

Supplementary Information I - Examples of climate-ready MPA approaches

Dimension	Climate-Ready Focus	MPA Case & Practices	References
Ecological Design	Robust spatial planning for climate resilience	California MPA Network (USA): • Designed for species persistence and ecological connectivity under climate variability • Uses habitat compression modelling, oceanographic layers, species distribution forecasts • MPAs are replicated across thermal gradients to buffer ecosystem loss (climate refugia targeting)	<i>Sullivan-Stack et al. (2022)</i> ; Arafteh-Dalmau et al. (2017); <i>Hofmann et al. (2021)</i>
Socio-Economic + Knowledge Integration	Equitable co-management; support local livelihoods, co-design & integration of local knowledge	Natural Marine Parks in Portugal • Participatory governance: small-scale fishers involved in planning • Traditional ecological knowledge integrated into zoning • Eco-tourism and biodiversity goals co-aligned with local economy • Proposed and co-designed by local community • Co-produce zoning and associated regulations	<i>Vasconcelos et al. (2013)</i> ; <i>Horta E Costa et al. (2022)</i> ; <i>Rangel et al. (2025)</i>
Governance Adaptability	Polycentric, responsive institutions	Great Barrier Reef Marine Park (Australia): • Rapid responses post-bleaching: dynamic zoning • Coral health index & real-time reef monitoring feed decisions • Cross-sector coordination involving fisheries, tourism, science	<i>Barnes et al. (2022)</i> ; <i>McLeod et al. (2022)</i> ; <i>Fidemann et al. (2019)</i> ; <i>Vella et al. (2025)</i>
Monitoring & Early Warning	Integrated, climate-informed monitoring	Mediterranean MPA Networks (MedPAN): • Regionally standardized climate metrics • Coordinated climate indicators (e.g. SST anomalies, invasive species) • Tiered alert system for thermal stress events • Early detection protocols for species shifts • Climate monitoring manual adopted across 30+ MPAs	<i>Otero del Mar et al. (2013)</i> ; <i>Garrabou et al. (2022)</i> ; <i>Pulido Mantas et al. (2024)</i>

Examples of climate-ready approaches in selected MPAs worldwide, showing key dimensions, practical actions, and supporting references. The table highlights strategies for ecological design, governance, monitoring, and knowledge integration that enhance MPA resilience under climate change.

Supplementary Information II - Insights of selected EU projects for climate-ready MPAs

Project	Objective(s)	Key focus areas	Relevance to climate-ready MPAs	Outputs & Findings
Future MARES (09/2020 – 08/2024, funded under EU Horizon 2020, Grant Agreement ID: 101000771), project link	- Provide socially and economically viable actions, strategies and nature-based solutions (NbS) for climate change adaptation and mitigation to safeguard future biodiversity and ecosystem functions and maximize natural capital to deliver ecosystem services from marine and transitional ecosystems. Specifically: - assessing the role of NbS in reducing climate risks to marine habitats and ecosystem services - understanding ecological functions, - identifying climate change hotspots, - assessing socio-ecological vulnerabilities, - conducting economic evaluations of adaptation strategies.	Restoration: Restoring habitat-forming species that act as 'climate rescuers,' buffering coastal habitats from negative climate change effects, improving seawater quality, and sequestering carbon Conservation: Implementing conservation actions that consider the impacts of climate change and other hazards on habitat suitability to preserve the integrity of food webs and protect endangered species, including the establishment and management of MPAs Nature-inclusive harvesting: Promoting sustainable, ecosystem-based harvesting practices (both capture and culture) of seafood to ensure the resilience of marine ecosystems under changing climatic conditions	Contributions through development of socially and economically viable strategies for climate adaptation and mitigation, targeted spatial planning and adaptive management tools. Projections of the distribution and productivity of marine species and habitats in climate futures highlighting important areas for decision-makers and managers to consider designating as new MPAs. Emphasis on dynamic conservation strategies: - identifying and protecting climate refugia, seagrass meadows, and ecologically connected areas critical for species adaptation. The project provides evidence that NbS enhance MPA resilience to climate stressors and demonstrated the benefits of proactive, climate-adaptive MPA management across European marine regions.	Statistically downscaled climate projections (CMIP6) tailored to European marine ecosystems, highlighting climate exposure and marine biodiversity's climate sensitivity, supporting precise spatial planning for climate resilience. Digital Laboratories, including a decision-support tool integrating ecological risk assessments and spatial modelling to NbS effectiveness under different management scenarios, aiding precise spatial planning for climate resilience. Bright Spot Mapping: Maps identifying areas with most potential for successful, climate-smart NbS interventions ('brightspots') co-located with activities of other marine sectors (energy, shipping, fishing) and users. A Climate-resilient Path for Ireland's Marine Protected Areas Network

MSP4BIO (08/2022 – 07/2025, funded under EU Horizon 2020, Grant Agreement ID: 101060707), project link	- Support implementation of EU Biodiversity Strategy 2030, Convention on Biological Diversity Post-2020 Global Biodiversity Framework, and EU Green Deal, by mainstreaming biodiversity into policy decisions on different governance levels. - Develop an integrated socio-ecological management of marine ecosystems to focus on better integrating MSPs and MPAs.	Development of integrative tools for MPA and MSP science-based planning: - Ecological-socio-economic (ESE) framework for management priorities emerging from diverse test sites of the project to address different conservation targets – e.g., from species to ecosystem diagnoses and policy implementation, covering the whole process from MPA/MSP planning to designation and monitoring design.	Climate-smart guidance: - ESE framework offers structured guidance to help managers and modelers incorporate climate change (CC) scenarios into MPA planning within MSP, using multi-scale, scenario-based approach. - Guidance includes activities to 1) reframe management issues through a climate lens, 2) select appropriate analyses using risk assessment, and 3) translate outputs into actionable management strategies. Knowledge co-production: emphasizes collaborative analysis & decision-making by engaging managers & stakeholders throughout processes. Climate-related criteria: updated by decision making knowledge & integrate ecological and socio-economic factors in the ESE model including three key criteria 1) Vulnerability 2) Stability 3) Climate-smart potential Flexible application (operational research): addresses diverse management questions across various spatial & temporal contexts, adapting to different conservation goals & CC incorporation levels	ESE Model: - Provides step-by-step guidance supporting planning teams to build most up-to-date framework answering and translating management questions into operational approaches. - three main modules which address three components of decision-making processes: 1) ecological considerations of climate-induced and other environmental changes with the ESE1, 2) criteria for the representation of the social and economic dimension of MPAs with the ESE2, 3) considerations and trade-offs with respect to a nature-inclusive operation of the blue economy sector with the ESE3. - includes review of related methodologies, decision-support tools and policy solutions available to answer management issues. - aims to provide integrative approach to management questions through connections between decision-scales and criteria from different scientific realms.
MPA4Change (01/2024 – 03/2026, funded under Interreg Euro-MED, Project ID: Euro-MED0200736), project link	- Improve Mediterranean coastal area resilience & support sustainable use of marine ecosystems - Enhance the role of MPAs & restoration as NbS for climate change adaptation - Align with EU Biodiversity Strategy & builds on previous Interreg Euro-MED projects	Capacity building: - Promoting & refining tools for risk assessment, monitoring, data sharing, restoration, citizen science, participatory approaches, & development of adaptation action plans to strengthen MPA management. Policy engagement: - Supporting policy dialogue and coordinating with EU, Mediterranean, and global	Development of practical tools, ongoing expert support, strategic engagement to ensure Mediterranean MPAs effectively advance climate adaptation & biodiversity conservation at regional scales. Creation of joint action plan for Mediterranean MPAs to enhance long-term sustainability and capacity to adapt to climate change	

	- Policy engagement at Mediterranean and European scales through targeted capacity-building & establishment of expert roster for sustained guidance - Urgency response to ecological impacts such as mass mortality events, invasive species expansion, and biodiversity loss (MedECC, 2020; Garrabou et al., 2022).	Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP) strategies to integrate climate adaptation measures into broader policy frameworks. - Establishing expert roster to operationalize implementation of policies and tools, ensuring long-term sustainability and capacity for climate change adaptation and mitigation in MPAs. - Leveraging methodologies tested in earlier initiatives, MPA4Change transitions from research to action, - emphasizing effective knowledge transfer and practical application.	Fine-tuning of existing toolkits on restoration & NbS to integrate their principles into effective public policies at Mediterranean and EU levels Facilitation of policy dialogues to incorporate climate strategies within ICZM and MSP frameworks, ensuring effective MPAs to advance climate adaptation and biodiversity conservation at regional scales.
PROTECT BALTIC (2023-2028, Grant Agreement ID: 101112866), project link	- Ensure sufficient spatial protection & restoration of Baltic Sea's marine environment, - Secure biodiversity, maintain ecosystem functions, produce ecosystem services, and enable sustainable use. - Adopt transdisciplinary approach aligned with HELCOM's Baltic Sea Action Plan & EU Biodiversity Strategy for 2030	Protection optimization framework: - Develop holistic transboundary decision support package to identify marine biodiversity protection and restoration targets - Facilitate shared approach to spatial protection and restoration. Ecosystem services assessment: - Advancing methodologies to identify, map, quantify, and value marine ecosystem services, supporting strategic planning and management of MPAs. Governance and policy Integration: - Implementing effective governance of spatial protection and restoration measures, ensuring transparency, accountability, stakeholder participation, and adaptive management. Coherence and connectivity:	- Strengthens climate-ready MPAs by integrating spatial protection, adaptive management, and governance improvements to enhance resilience in the Baltic Sea - Aims to evolve MPAs into flexible frameworks responding to climate-driven ecosystem shifts by advocating dynamic spatial planning and adaptive management - Underscores need for scientifically informed, governance-supported, financially sustainable MPA networks, reinforcing broader EU conservation and climate adaptation goals. Holistic transboundary decision support package for identifying marine biodiversity protection and restoration targets, facilitating a shared approach to spatial protection and restoration. Advanced methodologies for assessing and valuing marine ecosystem services, supporting strategic planning and management of MPAs. Enhanced governance by fostering stakeholder participation, transparency, and accountability in MPA management with more effective and equitable conservation outcomes.

		- Enhancing ecological coherence and connectivity of MPA network to ensure appropriately sized MPAs located to maintain ecosystem functions and services, and that species and habitats are protected representatively		
MEER:STARK (09/2022-11/2025, funded by the German Environment Agency / UBA), project link	- Explore governance and management strategies addressing interconnected challenges of marine conservation and climate adaptation, particularly in ecologically stressed North Sea and Baltic Sea regions. - Recognize need for integrated management approaches - Emphasize a nexus approach acknowledging cumulative anthropogenic pressures, and their exacerbation by climate change.	- Effective respond to challenges by developing cross-sectoral and evidence-based strategies and measures for strengthening of MPAs, implementation of NbS, and EBM approaches. - Inclusive framework: facilitating collaboration among policymakers, scientists, civil society, and other stakeholders through expert dialogues and co-developed policy recommendations. - Ensuring actionable, widely accepted, and scalable measures through instrumental collaborative structure	- Promotes cross-sectoral governance, adaptive management, & structured dialogue at EU and national level to enhance MPA effectiveness under climate change for strong climate-ready MPAs - Development of regional-level recommendations, like practical guidance for integrating climate adaptation into local and regional conservation planning - highlights importance of integrated governance in balancing ecological and socio-economic trade-offs, enhancing ecosystem resilience, and strengthening adaptive capacity to climate-induced pressures	- Integrated Governance Strategies: MEER:STARK developed cross-sectoral and evidence-based approaches to strengthen MPAs, NbS, and advance EBM, particularly in response to cumulative anthropogenic pressures and climate change impacts in the North and Baltic Seas. - Policy-Oriented Knowledge Co-Production: Through expert dialogues, the project co-developed practical policy recommendations and guidance to integrate climate adaptation into marine conservation planning. - Enhanced Collaborative Frameworks: MEER:STARK fostered structured, multi-level dialogue among policymakers, scientists, and civil society, promoting adaptive governance and scalable measures that balance ecological and socio-economic goals to improve the climate resilience of MPAs.