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# Are marine protected areas an adaptation measure against climate change impacts on coastal ecosystems? A UK case study

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ABSTRACT

Climate change is impacting marine seascapes against a backdrop of multiple anthropogenic stressors. These current impacts are projected to increase in the future with increasing warming, acidification, oxygen loss, and sea level rise. Marine Protected Areas (MPAs) have been established to protect features in the ocean, traditionally with a focus to reduce fishing pressures and infrastructure placements. These MPAs are static in nature and are rarely considering climate change; therefore, their potential adaptation effectiveness as local adaptation measures for conservation in response to climate change are not clear. Here we discuss the challenges to Marine Protected Areas as conservation tools and for adaptation to climate change threats. We use two case studies from the UK to ask how climate change resilience could be included in MPA management to future-proof these conservation measures. We conclude that the resilience of MPAs to climate change would be better supported when adaptive management measures and an ecosystem-based approaches are adopted. We emphasise the need to increase the recognition in the primary legislation of MPAs and the monitoring of sites to better understand climate change as it becomes more pronounced, and impacts emerge.

## 1. Introduction

Climate change is impacting species in the ocean, their geographical ranges, and phenology, and thereby altering food webs and other species interaction [1–7]. $CO_2$ is directly affecting the environment by causing ocean acidification, and indirectly via warming, changes in stratification, altered weather patterns, sea level rise and changes in ocean salinity and oxygen levels [8–13]. The impacts are projected to amplify as climate change becomes more pronounced [3, 6]. By 2100, global mean sea surface temperature is projected to rise between 0.08-2.89°C and sea surface pH between 0.08 and 0.37 units in response to SSP1-2.6 and SSP5-8.5 respectively [3]. Direct impacts of climate change on marine ecosystems include organism and habitat migration following temperature envelopes [14,15], shifts in ecosystem composition following the establishment of newly arrived species [8,3], difficulties in forming and maintaining calcium-based structures due to ocean acidification [16,17], and increased metabolic stress due to combined ocean acidification and warming [18,19]. In temperate environments, these environmental changes are expected to lead to migration, shifts in species composition, and losses of foundation species. In tropical communities, species will reach adaptation limits, resulting in unavoidable impacts and risks such as biodiversity loss and extirpation [20]. While risks differ amongst species and regionally, even in temperate regions such as the European Seas impacts of marine heat waves are now getting recorded [21].

The impact of climate change, especially in coastal systems, interacts with non-climatic drivers, increasing vulnerability to climate change and potentially weakening ecosystem resilience [22]. Resilience is broadly defined as the ability of a system to recover following stress or disturbance, applied to individuals, populations, and communities [23]. Resilience is comprised of resistance, recovery, and reorganization for example the response to and recovery from extreme events such as marine heatwaves [24–26]. In the current debate, resilience focusses on the health of the ecosystem itself, rather than individual components

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within it [1]. Secondary stressors include coastal development, nutrient runoff from terrestrial sources, fishing, invasive species, pollution, marine infrastructure projects, and anthropogenic noise (Fig. 1) [1,27,28].

For example, ocean acidification is projected to increase the stress benthic organisms like polychaetes experience by decreasing their fecundity, which is exacerbated when polychaetes are exposed to metal pollution [29]. Fishing practices like trawling can destroy shellfish spawning habitat or damage the organisms [30], resulting in the local loss of populations or habitat features. Protecting the ocean ecosystems and the services they provide to people is the focus on the United Nations "Decade of Ocean Science and Ecosystem Restoration" to further support the sustainable development goal 14 to "conserve and sustainable[ly] use the oceans, seas, and marine resources for sustainable development".

Marine protected areas (MPAs) are a well-established management approach, set up to protect seascapes, habitats, and species. The term MPA describes an area of the marine environment with restriction on detrimental human activities. MPAs, as they reduce secondary stressors, are assumed to increase resilience to climate change [31–33] and are considered to be one of the most effective tools adaptation tools for marine ecosystems facing environmental change [32,34,35]. Evidence from coral reefs suggests MPAs with high levels of protection can decrease the time ecological communities need to recover from disturbance events like bleaching because they are subjected to fewer stressors compared to unprotected surrounding habitat [36]. Direct ecological benefits from high levels of protection include protecting spawning stocks or nursery habitats for important species, increasing size of individuals, population size and organism biomass which enhances reproductive capacity in an area, enhanced biodiversity and ecosystem structural complexity, and the creation or maintenance of refugia habitats [27,37,38]. The direct benefits from protection can result in indirect benefits including biological spill over seeding surrounding environments, reducing coastal flooding and erosion, carbon storage and water filtration, cultural service and promoting social capital among stakeholders [3,27,28,39]. Properly established and fully protected MPAs can also have knock-on ecosystem impacts as documented in tropical regions where protecting fish species has resulted in increased coral cover and structural variability [40].

Marine ecosystems also contribute to adaptation and mitigation from climate change [32,41]. Trawling practices globally contributes an equivalent amount of carbon emissions to the ocean atmosphere systems as the aviation industry [32] and protection from sediment disturbance can therefore prevent the release of carbon stored in marine sediment and organisms and support carbon capture and storage [32,42]. Widening the focus of mitigation from terrestrial forests to marine ecosystems has the potential to engage local communities, provide livelihoods and benefit biodiversity [43].

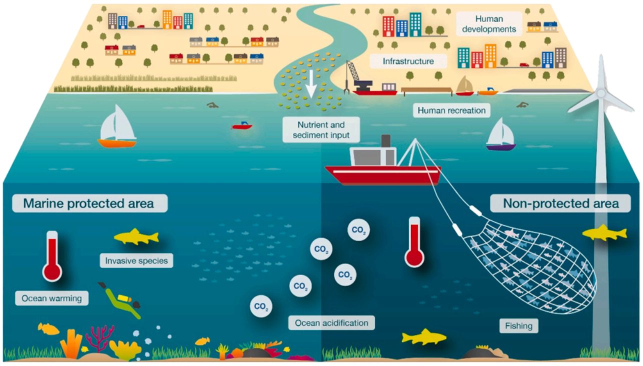

**Fig. 1.** A systematic diagram of an MPA and selected stressors it faces increasing its vulnerability to climate change such as coastal development, human recreation, nutrient inputs and siltation from rivers, trawling, infrastructure placement e.g. energy projects, and invasive species.

Coastal ecosystems like saltmarshes, kelp forests, and seagrass beds not only offer $CO_2$ storage, but also, coastal protection that safeguards coastal communities [41,44]. The restauration of coastal wetlands for example benefits climate mitigation, supports the ambition to limit warming below 2°C, and provides benefits for biodiversity, water, and air quality [45]. Healthy seagrass beds can increase the pH of the surrounding environment during daytime through photosynthesis [46], therefore offering partial respite for calcifying organisms impacted by ocean acidification at current day levels. These functions are jointly termed nature-based solutions [47] or ecosystem-based adaptation [48]. The IUCN defines Nature-based Solutions as "Actions to protect, sustainably manage and restore natural or modified ecosystems, providing human well-being and biodiversity benefits" [49]. The blue economy (the sustainable use of ocean resources preserving ocean ecosystems while promoting growth and improving livelihoods) [50], and Nature-based Solutions [43,45] therefore provide interconnections for UK MPAs but also challenges for justice and governance.

MPAs though vary in relation to the level of protection: they range from highly protected marine areas to areas where most sustainable uses of marine resources are allowed [51]. An activity removal has many direct and indirect benefits [27], though these vary depending on the target feature of an MPA, the degree of protection it offers and the extent to which it is complemented by other conservation measures such as fishery closures, integrated coastal zone management and marine spatial planning [21,32,52,53]. Other marine ecosystem management methods that are advocated to increase marine ecosystems resilience to climate change, like decreased fishing pressure, more sustainable fishing practices, and preventing seabed mining, operate in concert with MPA objectives [54].

Distribution changes amongst marine organisms are consistent with changes in marine temperature and larger than those for terrestrial ecosystems [55,56] creating an urgency to develop effective adaptation options. While in tropical seas species are expected to reach their thermal limits, in cold regions warming enables the establishment of warm water species that outcompete cold water species. While high levels of protection show clear benefits for marine ecosystems, MPAs and other spatial planning and management approaches have not until now been designed to consider ecological response to climate change [52,57,58] such as the shifts in ecosystem composition, structure and function already seen today and projected to increase in the future [3,8,59].

### 1.1. *The challenges to marine protected areas as conservation and adaptation tools*

To fulfil the vision of protection of marine ecosystems, MPAs need to protect critical ecosystem and biodiversity and not become 'paper parks' stopping at designation without implementation and management [60]. A paper park is defined as protected area that exists within legislation but offers no real protection to aid conservation objectives. Of the global MPAs, 69% are only partially protected with unclear ecological and social benefits [61,62]. While an increasing area is designated in Europe, many MPAs lack a management plan, which permit activities that represent threats, or are insufficiently resourced to enforce existing restrictions [60,63]. The most widespread threats are maritime traffic and fishing [60]. Conservation targets are typically centred around returning an environmental system to a baseline condition, but there is increasing recognition that this approach is unfeasible given a lack of information on these baseline conditions and the projected future pressures of climate change [8,14,20].

Within the existing MPAs, moving from conservation to resilience to climate change [1,20,36,64] is not supported by a clear understanding of the implications for of climate-smart management [35,65]. Many European MPAs have a feature-based approach where protection is linked to the presence of a particular habitat or species (feature) [66]. The success and durability of the MPA is therefore against the ability to protect the specific conservation feature for example, via increases in the abundance of the feature e.g., an increase in scallop numbers in response to a dredging ban. Such a features-based approach is risky in the context of climate change as organisms will migrate out of the MPA which is defined by their presence and abundance can change for example in response to increased $CO_2$ in seawater [2,35,67]. In this context, a small MPA outside a larger network might lose it status and not be able to fulfil its function.

Targeted action to adaptation conservation practice include zoning around and networks of protected areas to facilitate migration as they can facilitate interactions over larger regions, across ecosystems and stressors. Such larger areas not only increase the area and reduce fragmentation but also increase heterogeneity by including climate refugia where stressors such as warming will be lower than the regional average [68]. Linkages between sites facilitate migration to track niches for the different developmental stages [69] while recruitment from different sites can seed areas with local extinctions [70]. Larger areas also support and encompass a larger taxonomic, phylogenetic, and functional diversity and redundancy increasing ability to sustain shocks [68]. Given range changes in response to migration, transboundary management of protection will become increasingly important [14]. Therefore, networks of highly protected MPAs have been advocated as the most promising mechanism for supporting climate change resilience for marine biodiversity by providing mechanisms aiming to protect habitats, diversity, and wood webs [1].

While networks of MPAs exist, climate adaptive management of these has not been a priority. For example, in the UK a network of MPAs covering large portions of the maritime area has been designated (Fig. 2).

In the following examples, we explore how to better build climate change resilience into MPAs that did not focus on climate change at their inception. Using the UK as a model, we will discuss real-world challenges as seen by stakeholders responsible for protecting these systems through cases studies discussing the practice, the readiness for adaptation and the changes which need to be made.

### 1.2. *Main legal frameworks for protecting UK marine environments*

The first UK MPA was created through voluntary agreements between conservationists and local fishers at Lundy [71]. The UK MPAs comprises Sites of Special Scientific Interest (SSSIs), Ramsar sites, Marine Conservation Zones (MCZs), Special Areas of Conservation (SACs), Special Protected Areas (SPAs), Nature Conservation MPAs for Scotland, created under an umbrella of legal frameworks, at different operational levels [72], from domestic to European to international legislation. These diverse types of designation were brought together under a single UK ‘network’ by section 123 of the Marine and Coastal Access Act 2009 and section 79 of the Marine (Scotland) Act 2010.

The UK has recently completed the network of MPAs within its Exclusive Economic Zone (EEZ) with ∼38% of UK waters have been designated within 374 MPAs, aggregated by 47% protected inshore waters and 36% offshore waters [73]. While progress has been made in terms of quantitative MPA coverage, it is less clear if MPAs offer effective protection to the UK marine environment [74]. As marine conservation is a devolved matter, each UK administration (England, Northern Ireland, Scotland, and Wales) has developed its own legislation [58]. Climate change is only specifically mentioned by three pieces of legislation relating to marine conservation (Climate Change Act (2008), Climate Change (Scotland) Act 2009, and Marine (Scotland) Act (2010)), though general provisions for conservation in other legislation can be interpreted to apply to climate change [72]. In Scotland, the underlying marine conservation legislation specifically mentions climate change considerations in the designation of sites. The features-based approach adopted in Scotland though does not sufficiently account for climate change as it lacks wider ecosystem processes and sites are considered in isolation [75].

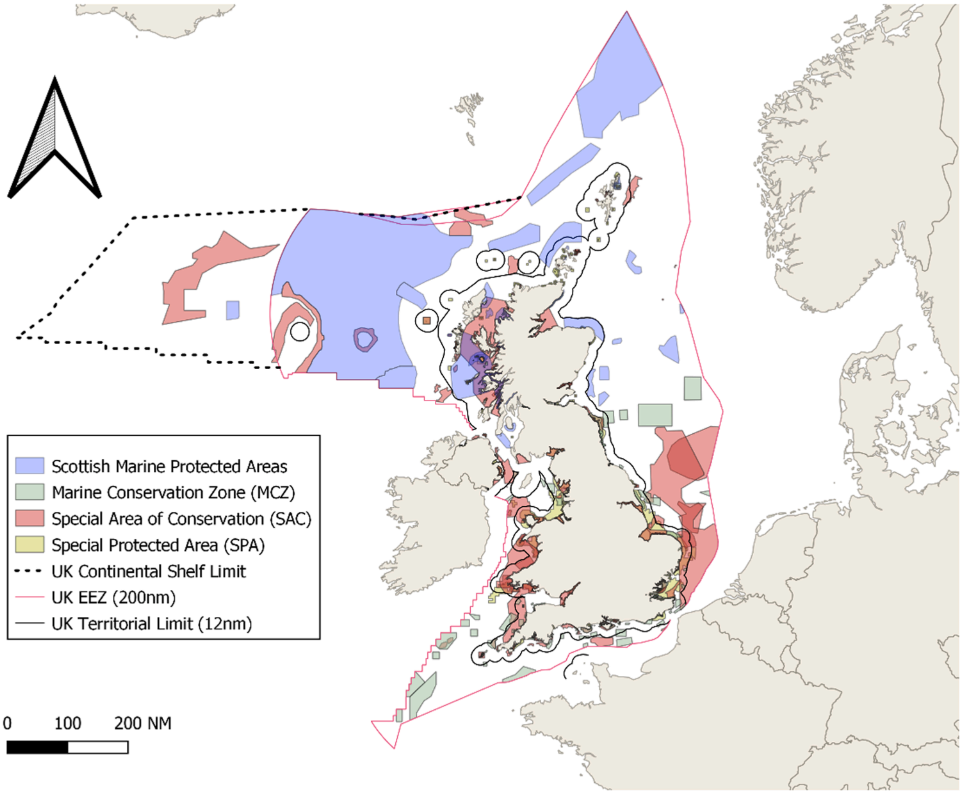

**Fig. 2.** The UK MPA Network. Scottish Marine Protected Areas data from Scottish Natural Heritage, MCZ data from Natural England, SAC and SPA data from JNCC. UK Continental Shelf Limit, EEZ, and Territorial Limit from Admiralty Maritime Data Solutions

### 1.3. The climate change challenges to UK MPAs

Between 1984 – 2014, seawater pH decreased at a rate of 0.0035 pH units per year in the North Sea and English Channel [76], and the seas around the UK warmed by up to 0.24°C per decade [77]. Future warming by 2.3C is expected by 2100 under SSP5-8.5 [21] and sea level rise 8-115 cm by 2100 relative to 1981-2000 averages [78].

Consequently, poleward shifts of the leading and trailing range edges of both benthic and pelagic species have been recorded, with many changes occurring in the biogeographic transition zone between cooler boreal and warmer Lusitanian waters that bisects the UK [55,79,80]. Large parts, approximately 1000 km, of the UK shoreline are rocky littoral and sublittoral habitats. Many rocky intertidal species of both boreal and lusitanian evolutionary origins have their leading or trailing distributional range edges on the UK coastline [55]. Driven by temperature, some of the fastest impacts of climate changes for any species in any natural system are recorded in the leading or trailing ranges edges in UK regional seas [55,81]. Species specific distribution changes [81,82] and adaptation to local conditions modulates the response; for example, the abundance of the important ecosystem forming kelp is declining in southern UK regions but is increasing in species of kelp and wrack in northern and central regions [83].

Changes in the regional distribution and composition of biogenic habitat forming species like kelp or wrack will alter the distribution of associated organisms like epiphytic seaweed or molluscs [82]. Modelling predicts that the theoretical niche for the horse mussel *Modiolus modiolus* (an OSPAR priority habitat) will disappear from UK MPA areas by 2100 to be replaced by seagrass (*Zostera* spp.) or the European flat oyster (*Ostrea edulis*) [84]. For coralline algae, a protected habitat former, the projected niche changes for temperature and those for carbonate chemistry are moving in diametrically different directions [2] impacting their skeletal growth [17,85], structural integrity degrading biodiversity hotspots [16].

Climate change has facilitated the invasion and establishment of new species of macroalgae in the intertidal ecosystems of the UK over the past half century. The invasive brown alga *Sargassum muticum* has expanded in rocky intertidal habitats around the UK coastline since it was first introduced in the 1970s due to the wider ecological tolerance than many native species of algae [55,86,87]. The warm-temperate benthic habitat forming kelp species *Laminaria ochroleuca* has colonised sites in the southwestern English Channel where it now co-exists, and competes, with *L. hyperborea*. This change impacts dependant faunal assemblages [88]. The red alga *Agarophyton vermiculophyllum* is a more recent arrival [89] with implications for ecosystem management [90].

Here, we are reflecting the challenges in in two case studies to highlight issues that practitioners face to ensure protected area effectiveness. We discuss the establishment of non-native taxa in the Pen Llŷn a'r Sarnau and the socio-ecological system Falmouth Harbour that adaptation and management of conservation are place and context dependent. Using these case studies, we show existing regulatory challenges within the context of climate change and discuss actions within their context that support climate change adaptation and management.

## 2. Case study 1: establishment of non-native taxa in the Pen Llŷn a'r Sarnau SAC

Globally, baseline assessment of ecology is missing, challenging assess of arrival and losses of species and damages to ecosystems to date and potential future success of conservation. Newly arriving species can pose threads to local taxa and ecosystems. There are indications that some invasive taxa are favoured by climate change over native species [91–93]. The drivers of invasions success are challenging to identify but human activities in general alter distribution though climate change, bridge natural dispersal barriers though relocation and open opportunities beyond natural distributions [94]. Monitoring and surveillance of sites is rare, e.g., with the long-term monitoring time series MarClim in England and Wales [55]. This monitoring though is fundamental in addressing migration of established species due to climate change but also arrival of non-native taxa.

Here we focus on one example of the practice of responding to changes in species distribution due to invasion and expansion of habitats in north Wales at Pen Llŷn a'r Sarnau Special Area of Conservation (SAC) (Fig. 3a). The SAC is an estuary protected under Annex I habitat of the Habitats Directive (Council Directive 92/43/EEC). Here, the Annex 1 habitat consists of three macro-tidal estuaries in Cardigan Bay: the Dwyryd / Glaslyn, Mawddach and Dyfi estuaries (4,525 ha). The estuaries also contain Annex I mudflats and sandflats not covered by sea water at low tide, Salicornia and other annuals colonising mud and sand and Atlantic salt meadows [95].

In July 2017, the invasive non-native alga *Agarophyton vermiculophyllum* (Fig. 3b) was recorded in the northern-most estuary, the Dwyryd. The species is a GB Non-native Species Secretariat (NNSS) alert species, high status surveillance species under the Marine Strategy Framework Directive (MSFD) and a marine INNS contingency species in Wales [96,97]. *A. vermiculophyllum* likely originates from Japan [89] and has been documented to increase the mortality of native algae it competes with for habitat space [98]. Furthermore, future warming is suggested to have minimal impacts on *A. vermiculophyllum* while increasing the mortality of native algae [99]. Rapid growth of the algal thalli is projected to result in changes to and loss of biodiversity because of anoxia in saltmarsh pools and changes in recruitment and sustained populations of invertebrate infauna in sediments that are smothered by the algal thalli.

*A. vermiculophyllum* was typically found in depositional or less tide-exposed locations within the estuary [89]. By May 2018, *A. vermiculophyllum* thalli filled the pools along a 1.7 km stretch of saltmarsh, causing extensive anoxia beneath the bleached algae. While the algae were embedded in the sediment of the pools, they were not actively growing. In 2019 *A. vermiculophyllum* expanded to the Mawddach estuary in the same SAC and further *ad-hoc* observations were confirmed in the Malltraeth estuary, 34 kilometres to the north (102 km by sea). These estuaries have no known active shellfisheries or any other possible pathway for its introduction from the next nearest known locations in Northern Ireland or southern England [89], meaning its establishment mechanism is unknown.

The extensive coverage by the alga may result in substantial areas of the Annex 1 habitats being affected in SACs in Wales, including changes in substratum and shore height, changes in shellfish (cockle) and other invertebrate infauna and epifauna of the sediment habitats and reducing access to sediment feeding areas for waders. The Welsh coastline is important for both tourism and fisheries, which are dependent on sustaining the wider ecosystem [100].

Several MPAs in Wales now record *A. vermiculophyllum*, a feature absent during their creation, changing the baseline ecology. The limited capacity to fully map the extent of the *A. vermiculophyllum* across all estuary features results in an incomplete picture of distribution and spread in mid and north Wales. Therefore, management opportunities to limit the rapid and unpredictable establishment are not available. Continued surveillance and reporting by Natural Resource Wales (NRW), on an *ad-hoc* basis will continue into the foreseeable future with no effective management methods identified.

While the example of Case Study 1 is not likely caused by climate change, the establishment of novel species will be repeated in other MPAs due to climate change highlighting the importance of this management challenge and our current inability to address the risk. Not only will this impact the local biodiversity but also wider habitat function due to the resulting anoxia [89]. While little can be done once species like algae have established in an area it is important to increase the capacity to survey sites to aid our understanding of how site conditions are changing due to species introductions or range shifts. A European Maritime and Fisheries (EMFF) funded project managed by Natural

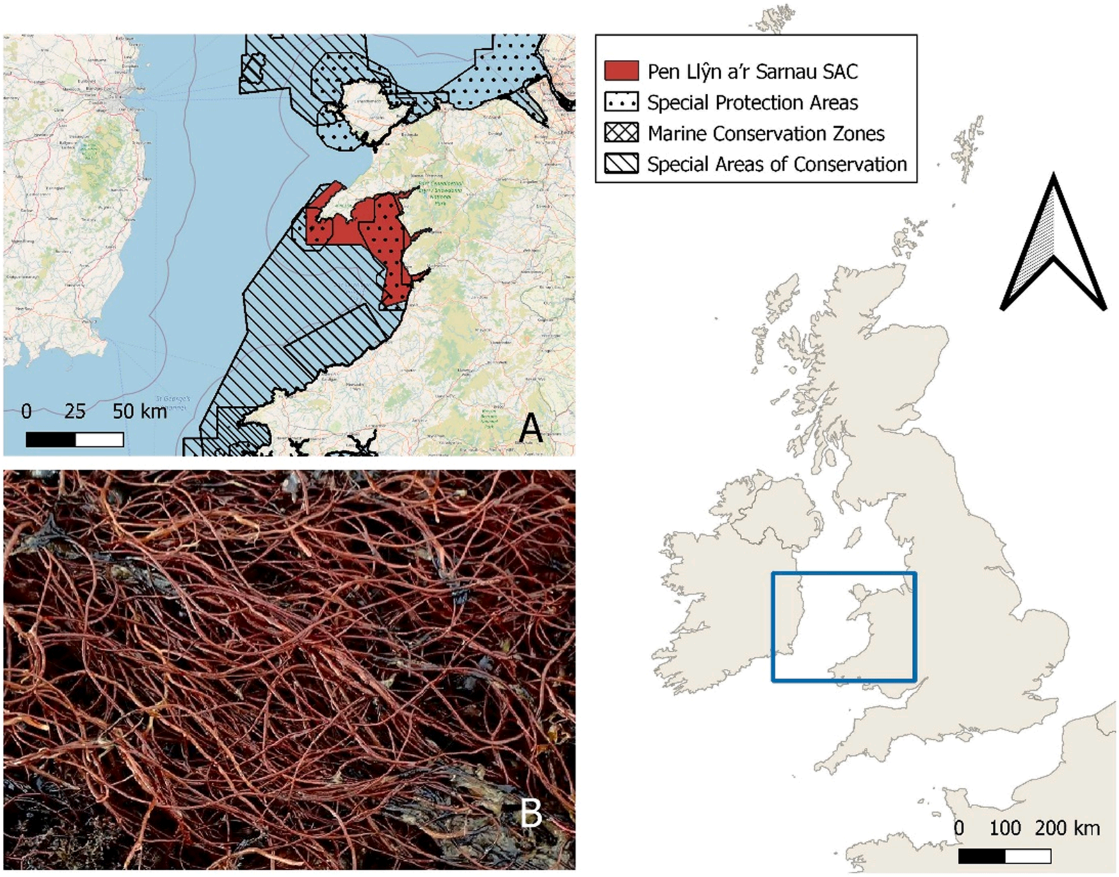

**Fig. 3.** Case study 1 location, A - Pen Llŷn a'r Sarnau SAC, B - non-native alga Agarophyton vermiculophyllum

Resources Wales is developing a biosecurity plan for the Pen Llŷn a'r Sarnau SAC, which includes investigating pathways of introduction and spread of INNS [101,102].

## 3. Case study 2: the socio-ecological system Falmouth harbour

The Fal and Helford SAC (Fig. 4a) primary conservation feature is a maerl bed [103] near Falmouth harbour. Maerl formed by coralline algae provide a habitat for other species (Fig. 4b), such as fish larvae and scallops. The protection removed the impact of dredging for scallops fishing on the maerl [104].

In 2004, proposals were put forward to deepen the channel to Falmouth Harbour to improve ship access to the Falmouth Marina to support local communities and their livelihoods. The port is a large employer, adding up to £90m to the local economy [105]. An environmental impact assessment was conducted by Royal Haskoning as the development of the harbour involved dredging inside the Fal and Helford SAC with potential impacts on the MPA's maerl bed (Natural [103]). Such assessment of the potential impacts on the site's protected features is mandatory in accordance with the Marine Works (Environmental Impact Assessment) Regulations 2007.

The Marine Management Organisation (MMO) as the relevant licensing body considered key impacts of the port development, including hydrodynamic and sedimentary changes decreasing sediment quality, water quality contamination from tributyltin, and loss of maerl and benthic communities [106]. Port development work has the potential to smother the maerl bed via resuspending sediment from the seabed into the water column, burying both the habitat and associated species [106]. The removal of secondary stressors like siltation of the maerl bed is critical to limiting the stress this habitat will undergo in response to increasing ocean acidification [107].

The Port of Falmouth Development initiative applied to create a deeper channel by removing 700,000 cubic meters of sediment, constructing a new berthing area and relocation of the dredged maerl substrate to the east of the navigation channel, close to the MPA. The ecological risks suggested were loss of the 3D matrix of the maerl bed, deepening the habitat beyond the light needs of the species, increase of turbidity, and increased erosion of the habitat [103]. The concerns about the scale of the impact were shared by stakeholders [108,109].

In 2013, the MMO decided that the application could not proceed as the integrity of the SAC could not be guaranteed due to potential ecological impacts and feasibility of the planned measures [110]. A maerl relocation trial was performed to alleviate the concerns, which included benthic sampling of the proposed trial sites, dredge and re-lay of dead and live maerl communities in six sites, resampling for impact assessment and turbidity monitoring which were conducted in 2013 [111]. The study concluded that this proposal is technically feasible, a finding disputed by an Independent Scientific advisory Panel (ISAP) [112]. The applicability of the assessment was challenged as the research focused on dead maerl matrixes [113] and not the live species. The case study shows that the MMO deliberated the port development against the integrity of the SAC and ensured the protection of the conservation feature of the MPA, after a lengthy consultation period.

The MMO will face future balancing between ecological and human needs for example when adapting to increasing sea level with coastal infrastructure threatening coastal MPAs. Decisions about their implementation of adaption and mitigation measures has the potential to increase the tension between conservation, energy production, fisheries, infrastructure and protecting our seascapes [21]. Future placements of climate mitigation infrastructure such as wind energy or tidal energy will pose further challenges, as these infrastructures can change the local hydrology, are steppingstones for invasive species and their construction

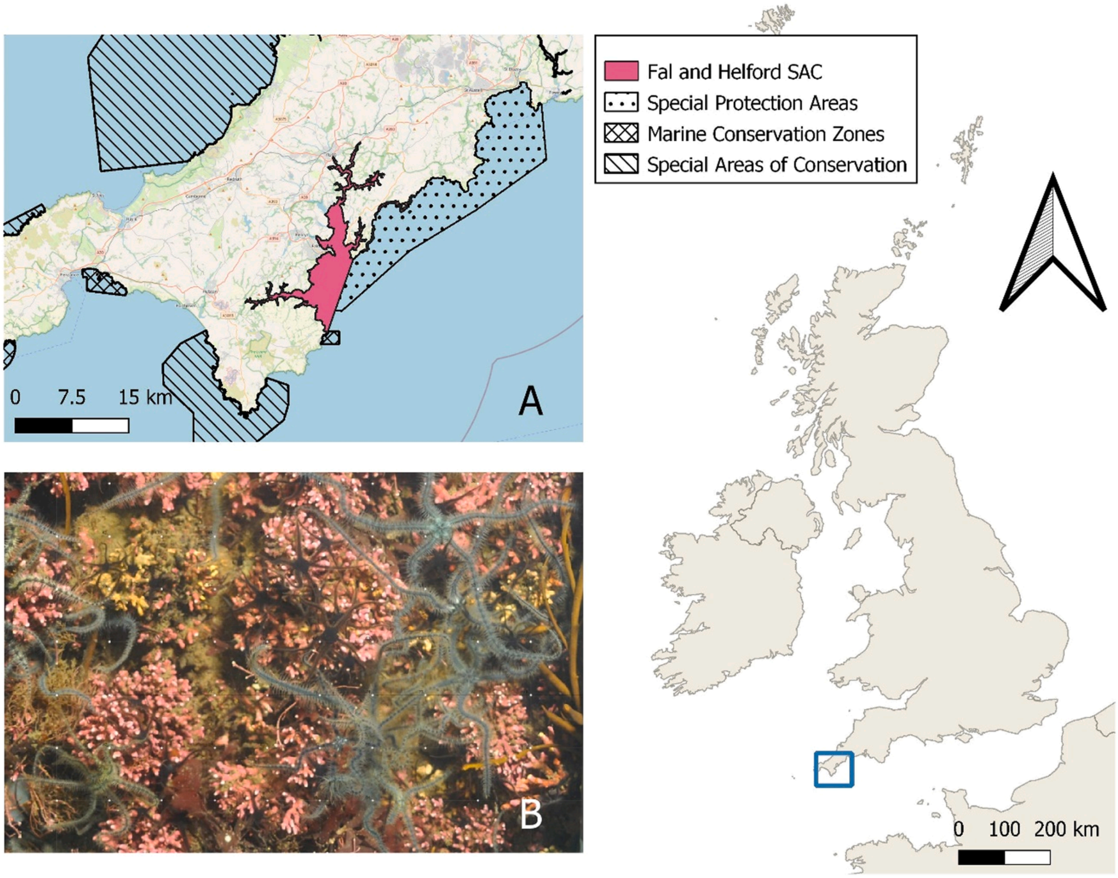

**Fig. 4.** Case study 2 location, A – Fal and Helford SAC, B – a maerl bed (photo credit: Elaine Azzopardi, Tritonia Scientific Ltd

creates a change of that habitat [21].

Derogations, i.e., exemptions from a law, both in Article 6 of the Habitats directive and in the Habitats Regulations enable different routes for essential management of the site such as Ministerial Stop Orders. This untested route could be used in relation to necessary actions to keep a site in optimum condition due to changes arising from climate change.

## 4. Moving towards a climate resilient MPA network for the UK

The feasibility and effectiveness of reducing climate change impacts on marine ecosystems depends on institutional, socio-economic, and cultural, technological, environmental, and physical boundary conditions (Singh et al., 2020). Governmental commitments through the 30 × 30 pledge and the 25 Year Environmental Plan to safeguard the UK marine environment suggest a clear political will to protect seascapes. MPAs though, defined by specific features, are challenged by the autonomous adaptation of species to climate change. As species will migrate in response to climate change, static MPAs will not be able to effectively protect individual features. For example coastal wetlands are threatened by sea level rise in the absence of ability to move inland. While data for the UK is missing, drowning of wetlands in the Dutch North Sea are expected in response to warmonger above 1.75°C [114]. The above examples show the challenges of MPAs to protect the species which were the basis of the designation. The disappearance of *M. modiolus*, a conservation feature in UK MPAs, would end the restriction of bottom contact activities such as dredging, thereby threatening wider ecosystem health. But MPAs can allow the short- or medium-term disappearance of species and retain protection while new features establish themselves, thus allowing the marine ecosystem to change into an alternative state [65].

Furthermore, less than half of UK MPAs have a management plan [115]. A management plan in this context is a formal written document specifying how a protected area is to be managed, ensuring the rules are known to all and what goals the MPA aims to accomplish. Current management plans mostly aim to maintain the status quo of their respective ecosystems, despite recognition that these were already highly degraded environments [116]. Management plans are fundamental to the success of protected areas. For example, trawling (one of the most environmentally destructive fishing practices) is higher inside European MPAs than outside partially because of inappropriate management [117]. This trawling has been suggested to have an ecological economic footprint of - £200 million over the past 25 years on just one site, the Dogger Bank MPA [118] though a government consultation proposes to ban bottom trawling from several MPAs, including Dogger Bank [119].

The current approach which focusses on keeping species conserved in a specific place should be replaced by an ecosystem-based management approach. Moving from a protection of the target feature to a protection of the total niche, the area itself and its potential new habitat in response to climate change would enable larger ecological processes [65]. To ensure representativity across the UK MPAs, JNCC have completed an assessment of the network, which identifies features that are under-represented [115]. The move to viewing MPAs as a collective network and not individual sites needs to be further embedded to ensure preparedness of climate change impacts on UK marine ecosystems. As migration occurs, species of conservation interest will transition between MPAs resulting in developmental changes to habitats [14]. The current locations of leading and trailing range edges are mostly located outside of MPAs, preventing management measures to reduce non-climatic impacts on these species.

## 5. Steps towards climate smart conservation and climate adaptive management

We emphasise that solutions are place dependent drawing on their local technical and economic feasibility, institutions, governance ecological constraints and social acceptability. Here, we use the UK's MPA network with its specificity to discuss approaches to future proof the marine environment from risks of climate change.

The UK MPA network coverage has achieved high levels of species and habitats representation [120] which provides foundations for a climate resilient future of the coastal ecosystems. While designation is ambitious, a clear gap exists between the level of protection offered to MPAs compared with what the scientific consensus outlines as necessary to safeguard marine ecosystems and promote sustainability and resilience [121]. Greater accountability is needed to ensure decisionmakers deliver on their commitments.

Higher levels of protection as showing in the UK [122,123,124] and supported by a wealth of studies globally hold the greatest potential for protecting the marine environment [1,36,64]. High levels of protection for MPAs have been shown to increase organism biomass inside reserves [125], increased organism reproductive outputs and growth rates [126], and improve a site's biodiversity [127]. Such high level of protection and associated management is rare though in UK MPAs and globally ([63,128]; Roberts et al., 2020) with lack of management planning and implementation or inappropriate activities being permitted being reported. While many MPAs limit but not exclude activities in the MPA, currently only three highly protected marine areas exist around the UK, out of 356 MPAs, covering 21.07km$^2$ (0.0024% of the UKs EEZ) [115,129] though several more are proposedly to be trailed starting 2022 [130]. What constitutes effective management is contextually dependant on each MPA, but many activities are ecologically incompatible such as trawling in areas set up to conserve benthic organisms. Effective management is seen by some synonymously with no-take MPAs (e.g., [131]) and increasing the number of no-take MPAs enhancing the current protected areas. However, even MPAs designated as no-take do not provide noticeable conservation benefits if people do not engage in its protection, local people are not engaged in their protection, and a clear management structure is lacking [132]. Protected areas must incorporate local knowledge [133], account for diverse and changing values of actors, promote equitable participation in decision making, and have efficient knowledge exchange between parties [58,134,135].

Within the context of climate change, adaptive management which refines management measures over time as scientific and cultural understanding changes is fundamental [136]. As new knowledge is generated, adaptive management uses the knowledge around protected areas and the features within them to modify MPA guidelines. Adaptive management requires the involvement of local stakeholders, scientists, and government officials cooperating in equitable forums [8,14,48,137]. In the UK between 85-95% of investigated MPAs had climate change pressures acting on conservation features including temperature increase, ocean acidification, sea level rise, and increased storminess [47]. Despite impacts being recorded, the information was not disseminated to the owners of MPAs, and subsequently not fed into management. A closer information flow between those assessing climate change impacts and stakeholder responsible for MPA management is fundamental to the success of adaptive management [134].

### 5.1. *Legal framework for climate resilient UK MPAs*

Most underlying legislation for UK marine conservation was not written with climate change in mind [72] but designed to manage existing human activities. The Habitats Directive aimed to ensure ecologically representative systems were protected increasing the coverage geographically and ecologically, although the number of marine species and habitats is not as wide as terrestrial counterparts [138]. DEFRA [139] produced guidance on the requirement to assess the impacts of anthropogenic actions preventing the landward shift of habitats responding to sea level rise, termed coastal squeeze, on SACs and SPAs to avoid loss of habitats [140]. Legislation assesses impacts of actions on individual locations; therefore, the lack of a direct link to the action which causes climate change limits the ability of the agencies to act. This problem is enhanced by the different frameworks and institutions protecting marine ecosystems [141], as overlapping organisational operational remits are common in the UK. For example, both the Marine Management Organisation and Environment Agency have operational scope for marine planning, monitoring, and fisheries management [142]. An effective protection of marine ecosystems, therefore, is dependent on established operational ownership of specific problems such as trawling [117].

Climate change and associated biodiversity loss is at the forefront of conservation thinking challenging legislation around designation, the area protected, and the flexibility in modifying these over the coming decades. Including climate change into UK marine conservation relevant legislation will depend on MPA design processes to account for the future risks of climate change [143], and consideration of existing sites and how they may respond to climate change [1]. Ecosystem-based management recognises the value in protecting ecological space that enables marine features to move throughout the UK MPA network akin to other international examples such as the Great Barrier Reef Marine Park in Australia, using the MPA as an ecological anchor point for present and future organism assemblages [65]. An integration of the aspects of marine ecosystems like hydrological, climatic, ecological, and geomorphological dimensions is the first step in considering wider environment in decision making [144]. An ecosystem-based management approach would allow the establishment of species and habitats in new areas [145]. Protecting ecological space enables MPAs to be used as steppingstones, with appropriate zoning, generating corridors for ecological transitions for example into climate refugia though it cannot avoid local extinction due to lack of suitable alternative viable habitat in alternative locations (e.g., a lack of suitable marine substrate for benthic organism) [68].

The other question arising is how long it is worth continuing protection given ongoing deterioration in response to climate change. In Case Study 2, the primary conservation feature (maerl) prevented the deepening of Falmouth Harbour but the future of the maerl bed is in question, due to ocean acidification weakening calcifying structures [16]. However, the wider geomorphological components of the MPA, e.g., the structure of the dead maerl bed, will persevere as will some of the associated ecosystem. If in the future the maerl bed deteriorates, protection of the MPA against development could not be based on the preservation of the feature. The dead structure though will still provide some biodiversity support and the lack of its protection would amplify the stress. Protecting the ecosystem itself, not a specific feature within it, grants the wider seascape the best chance to cope with climate change.

Enabling flexibility in the principal conservation feature of an MPA would enable it to protect future habitat, a key component of increasing protected area climate change resilience [145]. Such an approach would enable to respond to wider environmental change such as flexible MPA boundaries of MPAs accounting for changes in local environmental conditions [75]. Change of site boundaries under current legal frameworks are complex and time-consuming hindering adaptation to organismal adaptation. Another option could be to repurpose MPAs, changing the conservation focus from one feature to a new one should it establish itself in response to climate change caused migration (e.g., [14]). For Scottish MPAs there is evidence that stakeholders are willing to repurpose MPAs in response to climate driven ecological change, like changing the conservation focus to another marine feature to preserve existing protection arrangements agreed by stakeholders and practitioners [75].

### *5.2. Regular monitoring of protected areas*

The final question is about the balance between conservation, protection, and restoration. Climate change is happening against a backdrop of other anthropogenic impacts like overfishing and coastal development. UK seascapes have been modified heavily over the centuries by human impacts impacting the ecological baseline of UK marine ecosystems [146,147]. Conservation to preserve an old ecosystem will be questionable as it is snapshot in time and not resilient to projected environmental changes [1,10].

Highly protected marine areas are important to understand how a site responds to climate change without human inputs. Reference sites to detect the state of the system without human interference were proposed in several MPAs at the time of designation of MCZs [148] completely banning human activities. These sites were omitted from the final roll-out of MCZs in England [149]. Demonstrating that MPAs are contributing to resilience is difficult and depends on long-term monitoring to understand how the underlying biological community is changing over time and how it is responding to management practices. The UK combines some of the longest biological datasets through the continuous plankton records [150] and MarClim [55], translation of research findings via for example the MCCIPP report cards [151] and national climate projections (Lowe 2008, [78]). These high-resolution data can guide conservation strategies, supported by ground-truthing data. Otherwise, the success of MPAs is hard to determine as not only baseline assessments are missing but also quantification of the effectiveness of MPAs against their predetermined goals. To determine whether MPAs are delivering benefits monitoring of sites is needed to understand what impact the MPA is having on the seascape, and on target and non-target features. Rare studies show lags between establishment of the MPA and a change in the ecosystem health [152]. Currently, there is little recognition of MPAs and carbon ecosystem services which the lack of its inclusion in MPA management ([153]; Roberts et al. 2020) despite positive benefits between adaptation and mitigation in terrestrial forest and peat systems [154]. A financial reward of these ecosystem services and their protection could provide incentives and facilitate protection.

These above-mentioned changes to governance and management cannot wait until impacts of climate change, such as moving species, rising sea levels, and changing river fluxes have been quantified to accurately determine the size of the risk. A need for certainty about the potential size of the challenge posed by climate change will hinder action which would increase resilience of ecosystems. Warming, deoxygenation, sea level rise and acidification trends are projected to accelerate [6], all against a backdrop of continual infrastructure development [12,155] and human adaptation and mitigation needs [68]. Effectively protected MPAs limit the pressures that organisms and habitats face from climate change by removing additional disturbances, preventing detrimental synergistic impacts [35,64] and cover regions to facilitate autonomous biological adaptation [20] and speed up recovery from disturbance [36].

## Author continuations

DNS and NM designed the idea, PB provided practitioner insights, DNS and GH wrote the paper with contributions from all authors.

## NBS Impacts and Implications

### *Environmental concerns*

The impact of climate change, especially in coastal systems, interacts with non-climatic drivers, increasing vulnerability to climate change and potentially weakening ecosystem resilience. Marine protected areas (MPAs) are set up to protect seascapes, habitats, and species but have not been designed to consider ecological response to climate change.

### *Economic concerns*

Decisions about MPA implementation has the potential to increase the tension between conservation, economic consideration energy production, fisheries, infrastructure and protecting our seascapes. Protection can result in economic benefits via reducing coastal flooding and erosion or supporting carbon mitigation.

### *Social concerns*

The feasibility and effectiveness of reducing climate change impacts on marine ecosystems depends on institutional, socio-economic, and cultural, technological, environmental, and physical boundary conditions. The blue economy and nature-based solutions can address societal challenges, while providing biodiversity benefits.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

[1] A.E. Bates, R.S. Cooke, M.I. Duncan, G.J. Edgar, J.F. Bruno, L. Benedetti-Cecchi, I. M. Côté, J.S. Lefcheck, M.J. Costello, N. Barrett, T.J. Bird, Climate resilience in marine protected areas and the 'Protection Paradox, Biol. Conserv. 236 (2019) 305–314.

[2] J. Brodie, C.J. Williamson, D.A. Smale, N.A. Kamenos, N. Mieszkowska, R. Santos, M. Cunliffe, M. Steinke, C. Yesson, K.M. Anderson, V. Asnaghi, The future of the northeast Atlantic benthic flora in a high CO2 world, Ecol. Evol. 4 (13) (2014) 2787–2798.

[3] S. Cooley, D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, M. Skern-Mauritzen, Ocean and coastal ecosystems and their services, in: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, L. S, V. Möller, A. Okem, B. Rama (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel of Climate Change (IPCC), Cambridge University Press, Cambridge, UK and New York, USA, 2022 in press, https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_Chapter03.pdf.

[4] I.E. Hendriks, C.M. Duarte, M. Álvarez, Vulnerability of marine biodiversity to ocean acidification: a meta-analysis, Estuarine Coastal Shelf Sci. 86 (2) (2010) 157–164.

[5] K.M. Kleisner, M.J. Fogarty, S. McGee, J.A. Hare, S. Moret, C.T. Perretti, V. S. Saba, Marine species distribution shifts on the US Northeast Continental Shelf under continued ocean warming, Prog. Oceanogr. 153 (2017) 24–36.

[6] H.O. Pörtner, D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, IPCC Intergovernmental Panel on Climate Change, GenevaSwitzerland, 2019.

[7] A. Vergés, P.D. Steinberg, M.E. Hay, A.G. Poore, A.H. Campbell, E. Ballesteros, K. L. Heck Jr, D.J. Booth, M.A. Coleman, D.A. Feary, W. Figueira, The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts, Proc. R. Soc. B: Biol. Sci. 281 (1789) (2014), 20140846.

[8] N.L. Bindoff, W.W. Cheung, J.G. Kairo, J. Arstegui, V.A. Guinder, R. Hallberg, N. Hilmi, N. Jiao, M.S. Karim, L. Levin, S. ODonoghue, Changing ocean, marine ecosystems, and dependent communities, In: H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, (Editors), in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, 2019, Cambridge University Press, 2019, https://doi.org/10.1017/9781009157964.007. **DOI**.

[9] D. Breitburg, L.A. Levin, A. Oschlies, M. Grégoire, F.P. Chavez, D.J. Conley, V. Garçon, D. Gilbert, D. Gutiérrez, K. Isensee, G.S. Jacinto, Declining oxygen in the global ocean and coastal waters, Science 359 (6371) (2018) eaam7240.

[10] J.P. Gattuso, A. Magnan, R. Billé, W.W. Cheung, E.L. Howes, F. Joos, D. Allemand, L. Bopp, S.R. Cooley, C.M. Eakin, O. Hoegh-Guldberg, Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios, Science 349 (6243) (2015) p.aac4722.

[11] S.A. Henson, C. Beaulieu, T. Ilyina, J.G. John, M. Long, R. Séférian, J. Tjiputra, J. L. Sarmiento, Rapid emergence of climate change in environmental drivers of marine ecosystems, Nat. Commun. 8 (1) (2017) 1–9.

[12] O. Hoegh-Guldberg, D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, G. Zhou, et al., Impacts of 1.5°C of Global Warming on Natural and Human Systems, Global Warming of 1.5°C, in: V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, et al. (Eds.), An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, Cambridge Univeristy Press, 2018, 2018, https://www.ipcc.ch/sr15.

[13] J. van der Molen, J.N. Aldridge, C. Coughlan, E.R. Parker, D. Stephens, P. Ruardij, Modelling marine ecosystem response to climate change and trawling in the North Sea, Biogeochemistry 113 (1-3) (2013) 213–236.

[14] K.S. Gormley, A.D. Hull, J.S. Porter, M.C. Bell, W.G. Sanderson, Adaptive management, international co-operation and planning for marine conservation hotspots in a changing climate, Mar. Policy 53 (2015) 54–66.

[15] N. Mieszkowska, M.T. Burrows, S.J. Hawkins, H. Sudgen, Impacts of pervasive climate change and extreme events on rocky intertidal communities: evidence from long-term data, Front. Mar. Ecol. 8 (2021), 642764, https://doi.org/10.3389/fmars.2021.642764.

[16] L.A. Melbourne, M.W. Denny, R.L. Harniman, E.J. Rayfield, D.N. Schmidt, The importance of wave exposure on the structural integrity of rhodoliths, J. Exp. Mar. Biol. Ecol. 503 (2018) 109–119.

[17] F. Ragazzola, L.C. Foster, C.J. Jones, T.B. Scott, J. Fietzke, M.R. Kilburn, D. N. Schmidt, Impact of high CO 2 on the geochemistry of the coralline algae *Lithothamnion glaciale*, Sci. Rep. 6 (1) (2016) 1–9.

[18] C. Cattano, J. Claudet, P. Domenici, M. Milazzo, Living in a high CO2 world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification, Ecol. Monogr. 88 (3) (2018) 320–335.

[19] G Hoppit, DN Schmidt, A regional view of the response to climate change: a meta-analysis of European benthic organisms' responses, Front. Mar. Sci. 9 (2022), 896157, https://doi.org/10.3389/fmars.2022.896157.

[20] J.F. Bruno, A.E. Bates, C. Cacciapaglia, E.P. Pike, S.C. Amstrup, R. van Hooidonk, S.A. Henson, R.B. Aronson, Climate change threatens the world's marine protected areas, Nat. Clim. Change 8 (6) (2018) 499.

[21] B. Bednar-Friedl, R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, L. Whitmarsh, Europe, in: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, L. S, V. Möller, A. Okem, B. Rama (Eds.), Climate change 2022: Impacts, Adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel of Climate Change (IPCC), Cambridge University Press, Cambridge, UK and New York, USA, 2022 in press, https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_Chapter13.pdf.

[22] [ IPCC, in: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Eds.), Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2022 [(Editors)].

[23] C.S. Holling, Resilience and stability of ecological systems, Annu. Rev. Ecol. System. 4 (1) (1973) 1–23.

[24] T.D. Ainsworth, C.L. Hurd, R.D. Gates, P.W. Boyd, How do we overcome abrupt degradation of marine ecosystems and meet the challenge of heat waves and climate extremes? Global Change Biol. 26 (2) (2020) 343–354.

[25] J. Guest, The great barrier reef: how repeated marine heat waves are reshaping an iconic marine ecosystem, Curr. Biol. 31 (23) (2021) R1530–R1532.

[26] T. Wernberg, S. Bennett, R.C. Babcock, T. De Bettignies, K. Cure, M. Depczynski, F. Dufois, J. Fromont, C.J. Fulton, R.K. Hovey, E.S. Harvey, Climate-driven regime shift of a temperate marine ecosystem, Science 353 (6295) (2016) 169–172.

[27] J.A. Angulo-Valdés, B.G. Hatcher, A new typology of benefits derived from marine protected areas, Mar. Policy 34 (3) (2010) 635–644.

[28] F. Picone, E. Buonocore, J. Claudet, R. Chemello, G.F. Russo, P.P. Franzese, Marine protected areas overall success evaluation (MOSE): A novel integrated framework for assessing management performance and social-ecological benefits of MPAs, Ocean Coast. Manag. 198 (2020), 105370.

[29] C. Lewis, K. Clemow, W.V. Holt, Metal contamination increases the sensitivity of larvae but not gametes to ocean acidification in the polychaete Pomatoceros lamarckii (Quatrefages), Mar. Biol. 160 (8) (2013) 2089–2101.

[30] J.B. Jones, Environmental impact of trawling on the seabed: a review, N.Z. J. Mar. Freshwater Res. 26 (1) (1992) 59–67.

[31] J.S. Levy, N.C. Ban, A method for incorporating climate change modelling into marine conservation planning: an Indo-west Pacific example, Mar. Policy 38 (2013) 16–24.

[32] E. Sala, J. Mayorga, D. Bradley, R.B. Cabral, T.B. Atwood, A. Auber, W. Cheung, C. Costello, F. Ferretti, A.M. Friedlander, S.D. Gaines, Protecting the global ocean for biodiversity, food and climate, Nature 592 (7854) (2021) 397–402.

[33] D. Schmidt, P.W. Boyd, Forecast ocean variability, Nature 539 (7628) (2016) 162–163.

[34] F. Micheli, A. Saenz-Arroyo, A. Greenley, L. Vazquez, J.A.E. Montes, M. Rossetto, G.A. De Leo, Evidence that marine reserves enhance resilience to climatic impacts, PLoS One 7 (7) (2012) e40832.

[35] C.M. Roberts, B.C. O'Leary, D.J. McCauley, P.M. Cury, C.M. Duarte, J. Lubchenco, D. Pauly, A. Sáenz-Arroyo, U.R. Sumaila, R.W. Wilson, B. Worm, Marine reserves can mitigate and promote adaptation to climate change, Proc. Natl. Acad. Sci. 114 (24) (2017) 6167–6175.

[36] C. Mellin, M. Aaron MacNeil, A.J. Cheal, M.J. Emslie, M. Julian Caley, Marine protected areas increase resilience among coral reef communities, Ecol. Lett. 19 (6) (2016) 629–637.

[37] S.E. Lester, B.S. Halpern, K. Grorud-Colvert, J. Lubchenco, B.I. Ruttenberg, S. D. Gaines, S. Airamé, R.R. Warner, Biological effects within no-take marine reserves: a global synthesis, Mar. Ecol. Progress Ser. 384 (2009) 33–46.

[38] C.M. Roberts, J.A. Bohnsack, F. Gell, J.P. Hawkins, R. Goodridge, Effects of marine reserves on adjacent fisheries, Science 294 (5548) (2001) 1920–1923.

[39] M. Di Lorenzo, J. Claudet, P. Guidetti, Spillover from marine protected areas to adjacent fisheries has an ecological and a fishery component, J. Nat. Conserv. 32 (2016) 62–66.

[40] E.M. Strain, G.J. Edgar, D. Ceccarelli, R.D. Stuart-Smith, G.R. Hosack, R. J. Thomson, A global assessment of the direct and indirect benefits of marine protected areas for coral reef conservation, Divers. Distrib. 25 (1) (2019) 9–20.

[41] S. Narayan, M.W. Beck, B.G. Reguero, I.J. Losada, B. Van Wesenbeeck, N. Pontee, J.N. Sanchirico, J.C. Ingram, G.M. Lange, K.A. Burks-Copes, The effectiveness, costs and coastal protection benefits of natural and nature-based defences, PLoS One 11 (5) (2016), e0154735.

[42] T.G. Zarate-Barrera, J.H. Maldonado, Valuing blue carbon: carbon sequestration benefits provided by the marine protected areas in Colombia, PLoS One 10 (5) (2015), e0126627.

[43] N. Seddon, A. Smith, P. Smith, I. Key, A. Chausson, C. Girardin, J. House, S. Srivastava, B. Turner, Getting the message right on nature-based solutions to climate change, Glob. Change Biol. 27 (8) (2021) 1518–1546.

[44] I.K. Chung, J.H. Oak, J.A. Lee, J.A. Shin, J.G. Kim, K.S. Park, Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview, ICES J. Mar. Sci. 70 (5) (2013) 1038–1044.

[45] B.W. Griscom, J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W. H. Schlesinger, D. Shoch, J.V. Siikamäki, P. Smith, P. Woodbury, Natural climate solutions, Proc. Natl. Acad. Sci. 114 (44) (2017) 11645–11650.

[46] R.K. Unsworth, C.J. Collier, G.M. Henderson, L.J. McKenzie, Tropical seagrass meadows modify seawater carbon chemistry: implications for coral reefs impacted by ocean acidification, Environ. Res. Lett. 7 (2) (2012), 024026.

[47] B. Flavell, H. Carr, L. Robson, S. Byford, P. Chaniotis, E. Last, M. Long, L. Matear, E. Novak, Developing the evidence-base to support climate-smart decision making on MPAs, JNCC (2020). Report No. 648. JNCC, Peterborough, ISSN 0963-8091.

[48] J. Nalau, S. Becken, B. Mackey, Ecosystem-based adaptation: a review of the constraints, Environ. Sci. Policy 89 (2018) 357–364.

[49] E. Cohen-Shacham, G. Walters, C. Janzen, S. Maginnis, Nature-Based Solutions to Address Global Societal Challenges, IUCN, Gland, Switzerland, 2016, p. 97.

[50] N.J. Bennett, J. Blythe, C.S. White, C. Campero, Blue growth and blue justice: Ten risks and solutions for the ocean economy, Mar. Policy 125 (2021), 104387.

[51] N. Dudley, Guidelines for Applying Protected Area Management Categories, IUCN, 2008.

[52] M. Elliott, A. Borja, A. McQuatters-Gollop, K. Mazik, S. Birchenough, J. H. Andersen, S. Painting, M. Peck, Force majeure: will climate change affect our ability to attain Good Environmental Status for marine biodiversity? Mar. Pollut. Bull. 95 (1) (2015) 7–27.

[53] B.C. O'Leary, J.P. Copping, N. Mukherjee, S.L. Dorning, B.D. Stewart, E. McKinley, P.F. Addison, C. Williams, G. Carpenter, D. Righton, K.L. Yates, The nature and extent of evidence on methodologies for monitoring and evaluating marine spatial management measures in the UK and similar coastal waters: a systematic map, Environ. Evid. 10 (1) (2021) 1–23.

[54] U.R. Sumaila, T.C. Tai, End overfishing and increase the resilience of the ocean to climate change, Front. Mar. Sci. 7 (2020) 523.

[55] N. Mieszkowska, M.A. Kendall, S.J. Hawkins, R. Leaper, P. Williamson, N. J. Hardman-Mountford, A.J. Southward, Changes in the range of some common rocky shore species in Britain - a response to climate change? Hydrobiologia 555 (2006) 241–251, https://doi.org/10.1007/1-4020-4697-9_20.

[56] E.S. Poloczanska, C.J. Brown, W.J. Sydeman, W. Kiessling, D.S. Schoeman, P. J. Moore, K. Brander, J.F. Bruno, L.B. Buckley, M.T. Burrows, C.M. Duarte, Global imprint of climate change on marine life, Nat. Clim. Change 3 (10) (2013) 919–925.

[57] C.J. Lemieux, D.J. Scott, Changing climate, challenging choices: identifying and evaluating climate change adaptation options for protected areas management in Ontario, Canada, Environ. Manage. 48 (4) (2011) 675.

[58] D.N. Schmidt, M. Pieraccini, L. Evans, Marine protected areas in the context of climate change: key challenges for coastal socio-ecological systems, Phil. Trans. R. Soc. B. 377 (1854) (2022), https://doi.org/10.1098/rstb.2021.0131.

[59] IPBES, The regional assessment report on biodiversity and ecosystem services for Europe and Central Asia, in: M. Rounsevell, M. Fischer, A. Torre-Marin Rando, A. Mader (Eds.), IPBES Secretariat, Bonn, Germany, 2018, p. 892.

[60] A.L. Perry, J. Blanco, N. Fournier, S. Garcia, P. Marín, Unmanaged = Unprotected: Europe's Marine Paper Parks. Oceana, Brussels, 2020, p. 52.

[61] M.J. Costello, B. Ballantine, Biodiversity conservation should focus on no-take Marine Reserves: 94% of Marine Protected Areas allow fishing, Trends Ecol. Evol. 30 (9) (2015) 507–509.

[62] J.W. Turnbull, E.L. Johnston, G.F. Clark, Evaluating the social and ecological effectiveness of partially protected marine areas, Conserv. Biol. 35 (3) (2021) 921–932.

[63] A.N. Rife, B. Erisman, A. Sanchez, O. Aburto-Oropeza, When good intentions are not enough. Insights on networks of "paper park" marine protected areas, Conserv. Lett. 6 (3) (2013) 200–212.

[64] S.L. Maxwell, V. Cazalis, N. Dudley, M. Hoffmann, A.S. Rodrigues, S. Stolton, P. Visconti, S. Woodley, N. Kingston, E. Lewis, M. Maron, Area-based conservation in the twenty-first century, Nature 586 (7828) (2020) 217–227.

[65] D.P. Tittensor, M. Beger, K. Boerder, D.G. Boyce, R.D. Cavanagh, A. Cosandey-Godin, G.O. Crespo, D.C. Dunn, W. Ghiffary, S.M. Grant, L. Hannah, Integrating climate adaptation and biodiversity conservation in the global ocean, Sci. Adv. 5 (11) (2019) eaay9969.

[66] S.K. Pikesley, J.-L. Solandt, C. Trundle, M.J. Witt, Benefits beyond 'features': Cooperative monitoring highlights MPA value for enhanced seabed integrity, Mar. Policy 134 (2021), 104801, https://doi.org/10.1016/j.marpol.2021.104801.

[67] A.D. Olds, K.A. Pitt, P.S. Maxwell, R.M. Connolly, Synergistic effects of reserves and connectivity on ecological resilience, J. Appl. Ecol. 49 (6) (2012) 1195–1203.

[68] H.-O. Pörtner, D.C. Roberts, H. Adams, I. Adelekan, C. Adler, R. Adrian, P. Aldunce, E. Ali, R. Ara Begum, B. Bednar-Friedl, R. Bezner Kerr, R. Biesbroek, J. Birkmann, K. Bowen, M.A. Caretta, J. Carnicer, E. Castellanos, T.S. Cheong, W. Chow, G. Cissé, S. Clayton, A. Constable, S. Cooley, M.J. Costello, M. Craig, W. Cramer, R. Dawson, D. Dodman, J. Efitre, M. Garschagen, E.A. Gilmore, B. Glavovic, D. Gutzler, M. Haasnoot, S. Harper, T. Hasegawa, B. Hayward, J. A. Hicke, Y. Hirabayashi, C. Huang, K. Kalaba, W. Kiessling, A. Kitoh, R. Lasco, J. Lawrence, M.F. Lemos, R. Lempert, C. Lennard, D. Ley, T. Lissner, Q. Liu, E. Liwenga, S. Lluch-Cota, S. Löschke, S. Lucatello, Y. Luo, B. Mackey, K. Mintenbeck, A. Mirzabaev, V. Möller, M. Moncassim Vale, M.D. Morecroft, L. Mortsch, A. Mukherji, T. Mustonen, M. Mycoo, J. Nalau, M. New, A. Okem, J. P. Ometto, B. O'Neill, R. Pandey, C. Parmesan, M. Pelling, P.F. Pinho, J. Pinnegar, E.S. Poloczanska, A. Prakash, B. Preston, M.-F. Racault, D. Reckien, A. Revi, S. K. Rose, E.L.F. Schipper, D.N. Schmidt, D. Schoeman, R. Shaw, N.P. Simpson, C. Singh, W. Solecki, L. Stringer, E. Totin, C.H. Trisos, Y. Trisurat, M. van Aalst, D. Viner, M. Wairu, R. Warren, P. Wester, D. Wrathall, Z. Zaiton Ibrahim, Technical Summary [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In:. *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. In Press, 2022 [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)], https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_TechnicalSummary.pdf.

[69] A.C. Balbar, A. Metaxas, The current application of ecological connectivity in the design of marine protected areas, Glob. Ecol. Conserv. 17 (2019) e00569.

[70] M.R. Christie, B.N. Tissot, M.A. Albins, J.P. Beets, Y. Jia, D.M. Ortiz, S. E. Thompson, M.A. Hixon, Larval connectivity in an effective network of marine protected areas, PLoS One 5 (12) (2010) e15715.

[71] M.G. Hoskin, R.A. Coleman, E. Von Carlshausen, C.M. Davis, Variable population responses by large decapod crustaceans to the establishment of a temperate marine no-take zone, Can. J. Fish. Aquat.Sci. 68 (2) (2011) 185–200.

[72] M. Frost, G. Bayliss-Brown, P. Buckley, M. Cox, S.R. Dye, W.G. Sanderson, B. Stoker, N. Withers Harvey, A review of climate change and the implementation of marine biodiversity legislation in the United Kingdom, Aquat. Conserv.: Mar. Freshw. Ecosyst. 26 (3) (2016) 576–595.

[73] JNCC 2022, Available at: https://jncc.gov.uk/our-work/uk-marine-protected-area-network-statistics/. Accessed 18/3/2022.

[74] D.E. Johnson, S.E. Rees, D. Diz, P.J. Jones, C. Roberts, C. Barrio Froján, Securing effective and equitable coverage of marine protected areas: The UK's progress towards achieving convention on biological diversity commitments and lessons learned for the way forward, Aquat. Conserv.: Mar. Freshw. Ecosyst. 29 (2019) 181–194.

[75] C.R. Hopkins, D.M. Bailey, T. Potts, Navigating future uncertainty in marine protected area governance: Lessons from the Scottish MPA network, Estuar. Coastal Shelf Sci. 207 (2018) 303–311.

[76] C. Ostle, P. Willliamson, Y. Artioli, D.C. Bakker, S.N.R. Birchenough, C.E. Davis, S. Dye, M. Edwards, H.S. Findlay, N. Greenwood, S. Hartman, Carbon dioxide and ocean acidification observations in UK waters, Synth. Rep. Focus (2016) 2010–2015.

[77] J. Tinker, E. Howes, S. Wakelin, M. Menary, E. Kent, D.I. Berry, J. Hindson, J. Ribeiro, S. Dye, O. Andres, K. Lyons, The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK, MCCIP Sci. Rev. 2020 (2020) 1–30.

[78] J.A. Lowe, D. Bernie, P. Bett, L. Bricheno, S. Brown, D. Calvert, R. Clark, K. Eagle, T. Edwards, G. Fosser, F. Fung, UKCP18 Science Overview Report, Met Office Hadley Centre, Exeter, UK, 2018.

[79] G. Beaugrand, F. Ibanez, Monitoring marine plankton ecosystems. II: Long-term changes in North Sea calanoid copepods in relation to hydro-climatic variability, Mar. Ecol. Progress Ser. 284 (2004) 35–47.

[80] S.D. Simpson, S. Jennings, M.P. Johnson, J.L. Blanchard, P.J. Schön, D.W. Sims, M.J. Genner, Continental shelf-wide response of a fish assemblage to rapid warming of the sea, Curr. Biol. 21 (18) (2011) 1565–1570.

[81] N. Mieszkowska, H. Sugden, Climate-driven range shifts within benthic habitats across a marine biogeographic transition zone, Adv. Ecol. Res. 55 (2016) 325–369, https://doi.org/10.1016/bs.aecr.2016.08.007.

[82] M.T. Burrows, S.J. Hawkins, J.J. Moore, L. Adams, H. Sugden, L. Firth, N. Mieszkowska, Global-scale species distributions predict temperature-related changes in species composition of rocky shore communities in Britain, Glob. Change Biol. 26 (4) (2020) 2093–2105.

[83] C. Yesson, L.E. Bush, A.J. Davies, C.A. Maggs, J. Brodie, Large brown seaweeds of the British Isles: evidence of changes in abundance over four decades, Estuar. Coast. Shelf Sci. 155 (2015) 167–175.

[84] K.S. Gormley, J.S. Porter, M.C. Bell, A.D. Hull, W.G. Sanderson, Predictive habitat modelling as a tool to assess the change in distribution and extent of an OSPAR priority habitat under an increased ocean temperature scenario: consequences for marine protected area networks and management, PLoS One 8 (7) (2013).

[85] F. Ragazzola, L.C. Foster, A.U. Form, J. Büscher, T.H. Hansteen, J. Fietzke, Phenotypic plasticity of coralline algae in a high CO 2 world, Ecol. Evol. 3 (10) (2013) 3436–3446.

[86] W.F. Farnham, R.L. Fletcher, Irvine, Attached Sargassum found in Britain, Nature 243 (5404) (1973) 231–232.

[87] S. Le Cam, F. Viard, C. Daguin-Théibaut, S. Bouchemousse, N. Mieszkowska, A Engelen, A genome-wide investigation of the worldwide invader *Sargassum muticum* shows high success albeit (almost) no genetic diversity, Evolut. Appl. (2019), https://doi.org/10.1111/eva.12837.

[88] D.A. Smale, T. Wernberg, A.L. Yunnie, T. Vance, The rise of Laminaria ochroleuca in the Western English Channel (UK) and comparisons with its competitor and assemblage dominant Laminaria hyperborea, Mar. Ecol. 36 (4) (2015) 1033–1044.

[89] S. Krueger-Hadfield, C.L. Magill, F.S.P.D. Bunker, N. Mieszkowska, E.E. Sotka, C. A. Maggs, When invaders go unnoticed: the case of *Gracilaria vermiculophylla* in the British Isles, Cryoptogamie Algol. 38 (2017) 1–22, https://doi.org/10.7872/crya/v38.iss4.2017.379.

[90] B. Gallardo, D.C. Aldridge, P. González-Moreno, J. Pergl, M. Pizarro, P. Pyšek, W. Thuiller, C. Yesson, M. Vilà, Protected areas offer refuge from invasive species spreading under climate change, Glob. Change Biol. 23 (12) (2017) 5331–5343.

[91] J. Atkinson, N.G. King, S.B. Wilmes, P.J. Moore, Summer and winter marine heatwaves favor an invasive over native seaweeds, J. Phycol. 56 (6) (2020) 1591–1600.

[92] F. Gazeau, C. Quiblier, J.M. Jansen, J.P. Gattuso, J.J. Middelburg, C.H. Heip, Impact of elevated CO2 on shellfish calcification, Geophys. Res. Lett. (7) (2007) 34.

[93] E. Rinde, T. Tjomsland, D.Ø. Hjermann, M. Kempa, P. Norling, V.S. Kolluru, Increased spreading potential of the invasive Pacific oyster (Crassostrea gigas) at its northern distribution limit in Europe due to warmer climate, Mar. Freshwater Res. 68 (2) (2016) 252–262.

[94] T.S. Fristoe, M. Chytrý, W. Dawson, F. Essl, R. Heleno, H. Kreft, N. Maurel, J. Pergl, P. Pyšek, H. Seebens, P. Weigelt, Dimensions of invasiveness: Links between local abundance, geographic range size, and habitat breadth in Europe's alien and native floras, Proc. Natl. Acad. Sci. 118 (22) (2021), e2021173118.

[95] JNCC 2015. Natura, Standard Data Form, 2000. https://jncc.gov.uk/jncc-assets/SAC-N2K/UK0013117.pdf.

[96] H.E. Roy, C.D. Preston, C.A. Harrower, SL Rorke, D. Noble, J. Sewell, K. Walker, J. Marchant, B. Seeley, J. Bishop, A. Jukes, A. Musgrove, D Pearman, O Booy, GB non-native species information portal: documenting the arrival of non-native species in Britain, Biol. Invasions 16 (2014) 2495–2505, https://doi.org/10.1007/s10530-014-0687-0.

[97] Welsh Government. 2018. https://gov.wales/sites/default/files/publications/2018-02/invasive-aquatic-species-priority-marine-species.pdf.

[98] J. Martínez-Lüscher, M. Holmer, Potential effects of the invasive species *Gracilaria vermiculophylla* on *Zostera marina* metabolism and survival, Mar. Environ. Res. 69 (5) (2010) 345–349.

[99] H. Höffle, M.S. Thomsen, M. Holmer, High mortality of Zostera marina under high temperature regimes but minor effects of the invasive macroalgae Gracilaria vermiculophylla, Estuar. Coastal Shelf Sci. 92 (1) (2011) 35–46.

[100] M.R. Phillips, A.L. Jones, T. Thomas, Climate change, coastal management and acceptable risk: consequences for tourism, J. Coastal Res. 85 (10085) (2018) 1411–1415.

[101] N. Dewey, K Pack, D Williamson, A. Walsh, Welsh Marine Invasive Non-Native Pathways Assessment NRW Evidence Report No: 459, Natural Resources Wales, Bangor, 2020, p. 105, pp.

[102] Welsh Government., Wales Marine Action and Advisory group, Marine User Stakeholder Update, 2019. https://gov.wales/wales-marine-action-and-advisory-group-wmaag-stakeholder-update-may-2019.

[103] Natural England., Application for Capital Dredge and Replacement of maerl, Falmouth Harbour, 2009. Available at, https://webarchive.nationalarchives.gov.uk/20140305122028/http:/www.marinemanagement.org.uk/licensing/public_register/cases/documents/falmouth/ne_comments.pdf.

[104] J.M. Hall-Spencer, P.G. Moore, Impact of scallop dredging on maerl grounds. *Effects of fishing on non-target species and habitats: biological, conservation and socio-economic issues*, Blackwell Sci., Oxf. (2000) 105–118.

[105] Falmouth EIA Final Report., 2015., Accessed 08/09/2020. Available at: https://planforfalmouth.info/wp-content/uploads/2016/12/Penryn-River-Study-EIA-Final-Report_Redacted-PUBLIC-RELEASE-2-1.pdf-1.pdf.

[106] MMO, Falmouth harbour commissioners and falmouth docks & engineering company application decision process, Available at:. Evidence summary: Falmouth Harbour Commissioners and Falmouth Docks & Engineering Company application decision process, 2010 nationalarchives.gov.uk.

[107] F. Noisette, H. Egilsdottir, D. Davoult, S. Martin, Physiological responses of three temperate coralline algae from contrasting habitats to near-future ocean acidification, J. Exp. Mar. Biol. Ecol. 448 (2013) 179–187.

[108] CEFAS, Application by Falmouth Harbour Commissioners and Falmouth Docks and Engineering Company for Works Associated with the Port of Falmouth Development Initiative at Falmouth, Cornwall, 2010. Available at: https://webarchive.nationalarchives.gov.uk/20140305122025/http:/www.marinemanagement.org.uk/licensing/public_register/cases/documents/falmouth/cefas_comments.pdf.

[109] Cornwall Sea Fisheries, Application for the Disposal of Capital Dredged Material from Falmouth Harbour, maerl disposal and seabed mitigation, Falmouth, Cornwall, 2009. Available at, https://webarchive.nationalarchives.gov.uk/20140305122030/http:/www.marinemanagement.org.uk/licensing/public_register/cases/documents/falmouth/csfc_comments.pdf.

[110] MMO., Falmouth Harbour Construction Works, Capital Dredge and Maerl Mitigation Scheme, 2014. Available at, https://webarchive.nationalarchives.gov.uk/20140305103910/http://www.marinemanagement.org.uk/licensing/public_register/cases/falmouth.htm.

[111] E.V. Sheehan, D. Bridger, S.L. Cousens, M.J. Attrill, An Experimental Trial to Assess the Impact of Removing and Replacing the top 30cm of Maerl Habitat within the Fal Estuary Planned Dredge Area, Marine Institute Plymouth University, 2014. Final Report, January 201440 pp + Appendices.

[112] ISAP, Proposed Falmouth Bay maerl translocation trial, 2014. Available at, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/332244/140303-isapreport.pdf.

[113] E.V. Sheehan, D. Bridger, S.L. Cousens, M.J. Attrill, Testing the resilience of dead maerl infaunal assemblages to the experimental removal and re-lay of habitat, Mar. Ecol. Progress Ser. 535 (2015) 117–128.

[114] A.J. van der Spek, The development of the tidal basins in the Dutch Wadden Sea until 2100: the impact of accelerated sea-level rise and subsidence on their sediment budget–a synthesis, Neth. J. Geosci. 97 (3) (2018) 71–78.

[115] JNCC 2020, Available at: https://jncc.gov.uk/our-work/mpa-network-assessments/. Accessed 14/04/2022.

[116] A.A. Plumeridge, C.M. Roberts, Conservation targets in marine protected area management suffer from shifting baseline syndrome: A case study on the Dogger Bank, Mar. Pollut. Bull. 116 (1-2) (2017) 395–404.

[117] M. Dureuil, K. Boerder, K.A. Burnett, R. Froese, B. Worm, Elevated trawling inside protected areas undermines conservation outcomes in a global fishing hot spot, Science 362 (6421) (2018) 1403–1407.

[118] Marine Conservation Society., Marine Unprotected Areas, 2021. Available at, https://www.mcsuk.org/media/marine-unprotected-areas-summary-report.pdf.

[119] DEFRA, Next phase of Government's Ambitious Blue Belt Underway with MMO Consultation Launch, 2021. Available at, https://deframedia.blog.gov.uk/2021/02/02/next-phase-of-governments-ambitious-blue-belt-underway-with-mmo-consultation-launch/.

[120] S. Ware, A.L. Downie, Challenges of habitat mapping to inform marine protected area (MPA) designation and monitoring: an operational perspective, Mar. Policy 111 (2020), 103717.

[121] S.E. Rees, E.V. Sheehan, B.D. Stewart, R. Clark, T. Appleby, M.J. Attrill, P. J. Jones, D. Johnson, N. Bradshaw, S. Pittman, J. Oates, Emerging themes to support ambitious UK marine biodiversity conservation, Mar. Policy 117 (2020), 103864.

[122] S.K. Pikesley, B.J. Godley, H. Latham, P.B. Richardson, L.M. Robson, J.L. Solandt, C. Trundle, C. Wood, M.J. Witt, Pink sea fans (Eunicella verrucosa) as indicators of the spatial efficacy of Marine Protected Areas in southwest UK coastal waters, Mar. Policy 64 (2016) 38–45.

[123] S.E. Rees, M.J. Attrill, M.C. Austen, S.C. Mangi, J.P. Richards, L.D. Rodwell, Is there a win–win scenario for marine nature conservation? A case study of Lyme Bay, England, Ocean Coast. Manag. 53 (3) (2010) 135–145.

[124] B.D. Stewart, L.M. Howarth, H. Wood, K. Whiteside, W. Carney, É. Crimmins, B. C. O'Leary, J.P. Hawkins, C.M. Roberts, Marine conservation begins at home: how a local community and protection of a small bay sent waves of change around the UK and beyond, Front. Mar. Sci. 7 (2020) 76.

[125] N.T. Shears, R.V. Grace, N.R. Usmar, V. Kerr, R.C. Babcock, Long-term trends in lobster populations in a partially protected vs. no-take Marine Park, Biol. Conserv. 132 (2) (2006) 222–231.

[126] A.B. Florin, U. Bergström, D. Ustups, K. Lundström, P.R. Jonsson, Effects of a large northern European no-take zone on flatfish populations, J. Fish Biol. 83 (4) (2013) 939–962.

[127] L.M. Howarth, S.E. Pickup, L.E. Evans, T.J. Cross, J.P. Hawkins, C.M. Roberts, B. D. Stewart, Sessile and mobile components of a benthic ecosystem display mixed trends within a temperate marine reserve, Mar. Environ. Res. 107 (2015) 8–23.

[128] G.J. Edgar, R.D. Stuart-Smith, T.J. Willis, S. Kininmonth, S.C. Baker, S. Banks, N. S. Barrett, M.A. Becerro, A.T. Bernard, J. Berkhout, C.D. Buxton, Global conservation outcomes depend on marine protected areas with five key features, Nature 506 (7487) (2014) 216–220.

[129] J.L. Solandt, A stocktake of England's MPA network–taking a global perspective approach, Biodivers. 19 (1-2) (2018) 34–41.

[130] DEFRA, Government Response to the Highly Protected Marine Areas (HPMAs) review, 2022. Available at, https://www.gov.uk/government/publications/government-response-to-the-highly-protected-marine-areas-hpmas-review/government-response-to-the-highly-protected-marine-areas-hpmas-review. Accessed 29/03/2022.

[131] B.J. Bergseth, Effective marine protected areas require a sea change in compliance management, ICES J. Mar. Sci. 75 (3) (2018) 1178–1180.

[132] G. Halkos, S. Matsiori, Environmental attitude, motivations and values for marine biodiversity protection, J. Behav. Exp. Econ. 69 (2017) 61–70.

[133] T.F. Thornton, A.M. Scheer, Collaborative engagement of local and traditional knowledge and science in marine environments: a review, Ecol. Soc. 17 (3) (2012).

[134] C.N. Cook, E.A. Beever, L.L. Thurman, L.M. Thompson, J.E. Gross, A.R. Whiteley, A.B. Nicotra, J.A. Szymanski, C.A. Botero, K.R. Hall, A.A. Hoffmann, Supporting the adaptive capacity of species through more effective knowledge exchange with conservation practitioners, Evolut. Appl. 14 (8) (2021) 1969–1979.

[135] M. Pieraccini, Rethinking participation in environmental decision-making: epistemologies of marine conservation in South-East England, J. Environ. Law 27 (1) (2015) 45–67.

[136] E.L. Tompkins, W.N. Adger, Does adaptive management of natural resources enhance resilience to climate change? Ecol. Soc. 9 (2) (2004).

[137] E. Azzurro, V. Sbragaglia, J. Cerri, M. Bariche, L. Bolognini, J. Ben Souissi, G. Busoni, S. Coco, A. Chryssanthi, E. Fanelli, R. Ghanem, Climate change, biological invasions, and the shifting distribution of Mediterranean fishes: a large-scale survey based on local ecological knowledge, Global Change Biol. 25 (8) (2019) 2779–2792.

[138] M. Davis, S. Naumann, K. McFarland, A. Graf, D. Evans, Literature Review: the ecological effectiveness of the Natura 2000 network, ETC/BD Rep. EEA (2014) 30.

[139] DEFRA, Coastal squeeze implications for flood management - the requirements of the European birds and habitats directives, Defra Policy Guidance (2005).

[140] J. Oaten, A. Brooks, N. Frost, Coastal Squeeze Evidence and Monitoring Requirement Review. NRW Report No: 307, Natural Resources Wales, Cardiff, 2018, p. 188, pp.

[141] S.J. Boyes, M. Elliott, Marine legislation–The ultimate 'horrendogram': International law, European directives & national implementation, Mar. Pollut. Bull. 86 (1-2) (2014) 39–47.

[142] S.J. Boyes, M. Elliott, The excessive complexity of national marine governance systems–Has this decreased in England since the introduction of the Marine and Coastal Access Act 2009? Mar. Policy 51 (2015) 57–65.

[143] C.R. Hopkins, D.M. Bailey, T. Potts, Perceptions of practitioners: managing marine protected areas for climate change resilience, Ocean Coast. Manag. 128 (2016) 18–28.

[144] R. Sardá, S. Requena, C. Dominguez-Carrió, J.M. Gili, Ecosystem-based management for marine protected areas: a systematic approach, Manag. Mar. Protect. Areas: Netw. Perspect. (2017) 145–162.

[145] K.L. Wilson, D.P. Tittensor, B. Worm, H.K. Lotze, Incorporating climate change adaptation into marine protected area planning, Glob. Change Biol. (2020).

[146] L.A. Robinson, C.L. Frid, Historical marine ecology: examining the role of fisheries in changes in North Sea benthos, AMBIO: J. Hum. Environ. 37 (5) (2008) 362–372.

[147] R.H. Thurstan, C.M. Roberts, Ecological meltdown in the Firth of Clyde, Scotland: two centuries of change in a coastal marine ecosystem, PLoS One 5 (7) (2010) e11767.

[148] L.M. Lieberknecht, T.E.J. Hooper, T.M. Mullier, A. Murphy, M. Neilly, H. Carr, R. Haines, S. Lewin, E. Hughes, Finding Sanctuary final report and recommendations, in: A Report Submitted by the Finding Sanctuary Stakeholder project to Defra, the Joint Nature Conservation Committee and Natural England, 2011, p. 13.

[149] E.M. De Santo, Assessing public "participation" in environmental decision-making: lessons learned from the UK Marine Conservation Zone (MCZ) site selection process, Mar. Policy 64 (2016) 91–101.

[150] S.D. Batten, R. Abu-Alhaija, S. Chiba, M. Edwards, G. Graham, R. Jyothibabu, J. A. Kitchener, P. Koubbi, A. McQuatters-Gollop, E. Muxagata, C. Ostle, A global plankton diversity monitoring program, Front. Mar. Sci. 6 (2019) 321.

[151] N. Mieszkowska, M. Burrows, H. Sugden, Impacts of climate change on intertidal habitats relevant to the coastal and marine environment around the UK, MCCIP Sci. Rev. 2020 (2020) 256–271.

[152] E.R. Selig, J.F. Bruno, A global analysis of the effectiveness of marine protected areas in preventing coral loss, PLoS One 5 (2) (2010).

[153] L.M. Brander, P. Van Beukering, L. Nijsten, A. McVittie, C. Baulcomb, F.V. Eppink, J.A.C. van der Lelij, The global costs and benefits of expanding Marine Protected Areas, Mar. Policy 116 (2020), 103953.

[154] J.M. Melillo, X. Lu, D.W. Kicklighter, J.M. Reilly, Y. Cai, A.P. Sokolov, Protected areas' role in climate-change mitigation, Ambio 45 (2) (2016) 133–145.

[155] A.T. Williams, N. Rangel-Buitrago, E. Pranzini, G. Anfuso, The management of coastal erosion, Ocean Coast. Manag. 156 (2018) 4–20.