areas may be more challenging, and will likely require technical advancement in the industry. There are also important navigation routes in this part of the planning area, and deployment of any surface infrastructure (e.g. for farming) may not be permitted if it interferes with these routes. It is therefore possible that the whole site (approximately 44km^2) would not be feasible for the development of seabed aquaculture. It is worth noting that under climate change, it is possible that Welsh waters may become suitable for the aquaculture production of warmer water species. The modelling data that we used for our analysis of aquaculture (Queirós et al., 2024; Supplementary Information Table S5) included species distribution modelling for key UK aquaculture species (sugar kelp (*Saccharina latissimi*), blue mussel (*Mytilus edulis*) and salmon (*Salmo salar*), in the analysis for water column aquaculture), and a range of modelled environmental data to represent key drivers of species distributions (in the analyses for both water column and seafloor aquaculture). We did not include any "new" species in our analysis as their value to the sector will depend on consumer attitudes, and so we could not say for certain which species may be targeted for culture. However, it is possible that warmer water species may present opportunities for the sector in the future under climate change.

Table D.5.1: Summary of spatial interventions proposed in the Food Provision Scenario, and the potential ecological and economic effects of those interventions. Each intervention represents a possible mechanism which **supports climate resilient fisheries and facilitates the development of climate resilient aquaculture in Welsh waters**. Full descriptions of each intervention, and the reasoning behind them, can be found in the main text.

Spatial intervention	Potential sectoral effects	Expected economic effects
FP1: a) Avoid, minimise or mitigate proposals for activities that may be incompatible with access of demersal fisheries in areas identified as demersal fisheries priority areas; **b) Avoid, minimise or mitigate proposals for activities that may be incompatible with**	FP1: Continued/priority access to identified priority areas for demersal and pelagic fisheries could contribute to the climate resilience of the Welsh fishing sectors and help to support the	FP1: 10x increase in pelagic fisheries, relative to economic effects of BAU: • ~138% increase in Labour compensation and Gross Value Added

access by the pelagic fleet to pelagic fisheries priority areas.	industry in the face of climate change	• ~122% increase in employment • ~181% increase in GHG emissions
FP2: Avoid, minimise or mitigate proposals for activities that could limit the development of seafloor aquaculture in the identified priority areas for this sector.	FP2: Development of the identified priority area for seafloor aquaculture represents a possible opportunity for sectoral expansion.	FP2: Use of seabed for aquaculture (use of 5% or 100% of potential area), relative to economic effects of BAU: • 1200-24000% increase in Labour compensation and Gross Value Added • 1200-25000% increase in employment • 1000-20000% increase in GHG emissions
	FP1 & FP2: Restricting the future development of offshore wind in the identified priority fisheries and aquaculture areas could act to ensure that access to climate change refugia for the sectors is maintained.	

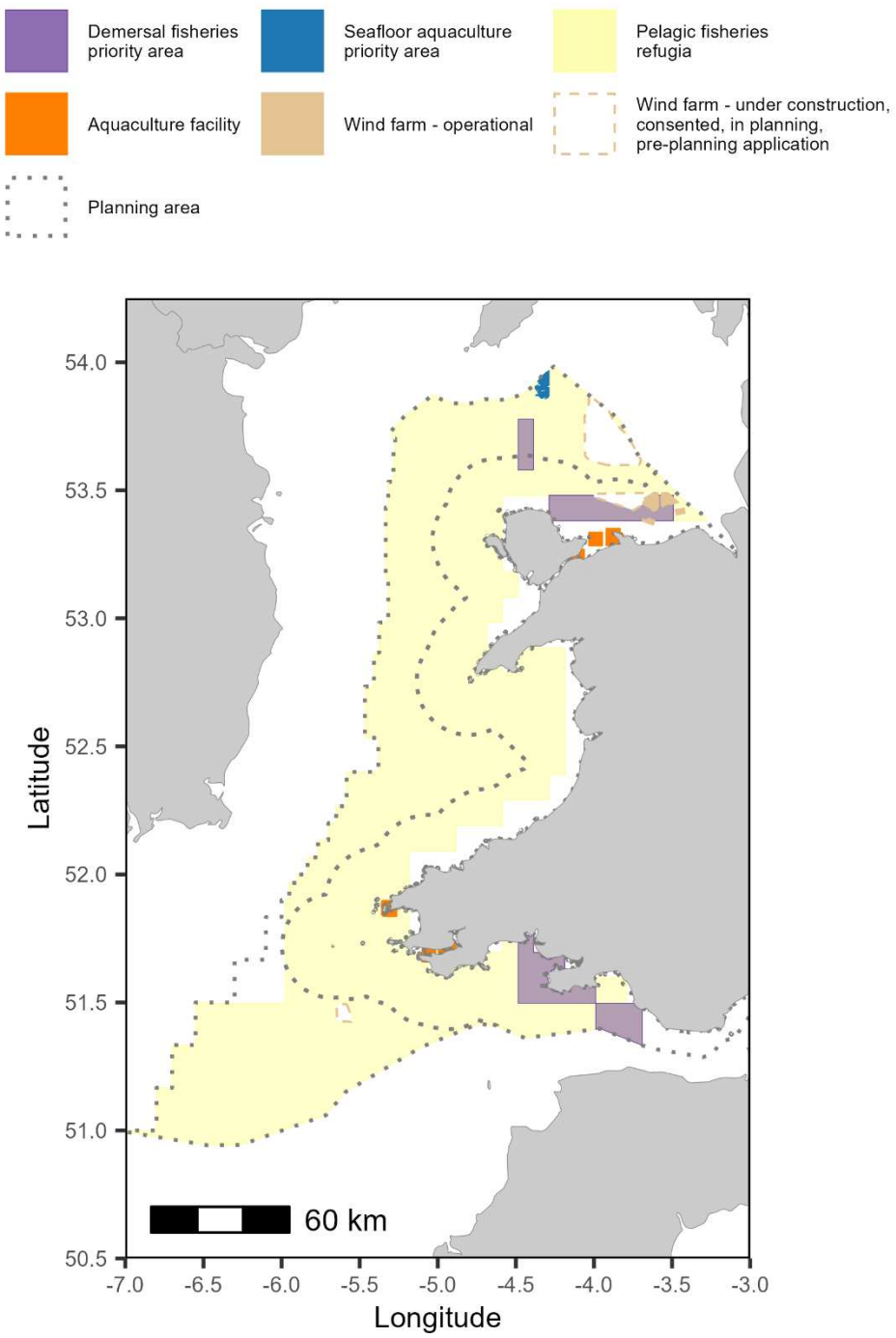

Figure D.5.1: Food provision scenario with the locations of identified priority areas for fisheries and aquaculture highlighted.

D5.2 Economic outcomes for the adjacent blue economy of the Welsh region

Relative to the Business as Usual Scenario, the Food Provision Scenario increases all our indicators (Figure D.5.2-4). We find that FP1 (expansion of the area available for pelagic fishing) has potential for incremental increases in all impact variables (all ~150% increase; Figure D.5.2). However, the largest potential appears to be from sectoral change toward seafloor aquaculture (Figure D.5.3-4).

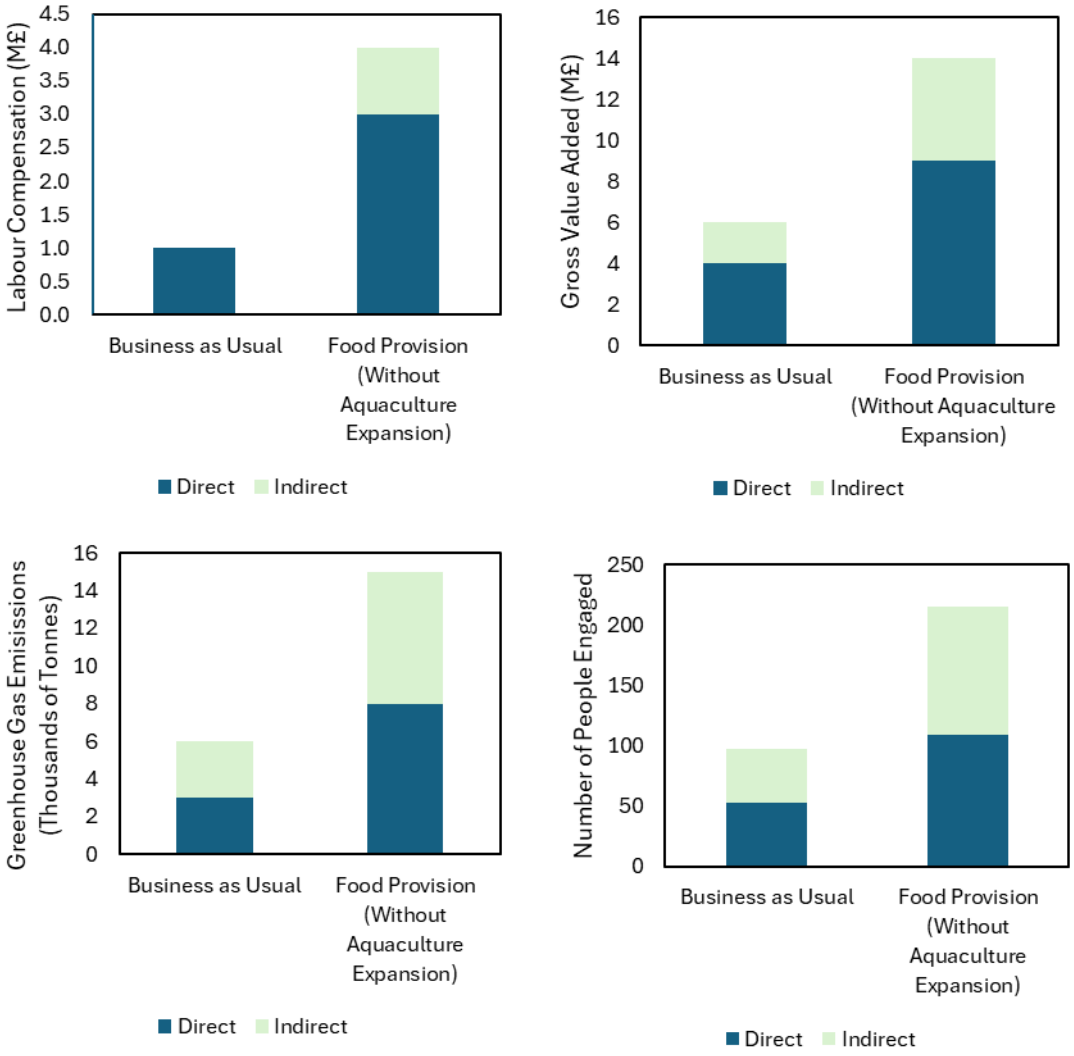

Figure D.5.2: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Food Provision Scenario (assuming only 5% of the identified potential area for seafloor aquaculture expansion is used) compared to the Business as Usual Scenario

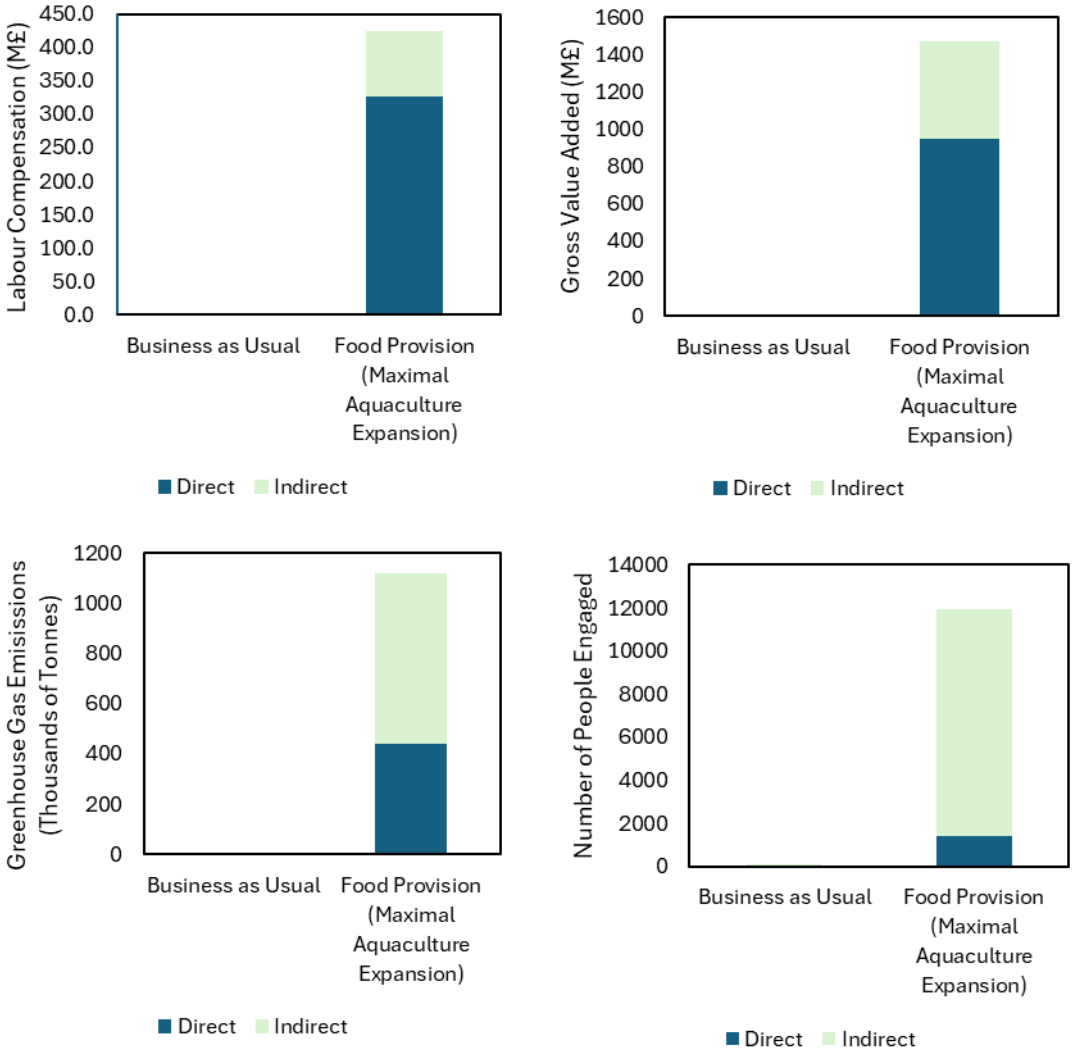

Figure D.5.3: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Food Provision Scenario with Aquaculture expansion, as compared to the Business as Usual Scenario

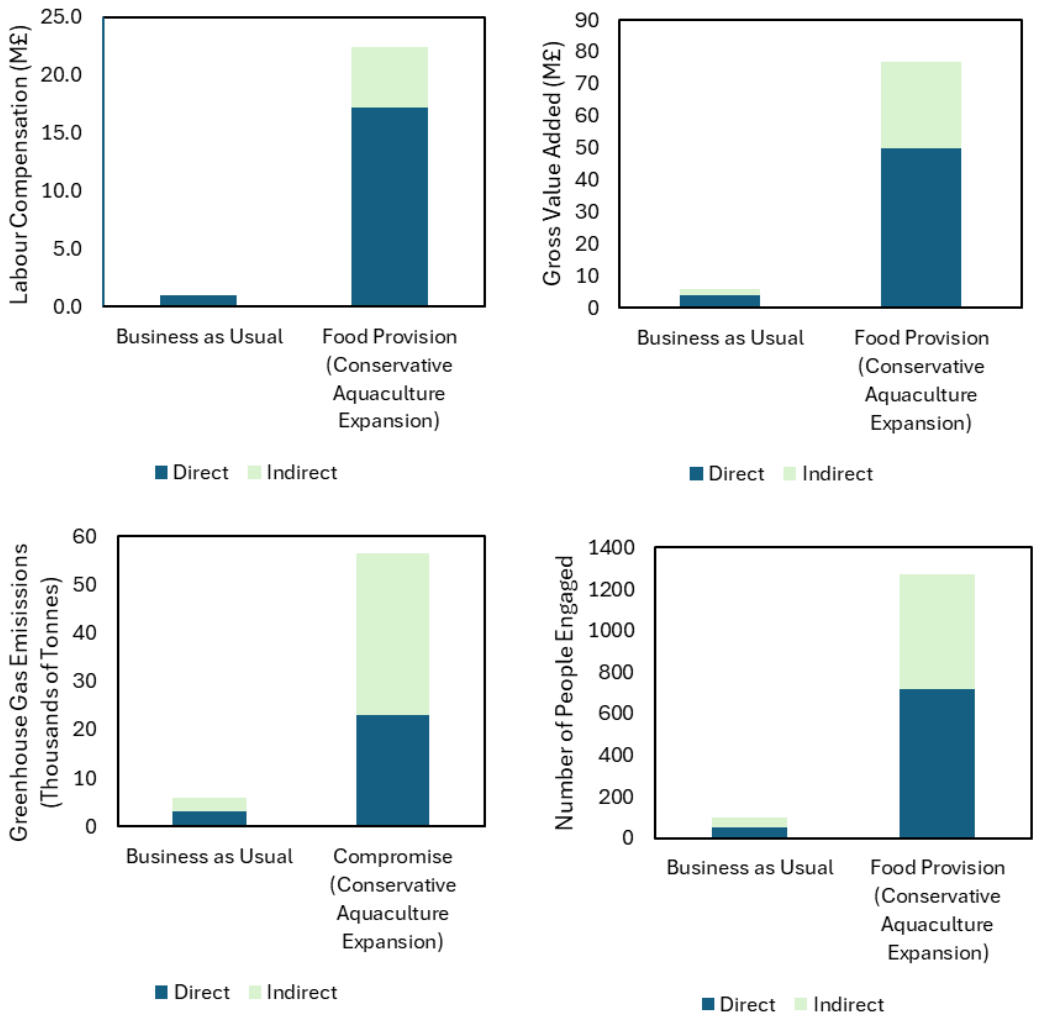

Figure D.5.4: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Food Provision Scenario (assuming only 5% of the identified potential area for seafloor aquaculture expansion is used) compared to the Business as Usual Scenario

The maximal simulated potential area for seafloor aquaculture development is more than 200 times greater than the currently used area. Accounting for direct and indirect effects we see increases in impact variables of between 20 and 25 thousand percent (Figure D.5.3). This level of expansion should be treated with extreme caution, because the economic model assumes a linear relationship between increase in area available for aquaculture and output from the sector and such a large expansion without nonlinear changes in the economic structure is implausible. For this reason, Figure D.5.4 presents a more cautious scenario, where only 5% of the simulated potential area for seafloor aquaculture development is actually used (This is equivalent to a 10x increase in current seafloor area used for Aquaculture). Here we see significant but smaller increases in impact variables: ~1200% for labour compensation, GVA and number of employees and ~1000% for Greenhouse Gases.

D.6. The Compromise Scenario

D6.1 Spatial interventions maximising outcomes under the compromise scenario

Measures considered in this *hypothetical scenario* have the following aims, given estimated climate change impacts and considering what other priorities stakeholders hold for the region (Reinhardt & Danahey Janin, 2025):

1. aim to encourage climate-resilient fisheries in Welsh waters given the effects of climate change. Simulated interventions are located in climate change refugia for demersal (finfish and shellfish) and pelagic species of commercial value in the UK
2. aim to encourage the development of climate-resilient aquaculture in Welsh waters given the impacts of climate change. Simulated interventions are located in climate change refugia for seafloor aquaculture
3. aim to avoid, minimise or mitigate the impacts of activities which could negatively affect the climate change resilience or adaptation potential of habitats and species of conservation interest in Welsh waters. Simulated interventions are located in climate change refugia for benthic habitats or benthic megafauna
4. aim to avoid, minimise or mitigate the impacts of activities which could negatively affect the future provision of climate services providing climate change mitigation (e.g. carbon sequestration). Simulated interventions are located in climate change refugia for climate services

This scenario is expected to balance the needs of capture fisheries and aquaculture production with the need to ensure that the Welsh marine environment is adequately protected in order to provide a healthy, resilient and adaptable marine ecosystem. It is expected that the Compromise Scenario may meet a broader set of objectives with regard to Welsh stakeholders than the other three scenarios.

The spatial interventions CM1 - CM3 below aim to avoid, minimise or mitigate the impacts of activities which could negatively affect benthic megafauna species and benthic habitats of conservation interest and the future provision of climate services in Welsh waters (Table D.6.1). In this hypothetical planning scenario, we assume this aim would be supported by additional fisheries legislation by Welsh Government, potentially reducing access to identified priority areas for conservation to mobile demersal gears in areas where it is permitted at present and additional legislation or policy changes that might allow 1) current MPAs to be managed more flexibly – e.g. with a whole site approach to management, rather than for designated features specifically and 2) sites to be designated for the protection of organic carbon stores.

The spatial interventions CM4 and CM5 have the purpose of encouraging climate-resilient fisheries and facilitating the development of climate-resilient aquaculture in Welsh waters despite climate change impacts (Table D.6.1). We simulate that these aims would be supported by the relevant (Welsh or UK Government) planning and licensing authorities and regulators considering the locations of identified priority areas for fisheries and aquaculture when evaluating applications for development of marine space by other industries and sectors. Finally, we simulate that offshore renewable energy development in priority areas for fisheries, aquaculture and conservation may be restricted, and that this aim would be supported by engagement of Welsh/UK planning and licensing authorities with industry and the Crown Estate to ensure that these areas are not leased in future bidding rounds.

Intervention CM1: Avoid, minimise or mitigate activities which would be incompatible with the conservation of priority areas for benthic megafauna identified in benthic megafauna refugia within the Carmarthen Bay and Llŷn Peninsula and Sarnau SACs. Under the Compromise Scenario, the identified climate change refugia for benthic megafauna in Carmarthen Bay and around the Llŷn Peninsula remain as priority areas for conservation (Figure D.6.1). The larger part of North Anglesey Marine SAC, which was included in the Conservation Scenario as a priority area, is not included in this Compromise Scenario, as the SAC is designated for the protection of harbour porpoise (*Phocoena phocoena*) only, rather than for any benthic features which may benefit from further conservation interventions. As noted in the Conservation Scenario (Section D.4) above, it is not possible to protect elasmobranchs in their own right within any Welsh SACs. New MCZs for elasmobranchs or changes to legislation maybe be required to allow the Welsh SACs identified to be managed at the whole site level, rather than for their specifically designated features.

Intervention CM2: Avoid, minimise or mitigate activities which would be incompatible with the conservation of a priority area for benthic habitats within the North Anglesey Marine SAC. The priority area identified in the Conservation Scenario, which overlaps with the "sea pens and burrowing megafauna" habitat and circalittoral sand within the northern tip of North Anglesey Marine SAC remains as such in this scenario (Figure D.6.1). As noted above, additional legislation which allows Welsh MPAs to be managed at the whole site level, rather than specifically for designated features (as is the case at present) may be required in order to fully maximise the use of identified priority areas for the conservation of benthic habitats in the area.

Intervention CM3: Avoid, minimise or mitigate activities which would be incompatible with the conservation of a priority area for climate services identified in Carmarthen Bay. This area has been identified as a priority area for climate services as carbon sequestration in the fully marine part of the SAC (e.g. outside the estuaries) is estimated at between 100-150 tonnes yr^{-1}, and it falls within a refuge for climate services. Please note that we exclude the estuary from any intervention simulated here as our modelling data, on which the identification of refugia was based, does not cover estuarine or intertidal areas.

Intervention CM4: a) Avoid, minimise or mitigate proposals that may be incompatible with access for demersal (finfish and shellfish) fisheries in those areas identified as priority areas for the demersal fishing sector. b) Avoid, minimise or mitigate proposals that may be incompatible with access by pelagic vessels to priority areas for the pelagic fishing sector. Two of the three priority areas for demersal fisheries identified in the Food Provision Scenario are used in this Compromise Scenario, reflecting the locations of climate change refugia identified for the sector (Figure D.6.1). These include an area in the Bristol Channel, which overlap partially with areas that have provided high catches to the Welsh demersal fleet (Wales Marine Planning Portal, accessed Oct 2024) and areas to the north and east of Anglesey. As noted in Section D.5 above, all of Welsh waters emerge as a climate change refuge for pelagic fisheries. Although we recognise that at present, Wales does not have a pelagic fleet (NRW, personal communication, Feb. 2025) it is possible that in the future, pelagic fishing could develop in Welsh waters.

Intervention CM5: Avoid, minimise or mitigate proposals for activities that would limit the development of seafloor aquaculture in the identified priority area for this sector. We simulate that the priority area for seafloor aquaculture identified in the Food Provision

Scenario, located in a climate change refuge for the sector, is used in this Compromise Scenario (Figure D.6.1). Although the priority area is in water of <50m, and we recognise that offshore *pelagic* aquaculture is commonplace in Europe and growing in the UK, developing *seabed* aquaculture facilities in exposed offshore areas may be more challenging.

Table D.6.1: Summary of spatial interventions proposed in the Compromise Scenario, and the potential ecological and economic effects of those interventions. Each intervention represents a possible mechanism which **supports climate-resilient fisheries, facilitates the development of climate-resilient aquaculture and seeks to avoid, minimise or mitigate the impacts of activities which could negatively affect habitats and species of conservation interest in Welsh waters**. Full descriptions of each intervention, and the reasoning behind them, can be found in the main text.

Spatial intervention	Expected ecological effects	Expected economic effects
CM1: Avoid, minimise or mitigate activities which would be incompatible with the conservation of priority areas for benthic megafauna identified in the waters of Carmarthen Bay and around the Llyn Peninsula.	CM1: Avoiding, minimising or mitigating the impacts of demersal trawls on several elasmobranch species of conservation interest could maximise the effectiveness of the identified conservation priority areas in promoting the climate change resilience of these species.	All measures apart from seafloor aquaculture expansion, relative to economic effects of BAU: • ~20% increase in Labour compensation and Gross Value Added • ~30% increase in employment • ~15% increase in GHG emissions All measures including seafloor aquaculture expansion (use of 5% or 100% of potential area), relative to economic effects of BAU: • ~1100-24000% increase in Labour compensation and Gross Value Added • ~1100-20000% increase in employment • ~1000-5000% increase in GHG emissions
CM2: Avoid, minimise or mitigate activities which would be incompatible with the conservation of a priority area for benthic habitats identified within North Anglesey Marine SAC.	CM2: Avoiding, minimising or mitigating impacts from mobile demersal gears to habitat features (e.g. seapens and burrowing megafauna), could maximise the effectiveness of the identified priority area in promoting the climate change resilience of these habitats.	
CM3: Avoid, minimise or mitigate activities which would be incompatible with the conservation of a priority area for climate services identified in Carmarthen Bay.	CM3: Avoiding, minimising or mitigating negative impacts in areas where sediment has a high carbon sequestration potential may limit direct carbon release and degradation (avoided emissions) from disturbed sediment.	
CM4: a) Avoid, minimise or mitigate proposals that may be incompatible with access for demersal fisheries in those areas identified as priority	CM4: Continued/priority access to sites identified as refugia for fisheries could contribute to the climate-	

areas for the sector. b) Avoid, minimise or mitigate proposals that may be incompatible with access by the pelagic fleet to priority areas for the sector.	resilience of the Welsh fishing sectors.	
CM5: Avoid, minimise or mitigate proposals for activities that would limit the development of seafloor aquaculture in the identified priority areas for this sector.	CM5: Development of the identified priority area for seafloor aquaculture represents a possible opportunity for sectoral expansion.	

D.6.2. Potential benefits of proposed spatial management measures

It is possible that intervention CM1 could go some way to support high quality foraging habitat for a range of benthic megafauna of conservation interest in Welsh waters. As noted in the Conservation Scenario (Section D.4 above), the identified priority areas for conservation are used by several elasmobranch species, including some considered as priority conservation species in Wales (listed in Section 7 of the Environment (Wales) Act 2016). In the wider Welsh region, the priority areas highlighted in interventions CM1 – CM3 have been shown to be spawning and nursery grounds for plaice, sole and sandeel (Ellis et al., 2010). This intervention may therefore benefit spawning aggregations and early life stages for key commercial and ecologically important species, which could be beneficial to fisheries in the long-term. Intervention CM2 could support the conservation of the OSPAR threatened and declining habitat "sea-pens and burrowing megafauna" which is also considered a habitat of conservation interest in Wales. The habitat has been assessed as being in poor condition (Queirós et al., 2024, Annex 2), and avoiding, minimising or mitigating negative seabed impacts in the identified priority area for benthic habitats may prove beneficial in supporting the recovery of this habitat. As noted in the Conservation Scenario, using these priority areas to benefit elasmobranch species of conservation interest or the OSPAR habitat would require a change in the way that MPAs in Wales are managed, moving from a "feature-based" approach to a "whole-site" approach to management (e.g. managing a site by considering the integrity of a site as a whole, not just where designated features are present).

In the case of the priority area for conservation identified for climate services in Carmarthen Bay, it is possible that intervention CM3 may limit direct carbon release and degradation (avoided emissions) from disturbed sediment. Although we acknowledge that it is unproven that protecting seafloor sediments from disturbance improves carbon storage or sequestration potential, the protection of marine carbon sinks may represent a sensible precautionary policy (Epstein et al., 2022; Epstein & Roberts, 2022; Jankowska et al., 2022), particularly given the current interest in the carbon storage and climate change mitigation potential of UK MPAs (Burrows et al., 2024). This intervention would require additional legislation that allowed sites to be designated for the protection of organic carbon stores. We note that interventions CM1-CM3 could also be supported by the adoption of technical measures that reduce fishing impacts on the seabed by the demersal fleet (see Section D.4.2 for details).

Interventions CM4 and CM5 could both present opportunities to support the fishing and aquaculture sectors in the face of climate change pressures. In the case of the fisheries sector, it is possible that pelagic fishing, which is not currently undertaken by Welsh vessels, could be possible in all Welsh waters under intervention CM4. Intervention CM5 could allow for the expansion of seafloor aquaculture in Wales, utilising the priority area for seafloor aquaculture north of Anglesey that we have identified. However, as noted in the Food Provision Scenario, it is unlikely that all of the priority aquaculture area could be developed without technical innovation of the industry, as it is in deep, offshore waters. Furthermore, new infrastructure may impede navigation routes.

D6.3 Economic outcomes for the adjacent blue economy of the Welsh region

Relative to the Business as Usual Scenario, the Compromise Scenario substantially increases all our indicators (Figure D.6.2-4). Again, results suggest that the biggest potential is in aquaculture expansion because the simulated expansions are very large relative to existing provision. The same caveats around uncertainties and model limitations apply and again we model both a maximal scenario where all the identified potential seafloor area is used for aquaculture (Figure D.6.2), and conservative scenario where only 5% of this area is used (Figure D.6.3). Figure D.6.4 shows the effects of the compromise interventions without the aquaculture expansion. We see smaller, but not insubstantial increases in all variables against Business as Usual, driven by an indicative 3 times increase in the activity of the pelagic fleet.

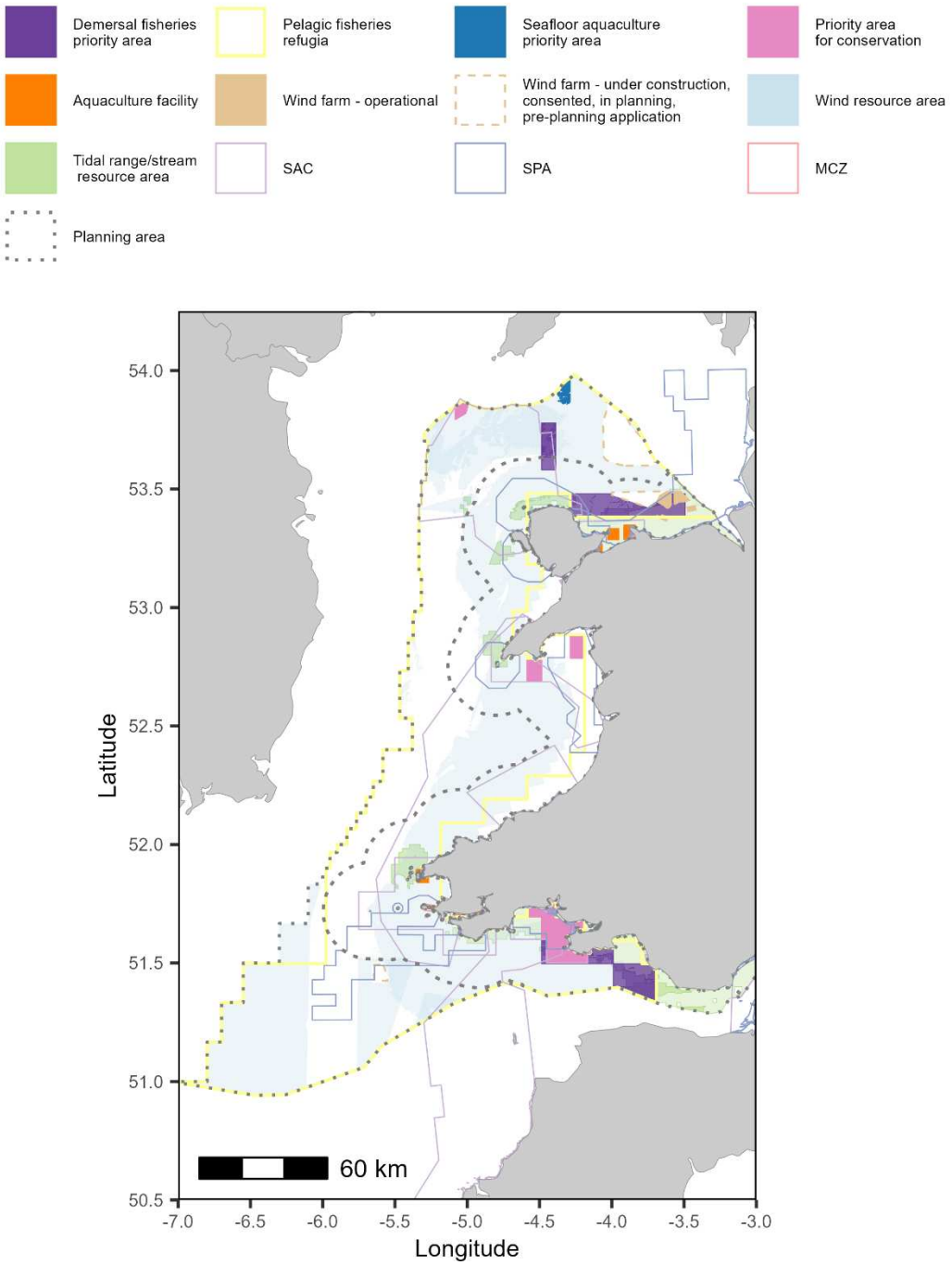

Figure D.6.1: Compromise scenario with identified priority areas for fisheries, aquaculture and conservation highlighted.

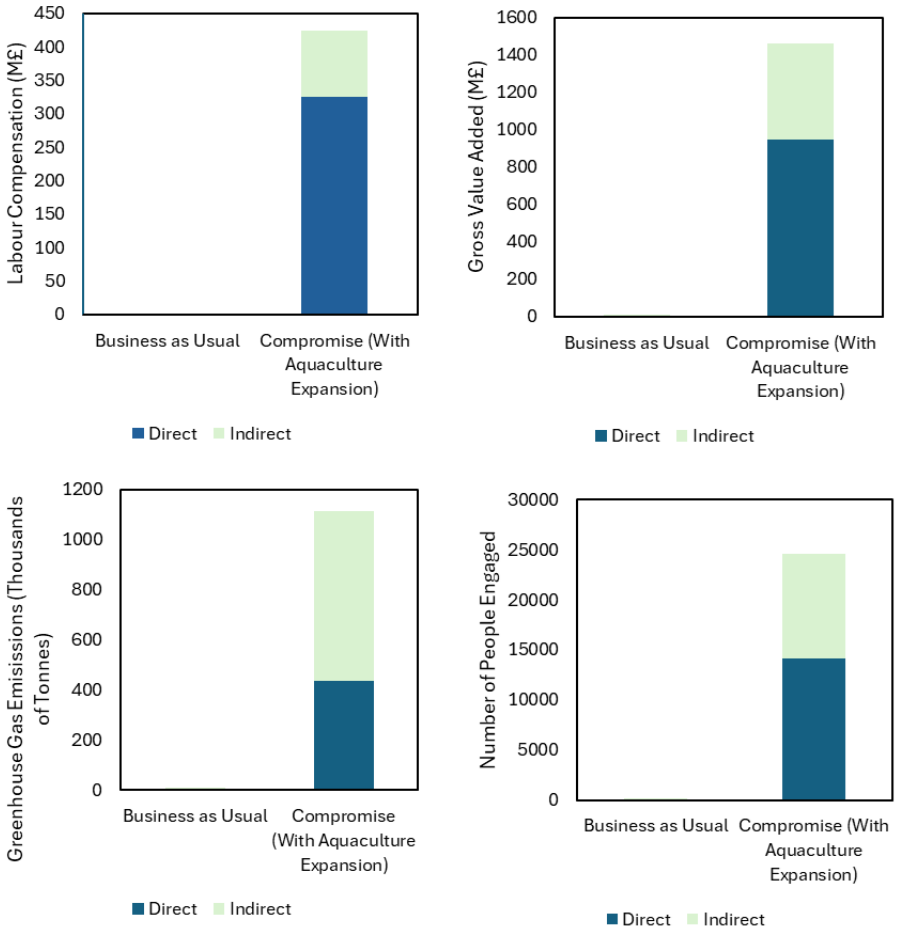

Figure D.6.2: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Compromise scenario with maximal aquaculture expansion, as compared to the Business as Usual Scenario.

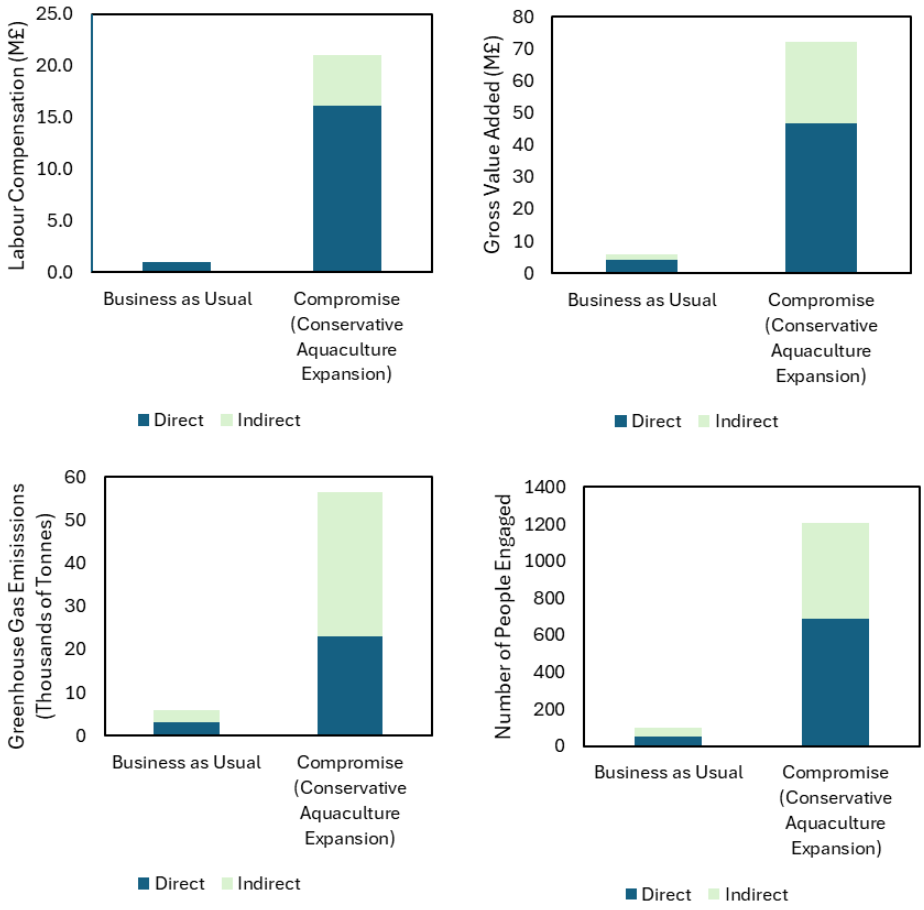

Figure D.6.3: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Compromise scenario (with 5% of potential seafloor area used to expand aquaculture), as compared to the Business as Usual Scenario.

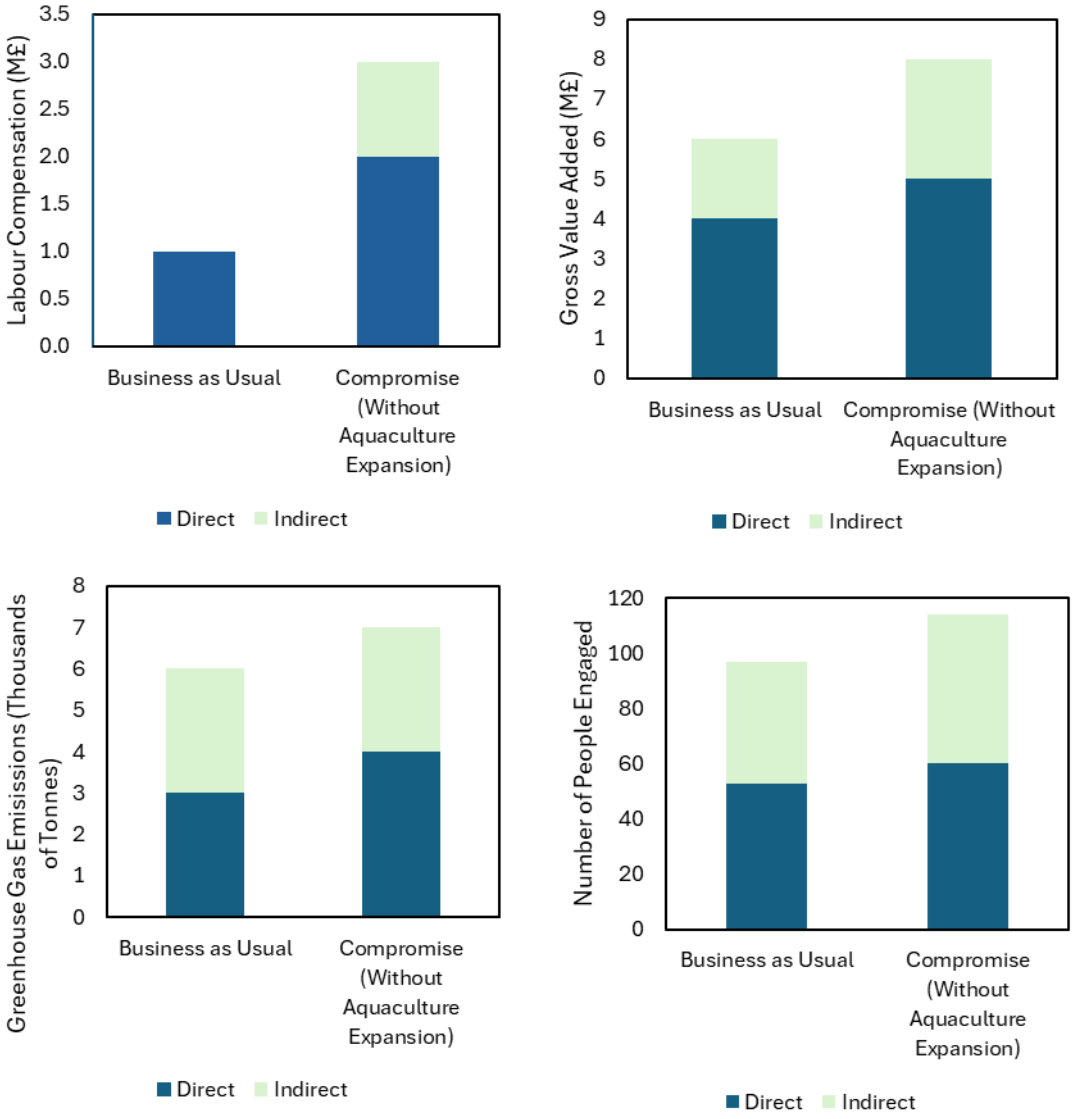

Figure D.6.4: Modelled changes in wages, GVA, GHG emissions and employment due to climate change in the Compromise scenario without the aquaculture expansion, as compared to the Business as Usual Scenario.

D.7. Cross scenario economic analysis

The model captures a variety of mechanisms that link marine resources and the adjacent blue economy in Welsh waters: 1) the area available for fishing or aquaculture 2) the supply chain structures of marine industries 3) the intensity of impact (labour compensation, gross value added, greenhouse gas emissions and number of people engaged) of a unit of output in different industries 4) the relative share of output of different industries. The relative area available for fishing or aquaculture is a major factor impacting the results. This is a major source of uncertainty in the model because of the assumption that all areas of the marine plan areas accessible to a particular fishing fleet segment or aquaculture producer are equally productive.

Another element to be aware of is that as there is currently no active pelagic fleet in Wales, there is very little data to guide scenarios with expansion of this activity. Indeed, MMO

logbook data suggests that pelagic catch is only around 5% of catch from Welsh waters landed at Welsh ports. Expansions of the pelagic fleet should be taken as indicative.

There are significant differences in the distribution of direct and indirect effects, driven by differences in supply chain and also impact intensities by industry. On average, the fishing fleet and aquaculture sectors are relatively greenhouse gas intensive but relatively employment light (Roca Florido & Mair, 2024). Of the 80 sectors in the model, the fishing fleet and aquaculture are all in the top third for direct greenhouse gas emissions intensity but the bottom half for direct employment intensity. This is reflected in the results where we see most greenhouse gas emissions/savings occurring in the direct portion of activity, but most additional employment in the indirect (supply chain) activity.

Annex 1: Scenario co-development formulae

The following are summary equations that represent the formulation of the management scenarios co-developed in MSPACE.

1. Business as Usual Scenario

Example with Revenue (R):

Total R_{BAU} = $R_p - R_h$

1.1. Effects on Fisheries

BAU = business as usual scenario

p = area fished at present

h = area fished at present that overlaps with fishery hotspot

1.2. Effects on Aquaculture

BAU = business as usual scenario

p = area where aquaculture infrastructure is located at present (note if pelagic or benthic)

h = area where aquaculture infrastructure is located at present that overlaps with aquaculture hotspot (note if both pelagic or benthic)

Climate-smart scenarios

2. Food Provision Scenario

2.1. Fishery (intermediate) Scenario: optimises outcomes for the fishing sector

Example with Revenue (R):

Total R_{FS} = $R_p - R_h + R_r$

FS = fishery scenario

p = area fished at present

h = area fished at present that overlaps with fishery hotspot

r = area in fishery refuge (pelagic or demersal) that is not currently fished

2.2. Aquaculture (intermediate) Scenario (optimises outcomes for the Aquaculture sector)

Example with Revenue (R):

Total R_{AS} = $R_p - R_h + R_r$

AS = aquaculture scenario

p = area where aquaculture infrastructure (water column or seafloor) is located at present

h = area where aquaculture infrastructure (water column or seafloor) is located at present that overlaps with aquaculture hotspot

r = area in aquaculture refuge (water column or seafloor) where there is no aquaculture infrastructure located at present

2.3. Final Estimate

Combines overall estimates from the above Fishery and Aquaculture scenarios

Total R_{FP} = $R_p – R_h + R_r$

FP = Food Provision scenario

p = area where aquaculture infrastructure is located at present (note if pelagic or benthic) + area fished at present

h = [area where aquaculture infrastructure is located at present that overlaps with aquaculture hotspot] + [area fished at present that overlaps with fishery hotspot]

r = [area in aquaculture refuge where there is no aquaculture infrastructure located at present] + [area in fishery refuge that is not currently fished]

3. Conservation scenario

3.1 For impacts on fishing

Total R_{CS} = $R_p – R_h – R_r$

CS = conservation scenario

p = area fished at present

h = area fished at present that overlaps with a fisheries hotspot

r = area identified in conservation analysis as a climate change refuge (benthic habitat, pelagic habitat, benthic megafauna, pelagic megafauna, climate services) that is proposed as a priority conservation area and in which fishing restrictions are proposed.

3.2. For impacts on tourism/recreation

Total R_{CS} = $R_p – R_h + R_r$

CS = conservation scenario

p = area protected at present (e.g. MCZ + SAC + SPA)

h = area protected at present that overlaps with hotspot

r = area identified in conservation analysis as a climate change refuge (benthic habitat, pelagic habitat, benthic megafauna, pelagic megafauna, climate services) that is proposed as a priority conservation area and in which we expect to see benefits to marine recreational activities e.g. scuba diving, wildlife watching

4. Compromise Scenario.

4.1 For impacts on fishing

Total R_{FS} = $R_p - R_h - R_r + R_f$

FS = conservation scenario

p = area fished at present

h = area fished at present that overlaps with a fisheries hotspot

r = area identified in conservation analysis as a climate change refuge (benthic habitat, pelagic habitat, benthic megafauna, pelagic megafauna, climate services) that is proposed as a priority conservation area and in which fishing restrictions are proposed.

f = area identified in fisheries analysis as a refuge for pelagic or demersal fisheries that is proposed as a fisheries priority area

4.2 For impacts on fishing

Total R_{AS} = $R_p - R_h + R_r$

AS = aquaculture scenario

p = area where aquaculture infrastructure (water column and seafloor) is located at present

h = area where aquaculture infrastructure (water column and seafloor) is located at present that overlaps with aquaculture hotspot

r = area in aquaculture refuge (water column and seafloor) where there is no aquaculture infrastructure located at present

4.3. For impacts on tourism/recreation

Total R_{TRS} = $R_p - R_h + R_r$

TRS = Tourism/recreation scenario

p = area protected at present (e.g. MCZ + SAC + SPA)

h = area protected at present that overlaps with hotspot

r = area identified in conservation analysis as a climate change refuge (benthic habitat, pelagic habitat, benthic megafauna, pelagic megafauna, climate services) that is proposed as a priority conservation area and in which we expect to see benefits to marine recreational activities e.g. scuba diving, wildlife watching

4.4 Final Estimate

Combines overall estimates from the above Fishery, Aquaculture and Tourism/recreation scenarios

Total R_{CS} = $R_p - R_h - R_f + R_r + R_c$

CS = Compromise scenario

p = area where aquaculture infrastructure (water column or seafloor) is located at present + area fished at present

h = [area where aquaculture infrastructure is located at present that overlaps with aquaculture hotspot] + [area fished at present that overlaps with fishery hotspot]

f = area identified in conservation analysis as a climate change refuge (benthic habitat, pelagic habitat, benthic megafauna, pelagic megafauna, climate services) that is proposed as a priority conservation area and in which fishing restrictions are proposed.

r = [area in aquaculture refuge where there is no aquaculture infrastructure located at present] + [area in fishery refuge that is not currently fished]

c = area identified in conservation analysis as a climate change refuge (benthic habitat, pelagic habitat, benthic megafauna, pelagic megafauna, climate services) that is proposed as a priority conservation area and in which we expect to see benefits to marine recreational activities e.g. scuba diving, wildlife watching

Annex 2: Supplementary Information

Table A1: Marine focussed sectors in the economic analysis. For a full list of sectors, please see Roca Florido et al. (2025)

	Sector
1	Under 10m drift and/or fixed nets
2	Under 10m pots and traps
3	Under 10m using hooks
4	Pots and traps 10-12m
5	UK scallop dredge
6	Demersal beamers trawlers
7	Other static gears using vessels
8	Low activity vessels
9	Aquaculture
10	Fish processing sector
11	Building of ships and structures
12	Pleasure boat shipbuilding
13	Repair and maintenance of ships and boats
14	Wholesale marine products
15	Retail marine products
16	Water transportation services
17	Renting transport equipment

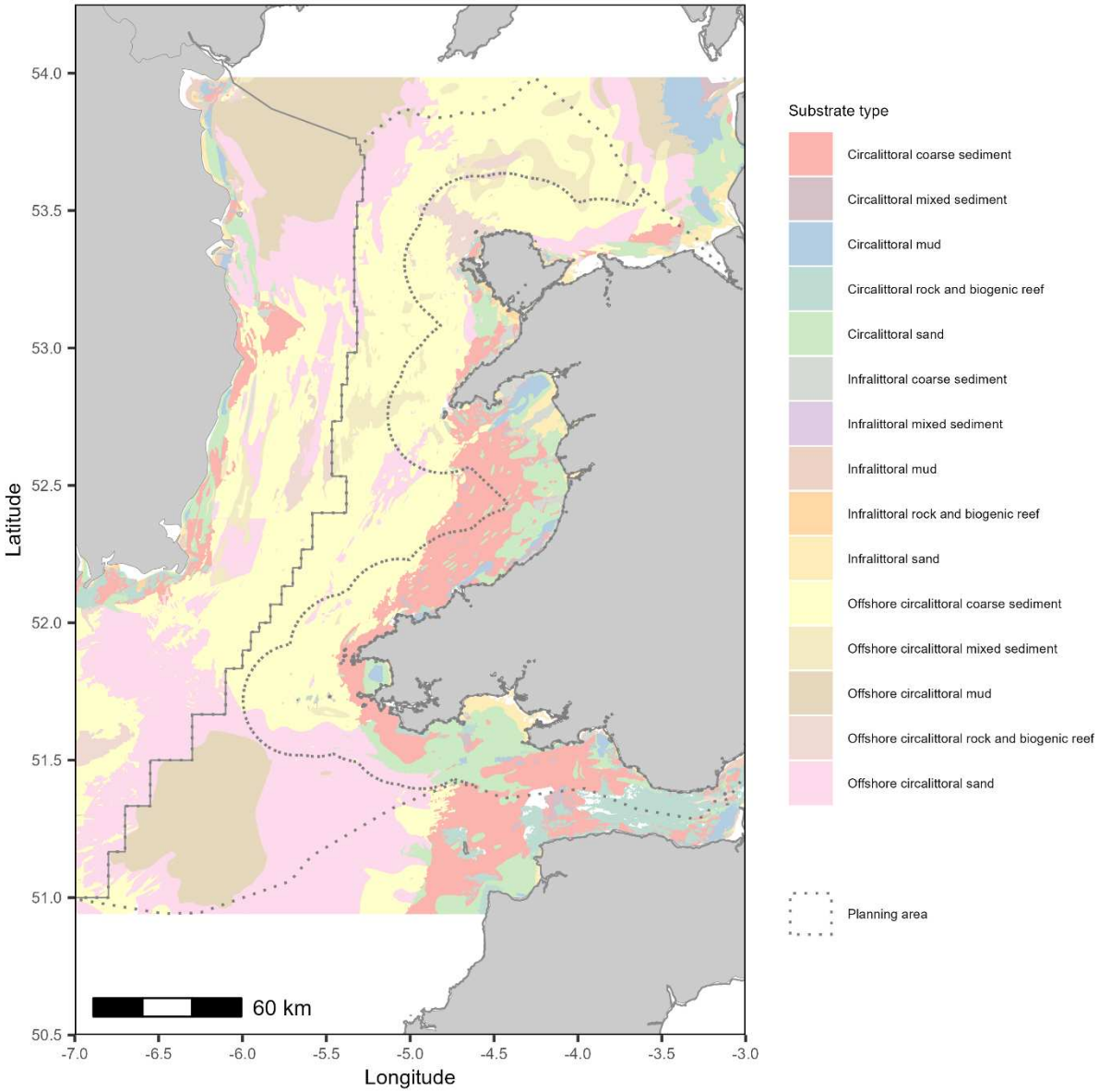

Figure A.1: Distribution of EUNIS broadscale habitat types in Welsh waters, produced by EUSeaMap Broad-Scale Predictive Habitat Map for Europe (2023). Downloaded from https://emodnet.ec.europa.eu/.

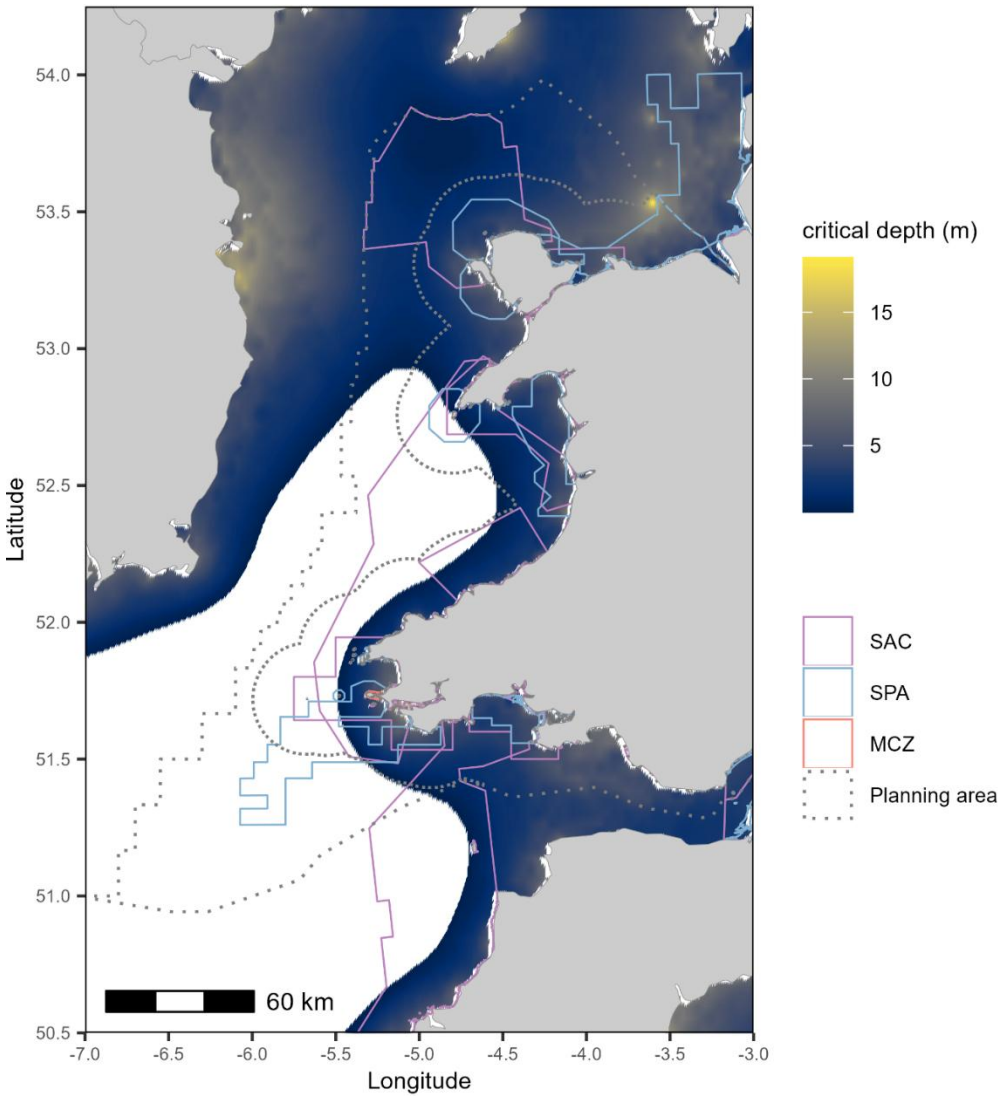

Figure A.2: Depth to which biologically relevant artificial light levels penetrate the water column in the Wales marine planning area (data from Smyth et al., 2024), along with the locations of designated conservation sites. It is likely that the source of the light pollution in Liverpool Bay and around Swansea is the oil and gas infrastructure present in both of these locations.

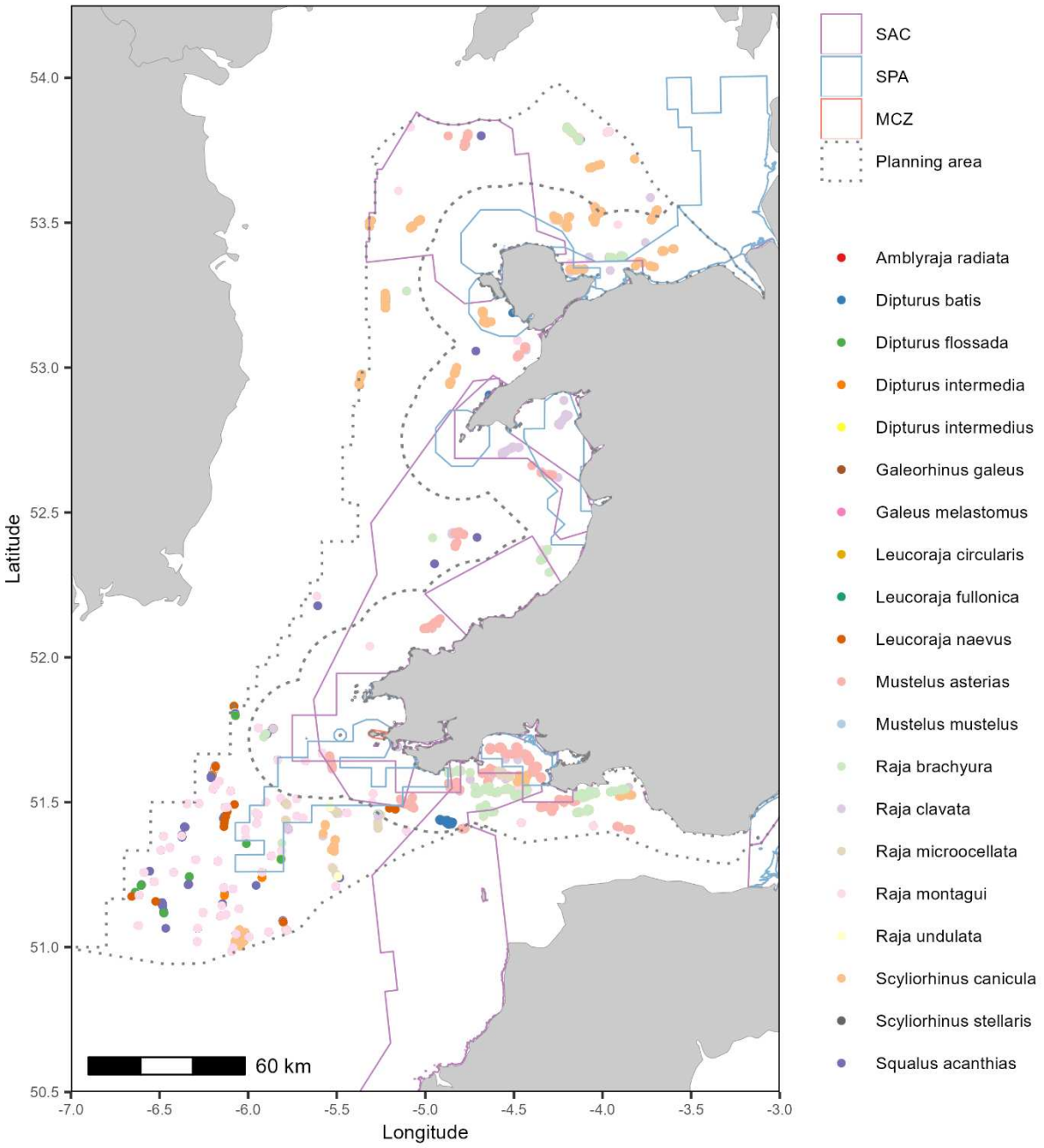

Figure A.3: Observed distributions of elasmobranch species within the Welsh planning area. Survey data from Irish Groundfish Survey, the Northern Irish Groundfish Survey and the Beam Trawl Survey (all 2000-2022), downloaded from https://datras.ices.dk/

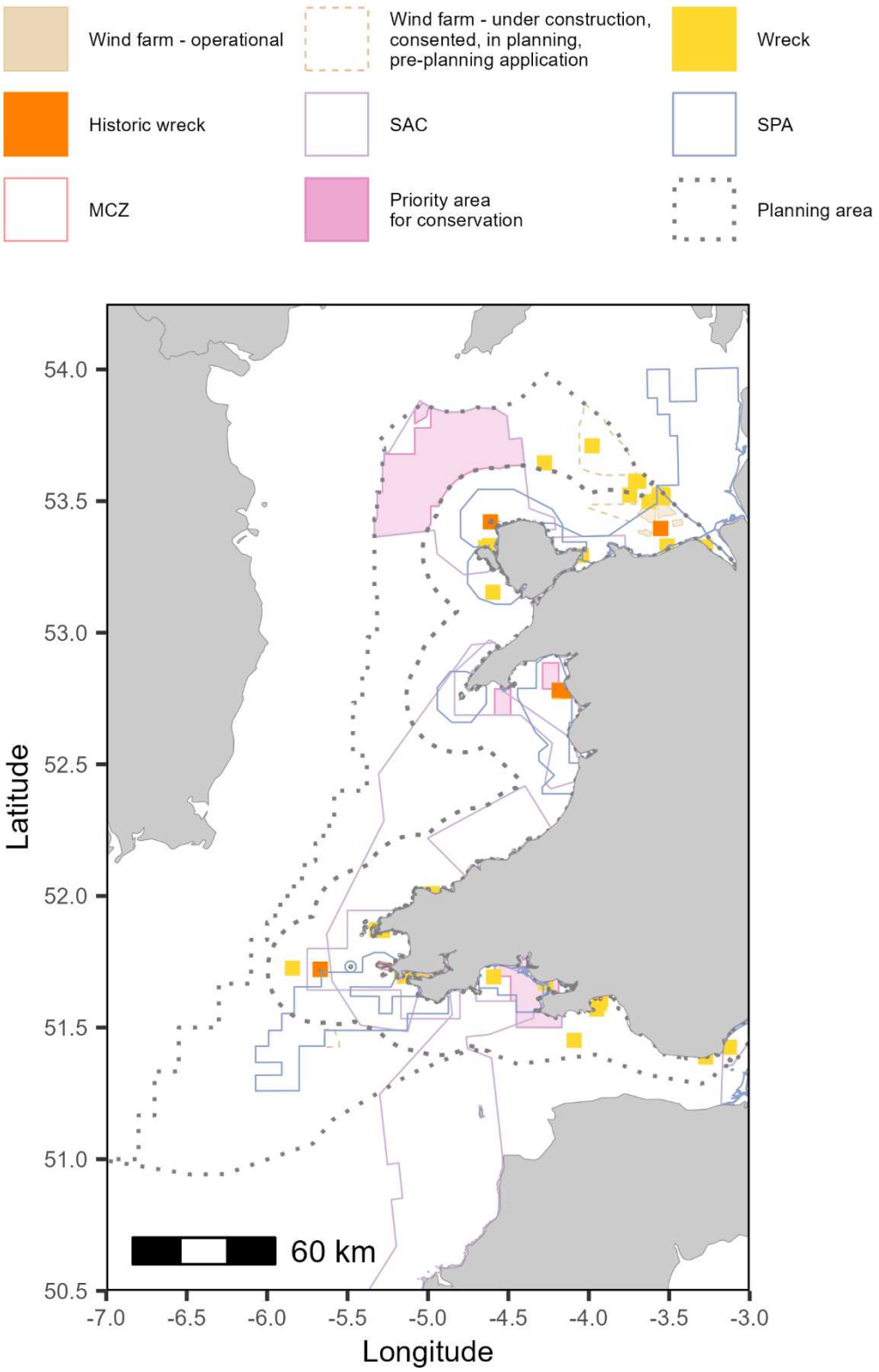

Figure A.4. Conservation scenario showing the locations of wrecks. One protected historic wreck in Cardigan Bay overlaps with a priority conservation area in the Llŷn Peninsula and Sarnau SAC.

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