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Mapping Marine Protected Area Expansion Opportunities Using Biodiversity Agreement and Low Human Pressure

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Abstract

Marine protected areas (MPAs) remain insufficient to meet global conservation ambitions. We overlaid four biodiversity-prioritization frameworks to map marine conservation priority zones (MCPZs), then intersected them with a published marine-wilderness layer to identify marine ecological expansion zones (MEEZs). The four sources contribute equally to a descriptive agreement score; the wilderness layer indicates low mapped cumulative human impact, not implementation cost. The global mapped MEEZ extent is 10,583,422.69 km^2. Within the 101 IHO sea areas used for scenario accounting, MEEZs cover 10,576,936.16 km^2 (2.91% of their summed area), and 16.92% overlaps effective 2026 protected-area (PA) polygons. Adding currently unprotected MEEZs to this PA-only baseline would raise coverage from 9.69% to 9.70%, 9.90%, and 12.11% under conservative, moderate, and ambitious scenarios, respectively. The largest absolute additions occur in the South Pacific, Southern, and North Pacific Seas; the largest within-sea percentage-point gains occur in the Beaufort, Chukchi, and Barents Seas. These candidates are a first-stage spatial screen, not a complete pathway to 30% protection; regional ecological, social, and governance assessment remains necessary.

Keywords: protected areas; marine conservation; spatial analysis; conservation prioritization; biodiversity conservation

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1. Introduction

Global biodiversity is declining rapidly, posing substantial risks to ecological stability and human well-being. Protected areas (PAs), particularly marine protected areas (MPAs), are a central instrument for biodiversity conservation. Protected Planet reported 9.82% marine protected-area coverage in its October 2026 global statistics [1], remaining well below international ambitions. Global frameworks, including the Sustainable Development Goals (SDGs), Aichi Target 11, and the Kunming–Montreal Global Biodiversity Framework ('30 × 30'), emphasize not only expanding protected-area coverage but also improving ecological representativeness and management effectiveness [2,3].

Despite the rapid expansion of MPAs [4–7], ecological outcomes remain uneven across regions [8–10]. Socio-economic constraints and management limitations, including inadequate staffing, weak enforcement, and limited financial support, can further reduce conservation performance [11]. These challenges raise an important planning question:

where can future MPA expansion capture recognized biodiversity priorities while avoiding, where possible, areas already subject to intense human pressure? Recent studies show that conservation outcomes vary across management types and social contexts, highlighting the value of diverse and well-managed MPA portfolios [12]. However, globally consistent, spatially explicit screening approaches that jointly consider conservation importance and human-pressure context remain comparatively limited. Recent global work has mapped productive low-impact waters [13], marine climate refugia under projected change [14], and practical pathways for coastal MPA implementation [15]. Our narrower contribution is to quantify where the four specified biodiversity layers agree within a published low-impact mask and how those candidate areas change polygon-based PA coverage among IHO seas.

A range of global biodiversity prioritization frameworks has been developed, including Biodiversity Hotspots (BHs) [16], Endemic Bird Areas (EBAs) [17], Key Biodiversity Areas (KBAs) [18], and the Global 200 Ecoregions (G200s) [19]. These frameworks were developed for different conservation purposes and differ in taxonomic focus, spatial scale, and ecological representation. Their spatial agreement can nevertheless provide a useful broad-scale signal of areas repeatedly recognized by independent prioritization approaches. Accordingly, in this study, their overlap is interpreted as cross-framework agreement rather than as a complete or weighted measure of marine biodiversity value. This distinction is important because broad-scale conservation screening should complement, rather than replace, marine-specific ecological and site-level assessments.

Marine wilderness refers to ocean areas with comparatively low cumulative human impact and represents some of the least modified parts of the marine environment [20–22]. Approximately 13.2% of the global ocean has been identified as marine wilderness [23]. Such areas can retain important ecological functions and may offer opportunities for conservation expansion with relatively low levels of direct human-use pressure. However, low human pressure should not be interpreted as a direct measure of monetary, opportunity, or management cost. Integrating marine wilderness with biodiversity-priority information can therefore help identify conservation opportunities with potentially lower conflict related to direct human-use pressure, while site-specific economic and governance assessments remain necessary before implementation.

To provide spatial decision support for the post-2020 Global Biodiversity Framework [24], this study evaluates the current distribution of MPAs and develops an integrated screening framework that combines multiple biodiversity-prioritization templates with marine wilderness. We first identify marine conservation priority zones (MCPZs) from cross-framework spatial agreement and then delineate marine ecological expansion zones (MEEZs) where MCPZs overlap areas of low human impact. We further quantify how much additional MPA coverage would result under three incremental expansion scenarios and compare these patterns among IHO sea areas. The framework is intended to identify broad-scale conservation opportunities and spatial gaps; it does not directly estimate economic costs, governance capacity, or site-level management feasibility. In this way, the analysis provides a first-stage screening tool that can inform, but not substitute for, subsequent ecological, socio-economic, and governance assessments.

2. Materials and Methods

2.1. MPA and IHO Sea Area Data

We used the October 2026 Protected Planet polygon export (Table 1) and restricted the baseline to records coded as protected areas (SITE_TYPE = PA) in marine or coastal realms. The supplied layer contains 17,303 polygons; after excluding 205 proposed or not-reported records, 17,098 effective PA polygons were eligible for analysis [25]. PA polygons were spatially dissolved within each analysis unit before area calculation. ArcGIS 10.8 was used

for source-data processing. Datasets were aligned in GCS_WGS_1984, and area calculations used the Eckert IV equal-area projection. Other effective area-based conservation measures (OECMs) were not included in this PA-only baseline.

Table 1. Summary of datasets used in this study.

Dataset	Data Year	Source	Data Format	Main Attributes
MPAs	2026	https://www.protectedplanet.net/en (accessed on 10 October 2026)	Shapefile (Polygon)	PA polygons only (SITE_TYPE, REALM, STATUS, SITE_ID and boundaries); proposed and not-reported records excluded.
IHO Sea Areas	2018	https://www.vliz.be/en/imis?dasid=5444&doiid=323 (accessed on 10 May 2026)	Shapefile (Polygon)	Defines 101 oceanic and sea regions worldwide.
BHs	2016	https://zenodo.org/records/3261807 (accessed on 8 April 2026)	Shapefile (Polygon)	Prepared BH input: 30 hotspot area and 17 outer limit polygons; both retained as one BH presence layer.
EBAs	1998	https://www.arcgis.com/sharing/rest/content/items/4eea031c5a2e4a7cbebbd2e8b7447fa0/info/metadata/metadata.xml?format=default&output=html (accessed on 8 April 2026)	Shapefile (Polygon)	Areas that fully contain the overlapping breeding ranges of ≥2 restricted-range species.
KBAs	2024	https://birdlife.fromsmash.com/KBA-Layer-Sept24 (accessed on 8 April 2026)	Shapefile (Polygon)	Sites contributing significantly to the global persistence of biodiversity.
G200s	2016	https://www.worldwildlife.org/publications/global-200 (accessed on 8 April 2026)	Shapefile (Polygon)	Representative ecoregions of global biodiversity importance.
Marine Wilderness	2013	https://knb.ecoinformatics.org/view/doi:10.5063/F1RR1WFT (accessed on 16 March 2026)	Raster (1 km)	Cumulative human impact (19 stressors); bottom 10% used to define wilderness.

The IHO Sea Areas (Table 1) in this study were digitized based on the "Limits of Oceans and Seas" publication [26]. The dataset, provided in ArcGIS shapefile format (polygons), delineates the boundaries of the global major oceans and seas.

2.2. Global Biodiversity Prioritization Framework Data

We conducted a spatial meta-analysis of four global biodiversity prioritization frameworks to identify MCPZs and MEEZs, using BHs, EBAs, KBAs, and G200s as complementary spatial screening layers (Table 1).

BHs identify biogeographic regions with exceptional concentrations of biodiversity and substantial habitat loss. EBAs delineate regions that encompass the overlapping breeding ranges of restricted-range bird species. KBAs identify sites that contribute significantly to the global persistence of biodiversity, and G200s represent globally important terrestrial, freshwater, and marine ecoregions. These datasets differ in their taxonomic emphasis, spatial scale, and original conservation purpose; their characteristics are summarized in Table 1. In this study, they are not treated as interchangeable measures of biodiversity value. Instead, their spatial agreement is used as a broad-scale indicator of repeated recognition across independent prioritization frameworks. In the prepared analysis files, 47 BH, 142 EBA, 5,316 KBA, and 48 marine G200 polygon features were available after preprocessing; these are processing-unit counts, not global inventories of sites (Supplementary Table S3). BHs and EBAs chiefly represent terrestrial or coastal phenomena, and the absence of a polygon cannot be interpreted as evidence of low marine biodiversity value. KBA inclusion depends on site assessments that vary geographically and taxonomically, whereas marine G200 polygons represent broad ecoregions rather than uniform assessment of conditions within them. The archived vector layers do not contain independent, complete-data masks that would allow non-inclusion to be separated from missing assessment everywhere in the ocean. The prepared BH layer contains both hotspot area and outer limit polygons (30 and 17 features, respectively). We retained both as supplied, treating their union as one BH presence indicator; an outer limit describes the broader mapped hotspot envelope rather than a separately verified marine habitat.

2.3. Identification of MCPZs

We conducted a spatial meta-analysis of four global biodiversity prioritization templates (BHs, EBAs, KBAs, and G200s) to identify MCPZs (Figure 1). The templates were overlaid in ArcGIS 10.8 after spatial standardization, and vector intersection was used to identify areas recognized by multiple frameworks. Each framework contributed one binary indication of whether a location was included. Areas recognized by three or more templates were classified as level 1 MCPZs, those recognized by two templates as level 2 MCPZs, and those recognized by one template as level 3 MCPZs. Thus, the three levels represent increasing cross-framework agreement, with level 1 showing the strongest agreement and level 3 representing single-framework recognition. This classification is used as a screening hierarchy and should not be interpreted as a weighted biodiversity index. We tested its dependence on source selection by omitting each of the four layers in turn, holding the wilderness mask fixed, and recalculating the one-, two-, and at-least-three-source classes from the recorded source-presence flags (Supplementary Table S2). Equal counting avoids assigning unsupported numerical weights to frameworks with different objectives and evidence bases. The three-of-four Level 1 cutoff denotes majority agreement among these four sources; it is a reporting threshold rather than an optimized ecological boundary. Source omission is reported for the global mapped extent in Supplementary Table S2.

The four templates were selected because they are globally recognized, spatially explicit, widely used in conservation research, and collectively represent complementary dimensions of biodiversity prioritization. BHs emphasize endemism and habitat loss; EBAs emphasize restricted-range bird distributions; KBAs identify sites of global significance for the persistence of biodiversity; and G200s identify representative ecoregions of exceptional ecological importance. Because the frameworks differ in purpose and ecological emphasis, agreement among them is used here to describe shared recognition among the selected sources rather than to imply that the datasets are ecologically equivalent.

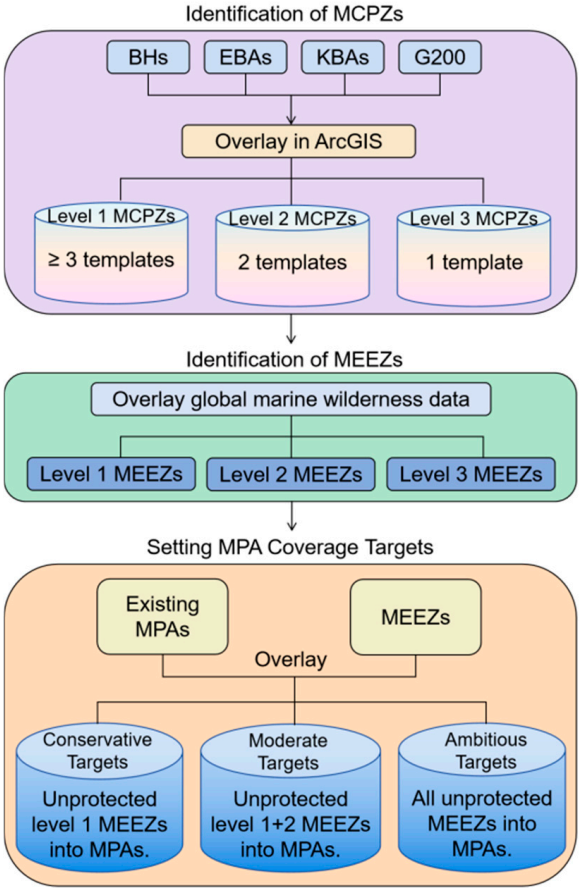

Figure 1. Integrated methodological framework for identifying marine conservation priority zones and MPA expansion opportunities.

No single template provides a comprehensive representation of marine biodiversity. The overlay analysis therefore serves as a broad-scale consensus screening approach that integrates multiple perspectives while retaining the limitations of the underlying datasets. Spatial data available in vector or raster format were standardized for overlay analysis. For accurate area calculation, all datasets were projected to Eckert IV [27] and converted to a vector format where necessary. The archived wilderness raster is in the Behrmann equal-area projection with a 934.48 m square grid and a NoData code of 3. The supplied downstream priority and wilderness intersections are vector polygons, and all revised PA and scenario overlays were conducted on vectors. Exact snap-grid, resampling, and raster-to-vector settings of the original ArcGIS workflow are not retained in the supplied archive, so the legacy conversion cannot be independently reconstructed from these files alone. Consistency across every legacy conversion therefore cannot be confirmed, and no separate quantitative comparison of coastal and open-ocean bias was performed.

2.4. Identification of MEEZs

Marine wilderness represents areas with relatively low cumulative human impact and can provide useful information on where conservation expansion may face lower levels of direct anthropogenic pressure [23,28]. In this study, marine wilderness is used as a human-pressure screening layer, not as a direct proxy for monetary or management cost. Global marine wilderness was identified by evaluating the intensity and cumulative impact of 19 anthropogenic stressors on the ocean [23]. Each stressor was normalized to a 0–1 scale, and cumulative impact scores were calculated by summing across stressors. Areas in the lowest 10% of cumulative impact scores were classified as marine wilderness, with the

original dataset further retaining areas meeting low-impact criteria across individual and cumulative stressors. Two scenarios were considered in the source dataset: one including all 19 stressors and another excluding climate-related variables such as temperature anomalies and ocean acidification. MEEZs were then defined as the spatial intersection between MCPZs and marine wilderness. Their three levels correspond directly to the MCPZ hierarchy and therefore represent the combination of cross-framework conservation agreement and low mapped human pressure. The wilderness layer represents the published 2013-era human-pressure inputs. Fishing, shipping, and climate-related pressures may have changed since then; the resulting MEEZs should not be described as verified low-pressure locations in 2026.

2.5. Defining MPA Expansion Scenarios

To quantify potential MPA expansion pathways, we identified MEEZs that are not currently covered by existing MPAs and summarized their area under three nested scenarios (Figure 1). The conservative target includes only unprotected level 1 MEEZs; the moderate target includes unprotected level 1 and level 2 MEEZs; and the ambitious target includes all unprotected level 1, level 2, and level 3 MEEZs. These scenarios are intended to quantify the spatial implications of progressively including broader MEEZ categories and are not presented as economically optimized or prescriptive designation plans. For each scenario, eligible MEEZ polygons were spatially dissolved, and their overlap with the dissolved 2026 PA baseline was removed before calculating additional area. The moderate and ambitious scenarios report cumulative additions from levels 1–2 and 1–3, respectively; each coverage percentage uses the same IHO sea-area denominator. The 101 IHO sea polygons define the common study domain for all scenario numerators and denominators. Within each sea, the same dissolved PA union was used to calculate both PA coverage and MEEZ overlap; MEEZ polygons were clipped to that sea before area accounting. Global map extents in Figures 2 and 3 are reported separately.

For each scenario, the corresponding coverage ratios are calculated as follows:

$$T_C = \frac{MPA + MEEZ_{u_1}}{A} \tag{1}$$

$$T_M = \frac{MPA + MEEZ_{u_1} + MEEZ_{u_2}}{A} \tag{2}$$

$$T_A = \frac{MPA + MEEZ_{u_1} + MEEZ_{u_2} + MEEZ_{u_3}}{A} \tag{3}$$

where T_C, T_M, and T_A represent the proportions of the total marine area required under the conservative, moderate, and ambitious scenarios, respectively; A denotes the total area of the corresponding ocean; and $MEEZ_{u_i}$ refers to the total area of unprotected level i MEEZs. Here, each MEEZ level is the intersection of the corresponding MCPZ agreement class with marine wilderness; the subscript u denotes only its portion outside the existing PA footprint. Removing the wilderness condition would define a different expansion scenario. The PA union and added MEEZ area are calculated without double-counting spatial overlaps.

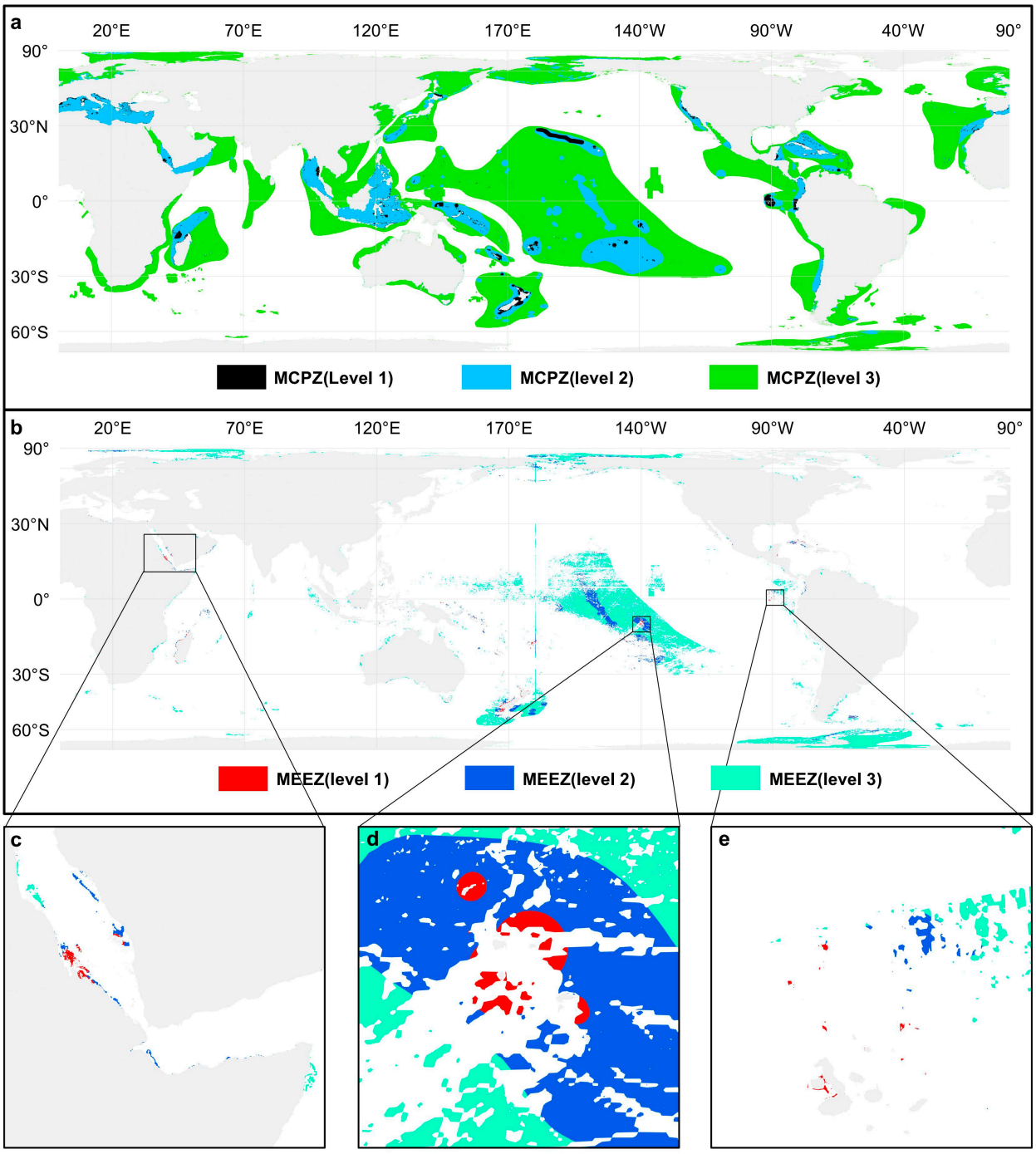

Figure 2. Global distribution of MCPZs (**a**) and MEEZs (**b**). (**c**–**e**) present zoomed-in views of selected areas highlighted in panel (**b**). MCPZs represent marine conservation priority zones identified from cross-framework agreement, while MEEZs represent marine ecological expansion zones where MCPZs overlap marine wilderness. Level 1 areas show the strongest cross-framework agreement, level 2 areas are identified by two frameworks, and level 3 areas are identified by one framework. Input years are BH 2016 [16], EBA 1998 [17], KBA 2024 [18], marine G200 2016 [19], and marine wilderness 2013 [23] (Table 1). Supplementary Figure S1 provides separate full-extent MCPZ and MEEZ maps with grayscale-distinguishable level classes. The panels display global source extents; the 101-IHO-sea clipping used for scenario percentages is described in Section 2.5 and does not limit the displayed map.

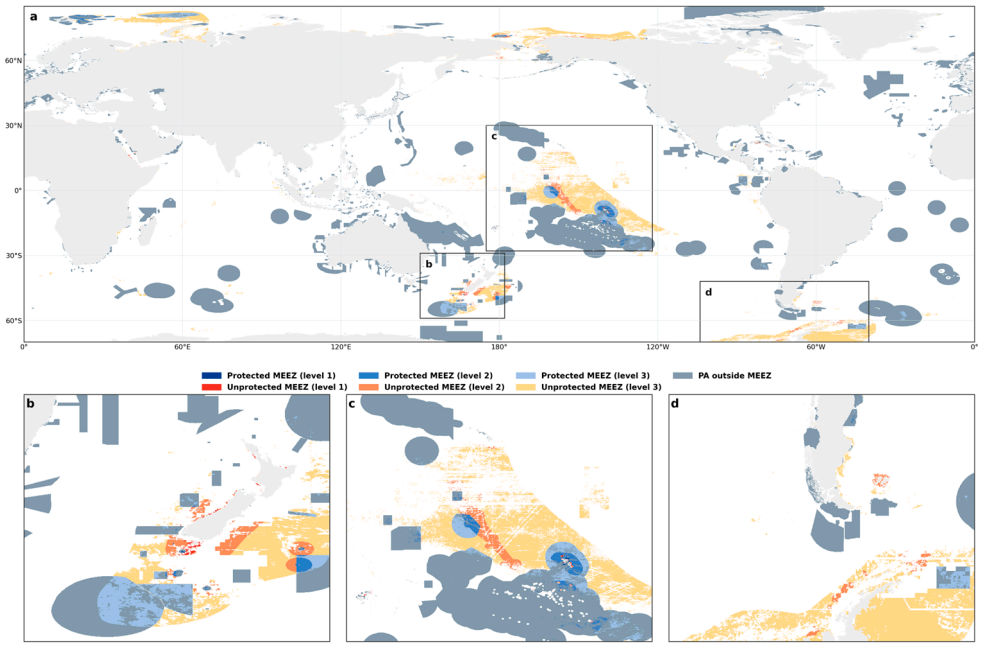

Figure 3. Global distribution of MEEZs and effective 2026 PA polygons. Panels (**b**–**d**) show the regions boxed and labeled in panel (**a**). Protected and unprotected MEEZs are distinguished by level. OECMs and proposed PAs are excluded from the PA baseline. Data sources: the four prioritization layers and 2013 marine-wilderness mask in Table 1, and the October 2026 Protected Planet PA polygon export. Area statistics use spatial unions; the map is a visual display of those polygons. Supplementary Figure S2 separates MEEZ level and PA overlap in full-extent grayscale panels. The main map retains the global distribution, whereas numerical coverage and scenario statistics are clipped to the 101 IHO sea areas; those two extents should not be combined in an area ratio.

3. Results

3.1. Marine Conservation Priority Zones

Figure 2a presents the global distribution of marine conservation priority zones (MCPZs), identified by integrating four global biodiversity prioritization frameworks. MCPZs collectively cover 31.22% of the global ocean (levels 1, 2, and 3 in Figure 2a), with concentrations along many continental margins and in parts of the open ocean. Some regions, including parts of the central Atlantic Ocean and southern Indian Ocean, show limited representation across the selected frameworks. The resulting pattern reflects spatial agreement among the four prioritization datasets rather than a comprehensive inventory of all marine biodiversity features. Because the source frameworks differ in geographic and taxonomic scope, sparse mapped agreement in the central Atlantic or southern Indian Ocean can reflect source-layer coverage as well as ecological pattern. We do not interpret absence of agreement as an absence of marine conservation value.

MCPZs are classified into three levels according to the number of biodiversity frameworks that identify the same area. Globally, level 1, 2, and 3 MCPZs account for approximately 0.43%, 6.22%, and 24.57% of the global ocean, respectively. Level 1 MCPZs, representing the highest cross-framework agreement within this screening framework, are concentrated mainly in coastal seas and parts of the central Pacific, with notable occurrences in tropical and subtropical regions. The coastal seas of Southeast Asia and islands of the South Pacific contain particularly dense clusters. Level 2 MCPZs, representing agreement between two frameworks, occur in areas such as the southern Gulf of Mexico, the Mediterranean Sea, and waters near northern Madagascar and India. Level 3 MCPZs, identified by a single framework, are more extensive and occur across temperate and subpolar regions

as well as large areas of the open ocean, including parts of the Atlantic, Pacific, Arctic, and Southern Oceans.

3.2. Marine Ecological Expansion Zones for Potential MPA Designation

Figure 2b maps the global extent of MEEZs, defined as MCPZs intersected with the published marine-wilderness mask. The spatially dissolved global mapped extent is 10,583,422.69 km^2. Clipping those polygons to the 101 IHO sea areas used for scenario accounting yields 10,576,936.16 km^2, or 2.91% of their summed 363,583,291.96 km^2 area. Within this common study domain, Levels 1, 2, and 3 cover 33,566.68, 1,204,995.22, and 9,338,374.26 km^2, respectively (0.01%, 0.33%, and 2.57%). The published marine-wilderness layer covers 13.2% of the global ocean [23], a statistic using its original global-ocean denominator. The leave-one-source-out test shows marked dependence on the selected inputs, especially BH; global-extent results by omitted source and agreement level are reported in Supplementary Table S2. At the global mapped extent, omitting EBA leaves the total MEEZ area essentially unchanged, whereas omitting BH retains approximately 42.00% of the baseline extent, a reduction of approximately 58.00%. This test measures source-selection sensitivity rather than ecological validity.

The spatial extent of MEEZs is substantially smaller than that of MCPZs, particularly in coastal waters of East Asia, Southeast Asia, and the Mediterranean, where human pressures are generally higher in the marine wilderness dataset. In contrast, in parts of the central Pacific and high-latitude oceans, MEEZs and MCPZs show greater spatial correspondence, reflecting lower mapped cumulative human impact in these regions.

Level 1 MEEZs are limited in extent and occur mainly in tropical regions (Figure 2c–e), including parts of the coastal seas of Central America and the central Pacific. Level 2 MEEZs cover a broader but fragmented area, with notable clusters in the central and southwestern Pacific. Level 3 MEEZs are the most extensive and are distributed mainly across the central Pacific and high-latitude regions, including waters off northern North America and the Drake Passage.

3.3. MPA Expansion Scenarios Within the 101 IHO Seas

Figure 3 shows the spatial relationship between MEEZs and effective marine or coastal PA polygons in the 2026 PA-only baseline. It identifies MEEZs that currently fall outside this network. Unprotected MEEZ areas remain extensive in parts of the Pacific (Figure 3b–d), especially among level 2 and level 3 zones. Existing PAs also extend beyond MEEZs along several continental margins. This spatial non-overlap should not be interpreted as evidence that existing PAs are misplaced, because they were designated under diverse ecological and policy objectives; it identifies additional low-human-pressure conservation opportunities under the present screening framework.

Within the 101 IHO sea areas, effective 2026 PA polygons cover 35,228,322.92 km^2, or 9.69% of their summed area. The MEEZ-PA intersection is 1,789,917.56 km^2, equivalent to 16.92% of the 10,576,936.16 km^2 in-domain MEEZ extent; 8,787,018.59 km^2 (83.08%) remains outside this PA-only baseline. These figures use the same sea-area clipping and dissolved PA union as the expansion scenarios. The global map in Figure 3 displays the full source polygons, so its mapped extent is slightly larger than the scenario study domain. Additional protection would require site-level ecological, social, and management assessment.

We used the three MEEZ levels to construct incremental MPA expansion scenarios. These scenarios are analytical rather than prescriptive: they quantify the area that would be added if progressively broader MEEZ categories were incorporated into the MPA network. The conservative target includes unprotected level 1 MEEZs, which have the highest cross-framework agreement and the smallest spatial extent. The moderate target additionally

includes unprotected level 2 MEEZs, while the ambitious target includes all unprotected level 1, 2, and 3 MEEZs. Because marine wilderness represents low cumulative human pressure rather than direct monetary or management cost, these scenarios should be interpreted as low-human-pressure expansion pathways rather than economically optimal solutions.

3.4. Regional MPA Expansion Scenarios

We summarized the three expansion scenarios across IHO (International Hydrographic Organization) Sea Areas and grouped sea areas according to the resulting protected-area proportions. Figure 4 shows the protection status of IHO sea areas under the ambitious scenario and highlights selected regional examples. Coverage was recalculated from spatial unions of effective 2026 PA polygons and unprotected MEEZs within each sea area.

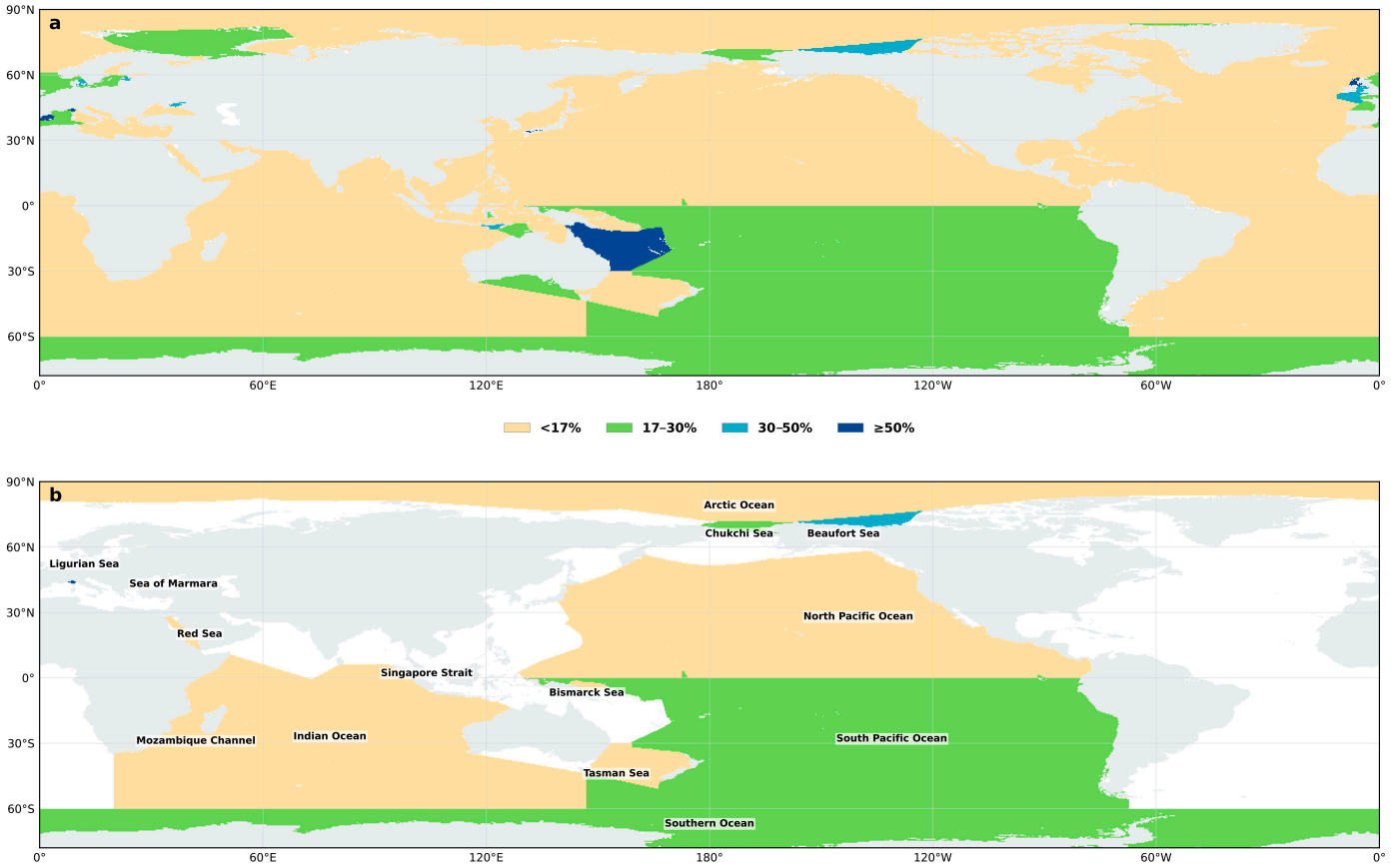

Figure 4. PA coverage of the 101 IHO sea areas under the ambitious scenario using the effective 2026 PA-only baseline (**a**), with selected regional examples (**b**). Each sea is categorized by its post-scenario PA coverage. Sources: 2018 IHO sea-area boundaries, the October 2026 Protected Planet PA polygons, and MEEZs based on the priority layers in Table 1 and the 2013 wilderness mask. Coverage uses each IHO sea's area as the denominator.

Analysis of existing PAs. Effective 2026 PA polygons cover 9.69% of the summed area of the 101 IHO sea areas analyzed. The largest mapped PA extents occur in the South Pacific Ocean (12,211,798.14 km^2), North Pacific Ocean (4,606,650.44 km^2), and Indian Ocean (4,286,129.71 km^2). Thirteen sea areas exceed 30% PA coverage, whereas 66 fall below 10%. The least-covered areas are the Sea of Marmara (0.00%), Labrador Sea (0.02%), and Bismarck Sea (0.10%).

Conservative target. Adding only unprotected Level 1 MEEZs contributes 22,336.50 km^2 (0.006 percentage points of the summed IHO sea area), raising PA coverage to 9.70%. The largest absolute additions occur in the South Pacific Ocean (11,736.47 km^2), Tasman Sea

(4449.27 km^2), and Red Sea (4352.01 km^2). The largest percentage-point increases occur in the Red Sea (0.97), Tasman Sea (0.13), and Mozambique Channel (0.06).

Moderate target. Cumulatively adding unprotected Levels 1 and 2 MEEZs contributes 755,924.94 km^2 (0.21 percentage points), raising PA coverage to 9.90%. The largest absolute additions occur in the South Pacific Ocean (438,900.95 km^2), North Pacific Ocean (132,898.57 km^2), and Tasman Sea (47,577.48 km^2). The largest percentage-point increases occur in the Beaufort Sea (3.17), Chukchi Sea (3.08), and Red Sea (2.11).

Ambitious target. Cumulatively adding all unprotected MEEZ levels contributes 8,787,018.59 km^2 (2.42 percentage points), raising coverage across the 101 seas to 12.11%. The largest absolute additions occur in the South Pacific Ocean (3,996,152.74 km^2), Southern Ocean (1,987,304.40 km^2), and North Pacific Ocean (1,631,769.42 km^2). The largest percentage-point increases occur in the Beaufort Sea (47.32), Chukchi Sea (26.70), and Barents Sea (11.24). Figure 5 maps the added PA area as a share of each sea.

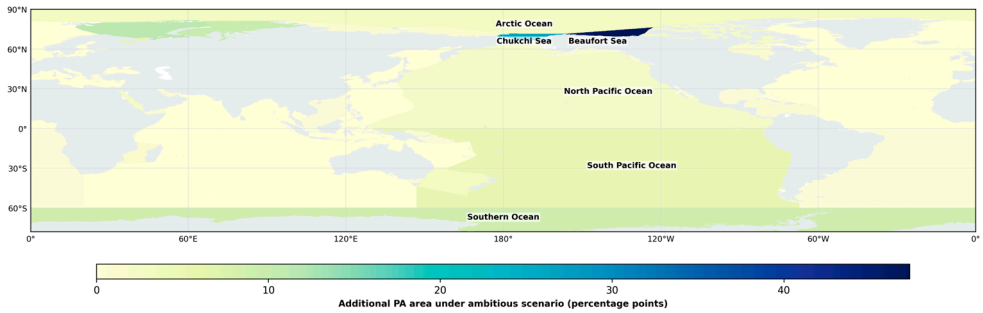

Figure 5. Additional PA area as a proportion of each IHO sea area (percentage-point increase) under the ambitious scenario relative to the effective 2026 PA-only baseline. Sources are the 2018 IHO sea-area boundaries, the October 2026 Protected Planet PA polygons, and the priority layers and 2013 marine-wilderness mask listed in Table 1. Full-resolution files for Figures 3–5 and Supplementary Figure S1 accompany the revision.

4. Discussion

4.1. Status of Current MPAs

MPAs are central to global biodiversity and sustainability agendas, but their spatial coverage and conservation outcomes vary substantially among regions. Our analysis shows that 16.92% of the in-domain, spatially deduplicated MEEZ extent overlaps effective 2026 PA polygons, leaving most mapped low-human-pressure conservation opportunities outside the present network. This result should not be interpreted as evidence that existing MPAs are ineffective or incorrectly located, because many MPAs were established to protect ecological features, species, fisheries, or social values that are not represented by the MEEZ framework. Instead, the observed non-overlap identifies areas that may complement the existing network if additional protection is pursued.

Implementation conditions also vary widely among countries and regions. Previous studies have shown that institutional capacity, funding, administrative coordination, stakeholder participation, and long-term marine spatial planning can strongly influence MPA performance and expansion [11,29,30]. Our spatial analysis does not directly measure these governance or socio-economic factors. Accordingly, marine wilderness is used here only to identify areas with relatively low cumulative human pressure. Such areas may present opportunities with potentially lower conflict related to direct human-use pressure, but decisions on designation still require explicit evaluation of local livelihoods, opportunity costs, enforcement needs, governance capacity, and ecological objectives.

4.2. Global Policy Implications

At the global scale, the MEEZ framework provides a spatially explicit screening of areas where cross-framework conservation importance coincides with comparatively low human pressure. These areas can contribute to broader implementation of the post-2020 Global Biodiversity Framework by identifying a subset of potential MPA expansion opportunities. Importantly, even the ambitious scenario raises polygon-based PA coverage across the 101 analyzed IHO sea areas only to 12.11%; the framework therefore does not constitute a complete spatial solution for achieving the 30 × 30 target. Rather, it identifies an initial set of areas that could be evaluated alongside additional biodiversity, connectivity, socio-economic, and governance criteria as countries and regions develop broader pathways toward 30 × 30.

This interpretation is consistent with recent work showing that conservation outcomes depend not only on spatial extent but also on management quality and local context [12,31]. The contribution of the present framework is therefore primarily spatial and ecological: it combines multiple biodiversity-prioritization signals with a low-human-pressure layer to identify candidate conservation opportunities. It does not directly quantify equity, economic efficiency, or governance feasibility. In practice, formal MPAs could be complemented by Other Effective Area-Based Conservation Measures (OECMs), particularly where local governance arrangements or resource-use patterns make formal protection less suitable [32]. Determining which instrument is appropriate requires context-specific assessment beyond the global screening conducted here.

Within the three-level framework, level 1 MEEZs represent the smallest set of areas with the strongest cross-framework agreement and may therefore provide a practical starting point for more detailed site-level evaluation. Level 2 and level 3 MEEZs broaden the spatial scope of potential expansion but also encompass increasingly heterogeneous ecological and management contexts. The accessibility of coastal areas, remoteness of offshore areas, fisheries use, enforcement requirements, and benefits or costs to local communities were not evaluated in this study and should not be inferred from MEEZ status alone. Consequently, MEEZs are best viewed as candidate areas for subsequent assessment rather than as locations that should automatically be designated as MPAs or OECMs.

4.3. Regional Policy Implications

Seven IHO sea areas have unprotected MEEZs occupying more than 5% of their area: the Beaufort Sea, Chukchi Sea, Barents Sea, Kara Sea, Southern Ocean, White Sea, and South Pacific Ocean. Six of these seven are high-latitude seas. This concentration indicates that the low-human-pressure opportunities identified by our framework are geographically uneven. High-latitude marine ecosystems are also important for climate regulation and carbon storage [33], but the presence of MEEZs in these regions should not be equated with low implementation cost or straightforward management. Their remoteness, transboundary setting, and exposure to rapid climate change may introduce substantial additional constraints [34]. Recent work on marine climate refugia considers projected environmental stability and cross-jurisdictional management [14]. The present analysis contains neither a climate-stability metric nor connectivity modeling; its high-latitude candidates must therefore not be described as climate refugia. Their remoteness and transboundary setting reinforce the need for regional governance and feasibility assessment.

Translating these spatial opportunities into conservation action would require coordinated governance and, in many cases, transboundary collaboration. Existing MPAs may provide a foundation for building more connected regional networks, while new candidate areas could be evaluated in relation to EEZ boundaries, ecological connectivity, national

priorities, governance capacity, and international cooperation [35,36]. These factors were not explicitly modeled here, but they are essential for moving from global screening to actionable marine spatial planning. The sea-by-sea results in Supplementary Table S1 summarize candidates selected by the same global rule; they do not normalize human pressure to regional baselines or rank all local conservation needs. Where no MEEZs are identified, the present output cannot supply a local candidate list and should not be interpreted as evidence of low conservation need. Regional application could instead rerun the overlay using updated, locally normalized pressure data together with marine species and habitat information, followed by governance assessment. More broadly, progress in marine conservation will depend on multilateral cooperation and context-sensitive implementation across national and international waters [31,37].

4.4. Limitations and Future Directions

This study has several limitations that define how the results should be interpreted. First, the four biodiversity prioritization frameworks were developed for different purposes, taxonomic groups, and spatial contexts; their overlap therefore represents cross-framework agreement rather than an exhaustive or weighted measure of marine biodiversity importance. Second, the marine wilderness dataset is static and does not fully capture temporal changes in anthropogenic pressures or climate impacts. Third, low cumulative human pressure is not equivalent to low economic, opportunity, enforcement, or management cost. The present analysis does not include fisheries value, shipping, offshore energy, distance to ports, governance capacity, or other socio-economic variables, and MEEZs should therefore not be interpreted as economically optimal sites. Fourth, the ambitious scenario reaches 12.11% polygon-based PA coverage across the 101 IHO sea areas analyzed and is intended to identify a subset of opportunities within a broader pathway toward the 30 × 30 target, not to specify the complete area needed to reach 30%. Future work should integrate dynamic human-pressure data, marine-specific biodiversity features, ecological connectivity, explicit socio-economic cost layers, governance indicators, and sensitivity analyses of alternative prioritization rules. Linking candidate areas with ecosystem-service valuation and blue-carbon storage could further clarify conservation co-benefits and the climate-biodiversity nexus [34,38,39]. Fifth, the global wilderness threshold is not locally normalized, so regions with relatively high background pressure may contain few or no MEEZs even when conservation needs are substantial. A regional analysis using locally normalized pressure data would produce a different candidate set and was not undertaken here. Sixth, marine-specific features such as seamounts, hydrothermal vents, deep-sea habitats, and migratory corridors are not independently represented, and no ecological-connectivity analysis was performed. Seventh, the input layers have uneven assessment coverage and the archived raster-to-vector settings cannot be completely recovered. No separate quantitative comparison of coastal and open-ocean bias was performed, so the influence of these limitations on that contrast remains unquantified. The 2013-era wilderness mask is a historical screening layer rather than verified present-day pressure. These limitations warrant regional pressure baselines, marine-specific data, connectivity analyses, and reconstruction of the overlay workflow in future applications. The BH input contains both hotspot area and outer limit polygons, and we retained both in the supplied source layer. The outer limit extends the broad regional envelope used in this cross-framework screen, so agreement classes and total MEEZ area depend on that source choice; Supplementary Table S2 quantifies the dependence. Neither BH category should be read as a direct marine-habitat validation.

5. Conclusions

This study combined four biodiversity-prioritization layers with marine wilderness to screen potential MPA expansion areas. The spatially dissolved global MEEZ map covers 10,583,422.69 km^2. Within the 101 IHO sea areas used for scenario accounting, MEEZs cover 10,576,936.16 km^2, including 1,789,917.56 km^2 (16.92%) overlapping effective 2026 PA polygons. Adding unprotected MEEZs across the three nested scenarios would raise PA coverage from 9.69% to 9.70%, 9.90%, or 12.11%. These candidate areas offer a first-stage spatial screen, not a complete pathway to the 30 × 30 target or a substitute for regional ecological, socioeconomic, and governance assessment. The largest absolute additions occur in the South Pacific, Southern, and North Pacific Seas, while the largest within-sea percentage-point gains occur in the Beaufort, Chukchi, and Barents Seas.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su182110843/s1, Figure S1: Full-extent maps of marine conservation priority zones (a) and marine ecological expansion zones (b) by agreement level; Figure S2: Full-extent maps of MEEZ agreement level (a) and MEEZ overlap with effective 2026 protected-area polygons (b); Table S1: Sea-by-sea PA and MEEZ areas and nested expansion scenarios across 101 IHO sea areas; Table S2: Leave-one-source-out sensitivity for the globally mapped MEEZ extent; Table S3: Scope and limitations of the prepared source layers used in the analysis.

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Data Availability Statement: The source datasets and access locations are listed in Table 1. The derived IHO scenario statistics, source-selection sensitivity results, and input-scope summary are supplied as Supplementary Tables S1–S3; full-extent maps are supplied as Supplementary Figures S1 and S2. No public repository or DOI has yet been assigned to the derived MCPZ and MEEZ polygons. The corresponding author can provide permissible derived outputs and processing details on reasonable request, subject to the redistribution terms of the underlying source datasets, including KBA boundary data.

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