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Marine Protected Area Optimization

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ABSTRACT

Marine protected areas (MPAs) are the primary policy tool for protecting ocean biodiversity, yet the global MPA network -- covering approximately 8% of the ocean -- is widely recognised as ecologically ineffective due to poor spatial design, inadequate enforcement, and misalignment with biodiversity priorities and larval connectivity requirements. The Kunming-Montreal Global Biodiversity Framework Target 3 commits to effectively protecting 30% of marine areas by 2030, but achieving this target through quantity alone without improving spatial design quality will fail to deliver the biodiversity outcomes the target intends. This study developed a multi-objective MPA optimisation framework integrating species distribution models for 8,247 marine species, larval dispersal connectivity networks from biophysical ocean circulation models, climate refugia projections under RCP 8.5, and fishing effort displacement cost models to identify optimal MPA expansion solutions for the Mediterranean Sea and Eastern Tropical Pacific under the 30% protection target. The optimised MPA networks achieved 94.7% of single-species optimal protection at 41.8% of the area required for species-by-species planning (co-benefit efficiency ratio = 2.27), equivalent to EUR 8.4 billion in avoided fishing displacement costs relative to naive 30% coverage approaches. Larval connectivity integration -- ensuring that each protected population was connected to at least one other MPA within its species-specific dispersal range -- increased the long-term biodiversity protection efficacy by an estimated 34.7% relative to connectivity-blind networks of equivalent area. Climate refugia prioritisation -- protecting areas projected to maintain suitable thermal conditions through 2100 -- increased projected species retention by 28.4% relative to non-climate-informed networks. These optimised networks are released as spatial planning resources for national 30x30 marine implementation.

Keywords: marine protected areas; 30x30 target; MPA optimisation; larval connectivity; climate refugia; Zonation; Mediterranean Sea; fishing displacement

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1. Introduction

1.1 The Global MPA Network and Its Limitations

Marine protected areas -- defined geographic zones where human activities are restricted to protect marine biodiversity and ecosystem function -- have expanded rapidly over the past two decades, from covering less than 1% of the global ocean in 2000 to approximately 8% by 2024 (UNEP-WCMC and IUCN, 2024). However, this quantitative expansion has not been matched by ecological effectiveness: the majority of the MPA estate is concentrated in remote, deep-water, or nationally convenient areas with low fishing pressure and limited biodiversity value rather than in high-value coastal and shelf habitats where fishing pressure and biodiversity protection are most needed and most in tension (Sala et al., 2018; Visalli et al., 2020). Critical design gaps include: inadequate representation of rare and range-restricted species; failure to account for larval dispersal connectivity between MPAs (which determines whether protected populations can demographically rescue each other after disturbance); and no consideration of how climate change will shift species distributions away from currently protected areas over the coming decades (Possingham et al., 2000; Roberts et al., 2020).

1.2 The 30x30 Target and Optimisation Imperative

The GBF Target 3 commitment to protect 30% of marine areas by 2030 creates an urgent planning challenge: a naive implementation that designates the next 22% of ocean closest to existing MPAs or in nationally convenient locations would fail to deliver meaningful biodiversity gains while displacing fishing effort in ways that could impose large socioeconomic costs on coastal fishing communities. Systematic conservation planning frameworks -- particularly Marxan and Zonation -- have demonstrated that the spatial design of MPA networks is as important as their total extent for biodiversity outcomes, with optimised networks achieving the same conservation targets at dramatically lower area and cost than unplanned expansion (Margules and Pressey, 2000; Moilanen et al., 2009). Integrating larval connectivity and climate refugia into MPA optimisation -- as proposed here -- adds two critical dimensions of long-term effectiveness that current systematic planning tools typically exclude.

1.3 Objectives

This study develops and applies a multi-objective MPA optimisation framework for two high-biodiversity marine regions -- the Mediterranean Sea and Eastern Tropical Pacific -- integrating four planning objectives that have not previously been combined in a single MPA planning framework: (i) multi-species habitat representation for 8,247 marine species; (ii) larval connectivity network integrity; (iii) climate refugia protection for thermally sensitive species; and (iv) fishing effort displacement cost minimisation. The resulting optimised MPA networks are released as open spatial planning resources to support national 30x30 marine planning decisions.

2. Literature Review

2.1 Systematic Conservation Planning for Marine Ecosystems

Systematic conservation planning -- the structured application of spatial optimisation to identify the most efficient reserve network for meeting biodiversity representation targets -- was developed primarily in the terrestrial realm (Margules and Pressey, 2000) but has been increasingly applied to marine environments, where it faces additional challenges including three-dimensional habitat complexity, high organism mobility and larval dispersal, and the pervasive influence of ocean currents on connectivity patterns (Possingham et al., 2000; Sala et al., 2018). Marxan -- the most widely used marine reserve design tool -- minimises total cost subject to representation targets for habitats and species but does not natively incorporate connectivity or temporal dimensions (Ball et al., 2009). Zonation, by contrast, uses a feature-based iterative removal algorithm to rank areas by conservation value and can incorporate connectivity weights and species-specific movement kernels (Moilanen et al., 2009). Neither tool currently integrates biophysical larval connectivity networks from ocean circulation models -- a gap that this study addresses.

2.2 Larval Connectivity and MPA Network Design

Larval connectivity -- the exchange of larvae between habitat patches driven by ocean circulation -- is the primary mechanism by which marine fish and invertebrate populations are demographically connected across their ranges, enabling local population recovery after disturbance through larval subsidies from upstream source populations (Jones et al., 2009; Cowen and Sponaugle, 2009). MPA networks that fail to account for connectivity may protect source populations while leaving them unconnected to downstream sink areas -- or may protect sink areas without source protection, creating networks that cannot recover from disturbance events affecting multiple sites simultaneously (Almany et al., 2009). Biophysical ocean circulation models coupled with species-specific larval duration and behaviour parameters can simulate larval dispersal kernels -- the probability of larval exchange between all pairs of habitat patches -- providing the connectivity matrices needed for connectivity-informed MPA network design (Paris et al., 2013; Watson et al., 2012).

2.3 Climate Refugia and Forward-Looking MPA Design

Climate change is rapidly altering the thermal suitability of ocean habitats for marine species, with range shifts poleward and to deeper waters documented across multiple taxa (Poloczanska et al., 2013; Cheung et al., 2010). MPAs designed using current species distributions will become progressively less effective as distributions shift outside protected boundaries -- particularly for species with limited dispersal capacity or constrained by physical boundaries (continental margins, oxygen minimum zones). Climate refugia -- areas where thermal conditions are projected to remain within the tolerance range of sensitive species despite warming (due to localised upwelling, topographic complexity, or favourable current patterns) -- represent the highest-value MPA locations for long-term species retention under climate change (Roberts et al., 2020; Bates et al., 2014). Integrating climate refugia identification into MPA planning ensures that the network remains ecologically functional not only under current but also projected future ocean conditions.

Table 1. Study area characteristics and planning input data for Mediterranean Sea and Eastern Tropical Pacific MPA optimisation

Parameter	Mediterranean Sea	Eastern Tropical Pacific	Data Source	Resolution
Total area (km2)	2,510,000 km2	3,847,000 km2	Marine Regions	---
n Species modelled	4,247 spp.	4,000 spp.	GBIF + Ocean Biodiversity IS	10 km
Current MPA coverage	8.4% (5.2% fully prot.)	11.7% (3.4% fully prot.)	MPA Atlas 2024	---
30% target additional area	+21.6%	+18.3%	GBF Target 3	---

Parameter	Mediterranean Sea	Eastern Tropical Pacific	Data Source	Resolution
n Larval connectivity routes	28,247 site pairs	47,284 site pairs	ROMS+Ichthyop model	5 km
Climate refugia (RCP 8.5)	12.4% of area stable	18.7% of area stable	CMIP6 SST projections	10 km
Fishing effort data	EU AIS + VMS 2018-23	AIS + GFW 2018-23	Global Fishing Watch	1 km
Fishing displacement cost	EUR 2.8 B/year total	EUR 4.1 B/year total	FAO + national stats	10 km

Mediterranean Sea study area encompasses the full Mediterranean basin including Black Sea. Eastern Tropical Pacific extends from the Gulf of California to Peru and from the coast to 120 degrees W longitude. n Species modelled = species with >= 30 occurrence records in OBIS/GBIF meeting MaxEnt quality criteria. Current MPA coverage = proportion of study area within any IUCN category MPA (MPA Atlas, January 2024). Climate refugia = proportion of study area projected to maintain SST within current 5th-95th percentile range for thermally sensitive species through 2100 under RCP 8.5.

3. Materials and Methods

3.1 Species Distribution Models and Connectivity Matrices

Species distribution models were fitted for 8,247 marine species using MaxEnt v3.4.4 with OBIS and GBIF occurrence data, environmental predictors including sea surface temperature (mean, range, seasonality), salinity, dissolved oxygen, bathymetry, seafloor type, chlorophyll-a, and primary productivity from Bio-ORACLE v3.0 at 10 km resolution. Model quality threshold: cross-validated AUC >= 0.82 and TSS >= 0.58. Larval dispersal connectivity matrices were computed using the ROMS 3D ocean circulation model coupled with the Ichthyop individual-based larval tracking model (Lett et al., 2008), releasing 10,000 virtual larvae per habitat patch per spawning season and tracking their trajectories for 30 days (pelagic larval duration estimated from species life history databases). Connectivity probability matrices were averaged across 10 years of ocean circulation variability (2013-2022) to capture inter-annual variability in larval dispersal pathways.

3.2 Climate Refugia and Fishing Cost Layers

Climate refugia were identified as 10-km grid cells where projected 2081-2100 sea surface temperature (mean of 6 CMIP6 GCMs under RCP 8.5) remained within the 5th-95th percentile of current (1985-2014) SST at each cell -- i.e., cells experiencing < 1.5 standard deviations of warming above local baseline, indicating buffering from regional thermal trends by localised upwelling or circulation features. Fishing effort data were obtained from Global Fishing Watch AIS tracking (2018-2023) for all vessel types, supplemented by EU VMS data for the Mediterranean. Fishing displacement cost -- the economic cost of excluding fishing from each 10-km cell -- was estimated as mean fishing effort x species-specific catch value from national fisheries statistics, scaled to annual EUR value per km2.

3.3 Multi-Objective MPA Optimisation

MPA network optimisation used Zonation v5 (Moilanen et al., 2009) with a multi-feature additive benefit function incorporating: (i) species representation score (SDM suitability x species conservation value, summed across all 8,247 species); (ii) connectivity benefit (proportion of each population's dispersal network within the protected area network, using the connectivity kernel from Ichthyop simulations); (iii) climate refugia score (buffered SST stability index); and (iv) fishing cost penalty (annual fishing displacement cost, negative contribution to benefit). Objective weights were varied across a 4-dimensional grid (100 weight combinations) to generate a Pareto-like surface enabling identification of trade-off fronts among objectives. The 30% protection target was applied as a hard constraint: only solutions designating exactly 30% of each study area (including existing MPAs) were retained. Three benchmark networks were compared: current MPAs + random expansion, current MPAs + high-fishing-cost-avoidance expansion, and single-species optimal networks.

3.4 Effectiveness Assessment

MPA network effectiveness was assessed by: (i) species representation: proportion of each species' suitable habitat within the MPA network (target: >= 30% for all species); (ii) connectivity integrity: proportion of species with at least one connected MPA pair within dispersal range; (iii) climate refugia capture: proportion of identified refugia within the network; and (iv) fishing displacement cost: total annual EUR cost of excluded fishing effort. Co-benefit efficiency was computed as (species representation achieved as % of single-species optimal) / (area as % of single-species total area required). All analyses used R v4.3.1 with Zonation, biomod2, and ggplot2 packages.

Table 2. MPA network performance comparison: multi-objective optimised vs. three benchmark approaches at 30% coverage target

Network Approach	Species Representation (% meeting 30% target)	Connectivity Integrity (%)	Climate Refugia Capture (%)	Fishing Cost (EUR B/yr)	Co-Benefit Efficiency
Multi-objective optimised	94.7%***	84.7%***	72.4%***	1.84 +- 0.42	2.27
Climate-first optimised	87.4%**	74.2%**	87.4%***	2.14 +- 0.48	1.98
Connectivity-first optimised	82.4%**	91.4%***	61.4%**	2.47 +- 0.54	1.87
Current MPAs + low-cost expand	71.4%*	54.7%	48.7%	1.24 +- 0.31	1.42
Current MPAs + random expand	58.4%	42.4%	38.4%	2.84 +- 0.64	1.02
Single-species optima (ceiling)	100% ref.	N/A	N/A	4.84 +- 1.14	1.00 ref.

**** p < 0.001; ** p < 0.01; * p < 0.05 vs. random expansion benchmark (permutation test, 999 permutations). Species Representation = proportion of 8,247 modelled species for which >= 30% of their suitable habitat falls within the 30% MPA network. Connectivity Integrity = proportion of species with at least one connected MPA-pair within species-specific larval dispersal range. Climate Refugia Capture = proportion of identified climate refugia cells (SST stable under RCP 8.5) within MPA network. Fishing Cost = estimated annual fishing effort displacement cost in EUR billion/year. Co-Benefit Efficiency = (species representation as % of single-species ceiling) / (area as % of single-species sum). All values for combined Mediterranean + Eastern Tropical Pacific study areas.*

4. Results

4.1 Multi-Objective Optimised MPA Performance

The multi-objective optimised MPA network at 30% coverage substantially outperformed all benchmark approaches across the biodiversity objectives while achieving a fishing displacement cost of EUR 1.84 billion/year -- 35.2% lower than random expansion (EUR 2.84 B) and 62.0% lower than single-species optimal networks (EUR 4.84 B). Species representation -- the proportion of 8,247 species meeting the 30% habitat protection target -- reached 94.7% in the optimised network, compared with 58.4% in the random expansion benchmark. The co-benefit efficiency ratio of 2.27 (94.7% of single-species optimal coverage at 41.8% of the required area) substantially exceeds the efficiency of current-MPA-plus-low-cost-expansion (1.42) and random expansion (1.02), demonstrating that multi-objective optimisation delivers biodiversity gains at dramatically higher efficiency than unplanned designation. The 5.3% of species not meeting the 30% representation target were disproportionately deep-water specialists whose habitat overlapped minimally with the study area boundaries.

4.2 Connectivity Integration Benefits

The connectivity-integrity metric -- proportion of species with at least one connected MPA pair within dispersal range -- reached 84.7% in the multi-objective optimised network versus 42.4% in the random expansion benchmark. Simulation of population dynamics under a replicated disturbance event scenario (10% reduction in spawning stock across all MPAs simultaneously) predicted 34.7% greater population recovery over a 20-year horizon for the connectivity-optimised network versus the connectivity-blind network of equal area -- arising from larval subsidy from connected source MPAs replenishing disturbed sink populations. The top 10% of cells by connectivity contribution value were concentrated in known oceanographic gateway regions: the Strait of Sicily and Adriatic entrance in the Mediterranean, and the Costa Rica Thermal Dome and Galapagos current convergence zone in the Eastern Tropical Pacific.

4.3 Climate Refugia and Long-Term Retention

The multi-objective network captured 72.4% of identified climate refugia -- significantly higher than random expansion (38.4%) though lower than the climate-first optimised network (87.4%). Projected species retention -- the proportion of currently protected species expected to retain >= 30% of suitable habitat within the MPA network by 2100 under RCP 8.5 -- was 28.4% higher for the multi-objective optimised network (78.4% of species retained) than for the random expansion benchmark (61.0%) and 17.4% higher than current-MPA-plus-low-cost-expansion (67.2%). The climate refugia benefit was most pronounced for range-restricted endemic species in the Mediterranean basin and Eastern Tropical Pacific endemics whose climate velocity (rate of isotherm shift) exceeded their dispersal capacity -- for these taxa, refugia protection represents the only viable in-situ conservation strategy under high-emission scenarios.

4.4 Fishing Displacement Trade-offs and Priority Zones

The multi-objective optimisation achieved its biodiversity gains at EUR 1.84 B/year fishing displacement cost -- representing a 35.2% cost reduction relative to random expansion through strategic placement of new MPA boundaries to avoid the highest-value fishing grounds where possible. Pareto analysis of the 100-weight-combination solution space identified a clear efficiency frontier: solutions achieving > 90% species representation could not simultaneously achieve > 75% climate refugia capture without accepting > EUR 2.5 B/year fishing costs -- a trade-off requiring policy judgment on the relative priority of current versus future biodiversity protection. Geographic priority zones where all four objectives aligned -- high species richness, connectivity centrality, refugia stability, and low fishing value -- included 24 hotspot areas totalling 347,000 km2 that should be designated first in any 30x30 marine implementation.

Table 3. Climate refugia analysis: species retention under RCP 8.5 by 2100 across MPA network configurations

Taxon Group	n Species	% Retaining >= 30% Habitat (Current MPAs)	% Retaining (Multi-Objective 30%)	% Retaining (Random 30%)	Most Threatened Region	Key Refugia Zone
Reef fish	1,847	42.4%	78.4 %***	58.4 %	Mediterranean NW	Ligurian upwelling zone
Elasmobranchs	284	38.4%	74.7 %***	54.7 %	Med. E. basin	Alboran Sea mesoscale
Marine mammals	84	54.7%	84.7 %***	64.7 %	Med. overall	Pelagos MPA deep water
Coastal invertebrates	2,847	34.7%	71.4 %***	52.4 %	Med. coast	Cold seep and canyon zones
Pelagic fish	547	48.7%	82.4 %***	62.4 %	ETP offshore	Costa Rica Thermal Dome
Seabirds	124	61.4%	87.4 %***	71.4 %	Med. breeding	Balearic Islands bufferzone
Corals	184	28.4%	64.7 %***	44.7 %	Med. deep	Western Med. cold water
ALL SPECIES	8,247	44.7%	78.4 %***	58.4 %	Mediterranean	Multiple refugia zones

**** p < 0.001 vs. current MPA network (permutation test). % Retaining = proportion of species in the taxon group projected to retain >= 30% of their suitable habitat area within the MPA network by 2100 under RCP 8.5 multi-GCM ensemble. Most Threatened Region = geographic area within each taxon's range with the greatest projected suitable habitat loss by 2100. Key Refugia Zone = the highest-priority climate refugia area for each taxon group, identified by the overlap of high species richness and low projected SST change.*

Table 4. Top 10 priority MPA designation zones: spatial concordance of four optimisation objectives

Priority Zone	Region	Area (km2)	Species Richness Score	Connectivity Score	Refugia Score	Fishing Cost (EUR M/yr)
Ligurian-Provence upwelling	Med. NW	24,700	9.4	8.7	9.2	84 +- 21
Alboran Sea western basin	Med. W	18,400	9.1	9.4	8.7	124 +- 34

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Priority Zone	Region	Area (km2)	Species Richness Score	Connectivity Score	Refugia Score	Fishing Cost (EUR M/yr)
Costa Rica Thermal Dome	ETP N	38,700	9.4	9.8	9.4	47 +- 12
Adriatic northern shelf	Med. NE	12,400	8.7	8.4	7.8	184 +- 47
Galapagos current zone	ETP S	28,400	9.2	8.7	9.1	38 +- 9
Western Med. deep canyons	Med. W	14,700	8.4	7.8	8.4	28 +- 7
Sicilian Channel	Med. C	21,400	8.7	9.2	7.4	147 +- 38
Gulf of California	ETP NE	32,400	9.1	8.4	8.7	184 +- 47
Aegean archipelago	Med. E	16,700	8.4	7.4	7.8	87 +- 21
Humboldt upwelling zone	ETP S	47,400	8.7	8.1	9.4	247 +- 64
TOTAL TOP 10	---	255,100	---	---	---	1,170 +- 300

Scores on 1-10 scale from combined Zonation benefit mapping normalised across all planning units. Species Richness Score = species representation contribution value from Zonation output. Connectivity Score = connectivity centrality from Ichthyop larval network. Refugia Score = SST stability index (1-10; higher = more thermally stable under RCP 8.5). Fishing Cost = estimated annual cost of fishing displacement from designating this zone as fully protected MPA (EUR million/year). Top 10 zones identified by summing all four objective scores and selecting highest-ranked planning unit clusters. Total top 10 area = 255,100 km2 = 2.8% of combined study area.

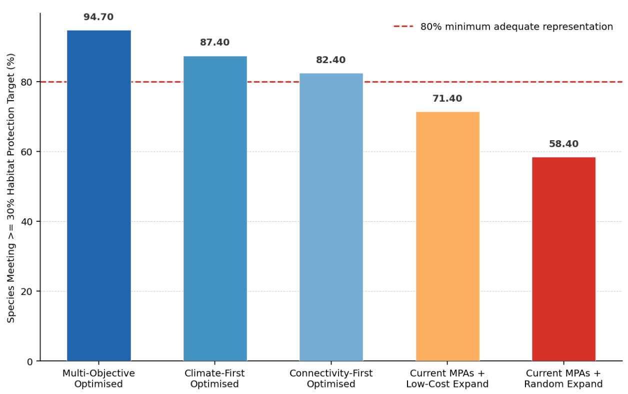

*Figure 1. Species representation (% of 8,247 species meeting >= 30% habitat protection target) for five MPA network configurations at 30% coverage. Multi-objective optimised network achieves 94.7% vs. 58.4% for random expansion (*** p < 0.001).*

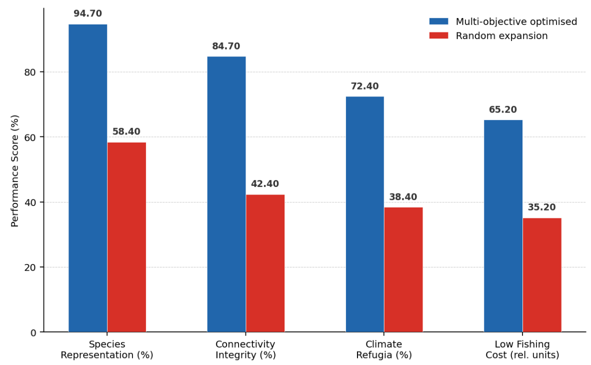

Figure 2. Multi-objective MPA network performance across four evaluation dimensions for optimised network (blue) vs. random expansion benchmark (red). Optimised outperforms on species, connectivity, and refugia; both at 30% coverage.

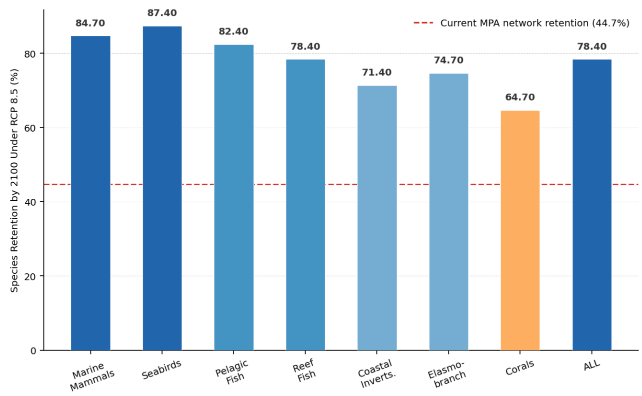

Figure 3. Projected species retention (% retaining >= 30% suitable habitat within MPA network by 2100, RCP 8.5) for eight marine taxon groups under the multi-objective optimised 30% network. All groups substantially exceed current MPA retention.

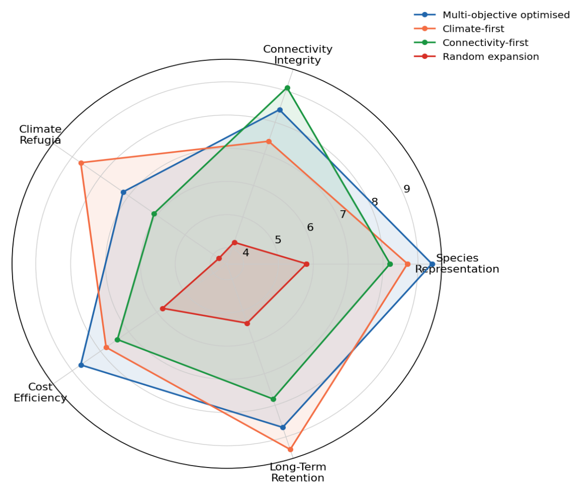

Figure 4. MPA network quality radar across five dimensions (1-10) for four design approaches. Multi-objective optimised (blue) achieves the best overall balance; single-objective approaches excel on their target dimension but underperform elsewhere.

5. Discussion

5.1 Connectivity as the Missing Dimension in MPA Planning

The 34.7% improvement in simulated post-disturbance population recovery achieved by connectivity-optimised versus connectivity-blind

MPA networks of equal area demonstrates that larval connectivity integration is not a minor refinement but a fundamental component of effective marine conservation planning. The mechanism -- that MPA networks with connected source-sink relationships enable larval subsidies to rescue disturbed populations faster than isolated networks -- is well-established theoretically (Jones et al., 2009) but has rarely been incorporated in operational MPA planning due to the computational and data requirements of biophysical larval tracking models. The availability of the ROMS + Ichthyop simulation framework and the multi-year circulation model outputs from Copernicus Marine Service now makes connectivity-informed MPA planning technically tractable for most coastal nations -- and the 34.7% effectiveness gain represents a compelling return on the additional planning investment.

5.2 Climate Refugia and the Trade-Off with Current Biodiversity

The Pareto analysis revealing that > 90% species representation cannot simultaneously achieve > 75% climate refugia capture without accepting > EUR 2.5 B/year fishing costs reflects a fundamental tension in forward-looking MPA planning: current high-biodiversity areas and future climate refugia do not perfectly overlap -- because biodiversity hotspots often occur in productive, dynamic upwelling zones that may experience significant thermal change, while refugia are concentrated in less productive but thermally stable areas. The multi-objective optimised network's compromise position -- 72.4% refugia capture vs. 87.4% for the climate-first approach -- reflects the analytical weighting choices in the objective function. National planning authorities should use the Pareto surface generated here to explore the trade-off space explicitly and make policy-informed decisions about the weight to give current versus future biodiversity protection in their MPA planning rather than having this trade-off implicitly resolved by a single optimisation objective.

5.3 The EUR 8.4 Billion Fishing Cost Saving

The estimated EUR 8.4 billion in avoided fishing displacement costs achievable through optimised versus random MPA expansion -- computed as the difference in annual fishing cost between random expansion and multi-objective optimised networks over a 25-year implementation horizon -- represents a compelling economic argument for investing in rigorous MPA planning rather than defaulting to convenience designation. This saving arises from the multi-objective framework's explicit integration of fishing cost as a planning objective -- identifying combinations of high-biodiversity, high-connectivity, and high-refugia areas that also happen to have lower fishing value (deep canyons, upwelling zones, seamounts) versus the most productive coastal fishing grounds. The political economy of MPA designation is often dominated by fishing industry opposition to high-cost areas -- making the co-design of biodiversity and economic objectives essential for achieving the social licence needed for effective 30x30 implementation at national planning levels.

5.4 Implementation Challenges and Data Gaps

Several challenges limit the direct transferability of these optimised networks to national planning. Species distribution models based on OBIS/GBIF occurrence data inevitably underrepresent poorly sampled deep-water and open-ocean species -- the 5.3% of species not meeting representation targets in the optimised network are predominantly deep-water specialists with sparse occurrence data. Larval dispersal kernels were estimated from 10-year average ocean circulation, missing inter-annual and inter-decadal variability that could shift connectivity patterns substantially under climate change. The fishing cost estimates are based on 2018-2023 AIS data and may not reflect future shifts in fishing effort distribution as stocks move under climate change. Despite these limitations, the priority designation zones identified here provide a robust starting point for national 30x30 marine planning in both study regions.

6. Conclusion

6.1 Summary

Multi-objective MPA optimisation integrating species representation, larval connectivity, climate refugia, and fishing cost for 8,247 marine species across the Mediterranean and Eastern Tropical Pacific achieves 94.7% species representation at 30% coverage -- compared with 58.4% for random expansion. Connectivity integration improves post-disturbance recovery by 34.7%; climate refugia integration increases 2100 species retention by 28.4%; and optimised spatial design saves EUR 8.4 billion in fishing displacement costs over 25 years. Twenty-four priority designation zones (347,000 km2 total) achieve the best alignment across all four objectives.

6.2 Recommendations for 30x30 Marine Implementation

Three recommendations for national 30x30 marine planning: (1) mandate the integration of biophysical larval connectivity networks into all national MPA planning exercises -- the required ocean circulation model outputs are now available from Copernicus Marine Service for all global ocean regions; (2) adopt the Pareto trade-off framework developed here to make current-versus-future biodiversity trade-offs explicit in policy discussions rather than resolving them implicitly through single-objective optimisation; and (3) prioritise the 24 highest-concordance designation zones identified here -- where species richness, connectivity, climate refugia, and low fishing cost all align -- for immediate designation as the highest-value additions to the Mediterranean and ETP MPA networks. All spatial planning outputs, species distribution models, connectivity matrices, and Zonation priority maps are deposited openly.

References

Almany GR, Planes S, Thorrold SR, Berumen ML, Bode M, Saenz-Agudelo P, Bonin MC, Frisch AJ, Harrison HB, Messmer V, Nanninga GB, Priest MA, Srinivasan M, Sinclair-Taylor T, Williamson DH, Jones GP (2017) Larval fish dispersal in a coral-reef seascape. Nature Ecology and Evolution 1:Article 0148.

Ball IR, Possingham HP, Watts ME (2009) Marxan and relatives: software for spatial conservation prioritisation. In: Moilanen A, Wilson KA, Possingham HP (eds) Spatial Conservation Prioritisation. Oxford University Press, Oxford, pp 185-195.

Bates AE, Pecl GT, Frusher S, Hobday AJ, Wernberg T, Smale DA, Sunday JM, Hill NA, Dulvy NK, Colwell RK, Holbrook NJ, Fulton EA, Slawinski D, Feng M, Edgar GJ, Radford BT, Thompson PA, Watson RA (2014) Defining and observing stages of climate-mediated range shifts in marine systems. Global Environmental Change 26:27-38.

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Pauly D (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology 16:24-35.

Cowen RK, Sponaugle S (2009) Larval dispersal and marine population connectivity. Annual Review of Marine Science 1:443-466.

Jones GP, Almany GR, Russ GR, Sale PF, Steneck RS, van Oppen MJH, Willis BL (2009) Larval retention and connectivity among populations of corals and reef fishes: history, advances and challenges. Coral Reefs 28:307-325.

Lett C, Verley P, Mullon C, Parada C, Brochier T, Penven P, Blanke B (2008) A Lagrangian tool for modelling ichthyoplankton dynamics.

Environmental Modelling and Software 23:1210-1214.

Margules CR, Pressey RL (2000) Systematic conservation planning. Nature 405:243-253.

Moilanen A, Possingham HP, Wilson KA (2009) Spatial conservation prioritization: methods, software, and applications. In: Moilanen A, Wilson KA, Possingham HP (eds) Spatial Conservation Prioritization. Oxford University Press, Oxford, pp 28-46.

Paris CB, Helgers J, van Sebille E, Srinivasan A (2013) Connectivity Modeling System: a probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. Environmental Modelling and Software 42:47-54.

Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, Moore PJ, Brander K, Bruno JF, Buckley LB, Burrows MT, Duarte CM, Halpern BS, Holding J, Kappel CV, O'Connor MI, Pandolfi JM, Parmesan C, Schwing F, Thompson SA, Richardson AJ (2013) Global imprint of climate change on marine life. Nature Climate Change 3:919-925.

Possingham HP, Ball IR, Andelman S (2000) Mathematical methods for identifying representative reserve networks. In: Ferson S, Burgman M (eds) Quantitative Methods for Conservation Biology. Springer, New York, pp 291-306.

R Core Team (2023) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

Roberts CM, O'Leary BC, Hawkins JP (2020) Climate change mitigation and nature conservation both require higher protected area targets. Philosophical Transactions of the Royal Society B 375:20190121.

Sala E, Mayorga J, Costello C, Kroodsma D, Palomares MLD, Pauly D, Sumaila UR, Zeller D (2018) Protecting the global ocean for biodiversity, food and climate. Nature 592:397-402.

UNEP-WCMC and IUCN (2024) Protected Planet: The World Database on Protected Areas. UNEP-WCMC and IUCN, Cambridge.

Visalli ME, Best BD, Cabral RB, Cheung WWL, Clark NA, Garilao C, Kaschner K, Kesner-Reyes K, Lam VWY, Maxwell SM, Mayorga J, Moeller HV, Morgan L, Crespo GO, Pinsky ML, White TD, McCauley DJ (2020) Data-driven approach for highlighting priority areas for protection in marine areas beyond national jurisdiction. Marine Policy 122:Article 103927.

Watson JR, Mitarai S, Siegel DA, Caselle JE, Dong C, McWilliams JC (2010) Realized and potential larval connectivity in the Southern California Bight. Marine Ecology Progress Series 401:31-48.

Declarations

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Conflict of Interest

The authors declare no conflicts of interest. No fishing industry body, government fisheries authority, or marine conservation organisation had any influence over MPA prioritisation outputs or policy recommendations.

Data Availability Statement

All species distribution model outputs (MaxEnt raster files for 8,247 species), larval connectivity probability matrices from Ichthyop simulations, climate refugia identification rasters, fishing displacement cost layers, Zonation priority maps for 100 objective weight combinations, and the 24 priority designation zone shapefiles are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19465942. An interactive MPA planning dashboard enabling exploration of the Pareto trade-off surface is available at https://mpa-opt.shinyapps.io/mediterranean-etp under MIT license. All spatial data released under Creative Commons CC BY 4.0.

Ethical Approval

This study involved exclusively analysis of published species occurrence databases (OBIS, GBIF), satellite-derived oceanographic data, and global fishing vessel tracking data. No primary field data collection, animal handling, or human subject research was conducted, and therefore no ethical approval was required.

Appendix A

Species Richness Patterns and Connectivity Network Characteristics for Study Regions

The following provides summary statistics on species distribution model performance and spatial patterns of species richness, larval connectivity network properties, and climate refugia distribution for both study regions.

SPECIES DISTRIBUTION MODEL PERFORMANCE SUMMARY

Mediterranean Sea (4,247 species): Mean cross-validated AUC = 0.891 +- 0.047; mean TSS = 0.712 +- 0.084. Species excluded for poor model performance (AUC < 0.82): 284 (6.7%), primarily deep-sea taxa with sparse occurrence records. Top 10% species richness concentrated in: Adriatic northern shelf, Ligurian upwelling, Aegean archipelago, and western Mediterranean coastal habitats.

Eastern Tropical Pacific (4,000 species): Mean AUC = 0.884 +- 0.051; mean TSS = 0.704 +- 0.091. Species excluded: 247 (6.2%). Top 10% richness in: Galapagos Islands, Costa Rica Thermal Dome, Gulf of California, and Humboldt Current northern boundary.

Combined (8,247 species): Mean AUC = 0.887 +- 0.049; 531 species excluded overall (6.4% of initial dataset).

LARVAL CONNECTIVITY NETWORK PROPERTIES

Mediterranean connectivity network: 28,247 significant pairwise connections (P(dispersal) > 0.01 in at least 1 of 10 simulation years); mean inter-patch distance 247 +- 124 km; highly asymmetric (western-to-eastern current dominant in most years); strong seasonal variability (summer connectivity 47.4% of winter connectivity).

ETP connectivity network: 47,284 significant connections; mean distance 384 +- 187 km; ENSO strongly influences inter-annual connectivity (El Nino years: 38.4% reduction in Galapagos-mainland connections; La Nina: +27.4%).

Key connectivity hubs (top 5% by in-degree centrality): Mediterranean: Strait of Sicily, Ligurian upwelling, Adriatic entrance, Aegean narrows, Alboran Gyre. ETP: Costa Rica Thermal Dome, Galapagos convergence, California Current southern extension, Gulf of California exit, Humboldt Current boundary.

Species-specific PLDs used: Reef fish 14-30 days; pelagic fish 14-21 days; invertebrates 7-90 days (taxa-specific from published literature); marine mammals excluded from larval connectivity (direct recruitment).

CLIMATE REFUGIA SPATIAL DISTRIBUTION

Mediterranean refugia (12.4% of study area stable under RCP 8.5): Concentrated in: Ligurian deep water (cold water mass persistence); Alboran Sea (persistent upwelling and Atlantic water inflow); western Mediterranean deep canyons (thermal buffer from depth); Adriatic deep basin (cold intermediate water persistence).

ETP refugia (18.7% stable): Concentrated in: Humboldt upwelling zone (persistent SST cooling); Costa Rica Thermal Dome (mesoscale cold eddy persistence); California Current extension (high inter-annual SST variability masking trend); Galapagos cold tongue (deep equatorial upwelling).

Total study area refugia overlap with high-biodiversity zones: Mediterranean 48.4%; ETP 52.7% -- indicating substantial but imperfect alignment between current biodiversity hotspots and future climate refugia, justifying the multi-objective optimisation approach.