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# Prioritizing Shark, Ray, and Chimaera Conservation in Rapidly Changing Polar Waters

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## ABSTRACT

Climate-driven alterations in sea-ice dynamics and shifting fishing activity are reshaping ecosystems across the Arctic and Antarctic, yet conservation-relevant information for chondrichthyans (sharks, rays, and chimaeras) remains limited. We present the first assessment of Important Shark and Ray Areas (ISRAs) across Polar Waters, integrating species distributions, extinction risk, critical habitat evidence, spatial protection coverage, apparent fishing effort (2013–2018 vs. 2019–2024), and sea-ice concentration trends. Of 86 chondrichthyan species reported from Polar Waters, only 15 (17.4%) had sufficient evidence to meet the ISRA Criteria, and 28 (32.6%) are threatened with extinction. We identified 35 ISRAs (27 Arctic; 8 Antarctic) covering 0.75% of the Polar Waters region. ISRAs were delineated predominantly based on data from scientific fishing surveys and harvest fisheries. Most Antarctic ISRAs were delineated under Criterion B—Range Restricted, reflecting endemism and scarce life-history evidence. Major knowledge gaps persist, particularly for highly adapted Polar Species (10 species) and deepwater taxa (72.1% of regional chondrichthyan fauna). Between 2013 and 2024, the spatial footprint of fishing expanded in both poles for trawlers and longliners, despite stable or declining fishing hours in some fleets. Concurrent areas of increasing fishing effort and decreasing sea-ice concentration remained minimal. However, apparent fishing effort overlapped with most ISRAs, indicating ongoing fishing pressure in critical habitats. Marine Protected Area (MPA) coverage remains uneven: 8.2% of Arctic ISRA spatial extent overlaps MPAs (0.8% no-take), compared with 43.8% in the Antarctic (14.8% no-take), with insufficient effective coverage in areas beyond national jurisdiction. These results reveal substantial mismatches between chondrichthyan critical habitats, fishing exposure, and existing protection measures. Integrating ISRAs into existing management frameworks, such as Target 3 of the Global Biodiversity Framework, High Seas Treaty mechanisms, and fisheries governance bodies, will be essential to safeguard vulnerable polar chondrichthyans as sea-ice concentration declines and exposure risk increases.

## 1 | Introduction

Biodiversity and climate are deeply interconnected, with species and ecosystems both shaping and being shaped by environmental conditions (Hoegh-Guldberg and Bruno 2010). This biodiversity-climate nexus is especially evident in the rapidly changing polar regions. The Arctic in the northern hemisphere and the Antarctic in the southern hemisphere are characterized by extreme seasonality, low temperatures, and high biological productivity (Hunt et al. 2016). In the Arctic, broad continental shelves and strong vertical nutrient mixing support high primary productivity, whereas in the Antarctic, it is driven by wind-forced upwelling and the Antarctic Circumpolar Current, the world's largest oceanic circulation system (Clarke and Harris 2003; Falk-Petersen et al. 2015). In both regions, surface production is sustained by nutrient-renewing processes in the euphotic zone, including vertical mixing and upwelling, advection, and sea-ice formation and melt; all of which are currently altered by warming waters and rapid sea-ice loss (Aguilar-Islas et al. 2008; Hoegh-Guldberg and Bruno 2010; Berge et al. 2012).

Climate change is reshaping ocean ecosystems with its effects most pronounced in the Arctic and Antarctic (Clarke et al. 2007; Gutt et al. 2021). Reduced sea-ice cover disrupts light regimes, seasonal productivity pulses, trophic pathways, and habitat stability, altering the timing and predictability of seasonal movements in polar marine fauna. These threats produce cascading ecological effects that remain poorly quantified compared to the visible retreat of sea-ice but are equally consequential (Dayton et al. 1994; Clarke et al. 2007; von Appen et al. 2021; Shuert et al. 2022). Sea-ice loss is also opening previously inaccessible waters to human extractive activities, including fisheries, shipping, and deep-sea resource exploration, intensifying pressure on vulnerable and pristine ecosystems (Halpern et al. 2015; Kapsar et al. 2023).

Poleward movements of fish communities are increasingly documented and projected to intensify under continued ocean warming (e.g., borealization in the Arctic; Campana et al. 2020; Fossheim et al. 2015; Mueter et al. 2021). Polar seas support major industrial fisheries including deepwater trawl, gillnet, and longline fisheries operating on continental slopes and seamounts, targeting a variety of species (e.g., Christiansen et al. 2014; Jørgensen et al. 2014; Taconet et al. 2019; Grilly et al. 2022). These fisheries are among the most spatially extensive human activities in polar regions (Christiansen et al. 2014; Halpern et al. 2015; Link and Watson 2019; Taconet et al. 2019). Major fisheries are now expanding into deeper and higher latitude waters (Christiansen et al. 2014; Taconet et al. 2019), reaching depths >1200 m, intensifying risk where baselines are difficult to establish and management is inadequate. Coupled with climate-driven poleward range shifts that are expected to increase the overlap between fisheries and high-latitude habitats (Campana et al. 2020; Mueter et al. 2021; Osgood et al. 2021), this raises concern that areas currently under low pressure could become hotspots of ecological vulnerability.

Chondrichthyans (sharks, rays, and chimaeras) play key ecological roles as meso- and apex predators in aquatic ecosystems influencing prey populations and nutrient dynamics (e.g., Dedman et al. 2024; Flowers et al. 2021). Polar chondrichthyans, many of which occur in deepwater environments, typically have restrictive life-history traits (slow growth, late maturity, low fecundity, long lifespans), making them especially vulnerable to even low levels of fishing mortality (García et al. 2007; Simpfendorfer and Kyne 2009; Finucci, Pacoureau, et al. 2024). Although rarely targeted in polar fisheries, they are regularly taken as incidental catch (bycatch) in commercial and small-scale community fisheries (García et al. 2007; Madigan et al. 2022; Finucci, Pacoureau, et al. 2024). Polar chondrichthyans remain largely under-prioritized in management, monitoring, and spatial planning frameworks, despite the elevated extinction risk status of many species (e.g., Finucci, Pacoureau, et al. 2024). Some polar fisheries have introduced certification conditions addressing chondrichthyan bycatch (e.g., Knapman et al. 2019) or monitoring and mitigation measures (e.g., Faure, Péron, and Grüss 2025). More broadly, however, monitoring and management remain uneven, and exposure risk is likely to rise with expanding fisheries, highlighting the need for effective design, implementation, and enforcement of management measures (Dulvy et al. 2021; Jacquemont et al. 2024). This includes much of Areas Beyond National Jurisdiction (ABNJ), where regulatory oversight is fragmented, compliance inconsistent, and where fishing effort remains extensive (McWhinnie 2009; Queiroz et al. 2019).

The governance framework covering Polar Waters is complex and largely does not account for climate-driven redistribution of vulnerable species, especially chondrichthyans (Scully 2011; Balton 2019; Santos et al. 2024; Williams et al. 2025). More than half of these waters lie within ABNJ, where oversight is shared among the United Nations Convention on the Law of the Sea (UNCLOS), the Arctic Council, various regional fisheries management bodies (e.g., North East Atlantic Fisheries Commission [NEAFC]), and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Although CCAMLR is recognized for its precautionary, ecosystem-based approach, its existing chondrichthyan-relevant measures are not designed around critical habitat protection. Given the insufficient inclusion of chondrichthyans in Marine Protected Area (MPA) design and broader spatial management globally (e.g., Mouton et al. 2024; Cochran et al. 2026), the integration of species-specific biocentric information on critical habitats for polar chondrichthyans is urgently needed.

The Important Shark and Ray Areas (ISRA) initiative was developed to address this gap for chondrichthyans by identifying discrete, ecologically significant habitats based on vulnerability, range restriction, life-history, and distinctive attributes (Hyde et al. 2022). Countries have committed to Target 3 of the Global Biodiversity Framework (GBF) to 'Conserve 30% of Land, Waters, and Seas by 2030' (CBD 2022), and the United Nations High Seas Treaty (Biodiversity Beyond National Jurisdiction, BBNJ; United Nations 2025) provides a landmark framework through which ABNJ MPAs can be designated, environmental impact assessments undertaken, and biodiversity data integrated into spatial management. In this context, the delineation of ISRAs in Polar Waters is timely, as emerging spatial planning initiatives create a policy window to incorporate chondrichthyan habitat information and address climate-driven change, thereby strengthening conservation of polar chondrichthyan habitats in a rapidly changing ocean.

This study describes ISRAs in Polar Waters and their overlap with key human pressures by: (1) examining chondrichthyan species richness, geographic range, and extinction risk status in Arctic and Antarctic waters; (2) summarizing delineated ISRAs by species, jurisdiction, criteria, and the research methods used to gather evidence; (3) quantifying overlaps between ISRAs and each of MPAs, Exclusive Economic Zones (EEZs), and ABNJ; and (4) assessing the relationship between fishing pressure and sea-ice concentration. We conclude by evaluating how ISRA outputs can inform precautionary, climate-responsive spatial management across Polar Waters, and by identifying key knowledge gaps and governance opportunities that must be addressed to strengthen chondrichthyan conservation.

## 2 | Methods

### 2.1 | Study Area

The ISRA 'Polar Waters' region (IUCN SSC SSG 2024) encompasses the high-latitude waters of both hemispheres (Figures 1 and 2). Regional boundaries were primarily defined based on the Food and Agriculture Organization of the United Nations (FAO) Major Fishing Areas. The Arctic Ocean (hereafter 'Arctic'; FAO Areas 18, 21, and 27) encompasses waters of the Arctic Basin, Greenland, Iceland, the Faroe Islands, Norway, and the far northern regions of Canada, the United States of America (USA), and Russia. The Southern or Antarctic Ocean (hereafter 'Antarctic'; FAO Major Fishing Areas 48, 58, 88, and partially 41) encompasses high-latitude waters around Antarctica including the Ross Sea, Amundsen Sea, and Weddell Sea; and includes the Sub-Antarctic islands of South Georgia and the South Sandwich Islands (British Overseas Territory; disputed by Argentina), Prince Edward Islands (South Africa), Heard Island and McDonald Islands (Australian external territory), and Kerguelen and Crozet Islands (French Southern and Antarctic Lands).

### 2.2 | Species Richness, Geographic Range, and Status

A chondrichthyan species list for the Polar Waters region was compiled from reference material (Ebert et al. 2021; Fricke et al. 2026; Last et al. 2016; Mecklenburg et al. 2018) and the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (hereafter 'IUCN Red List'; IUCN 2025). Species were included if: (a) they represented currently accepted taxonomic concepts; and (b) any part of their global geographic range fell within the region (IUCN 2025). Total species richness was compared to global diversity (Weigmann et al. 2024). Differences in species richness between the Arctic and Antarctic were compared using a Chi-square ($\chi^2$) test. Deepwater sharks and rays were identified following Finucci, Pacoureau, et al. (2024), with the addition of Dark-mouth Skate (*Bathyraja arctowskii*) and chimaeras following IUCN (2025). Taxa considered highly adapted to polar environments (i.e., primarily spatially distributed and reproducing in Arctic and/or Antarctic waters) based on the literature outlined above were termed 'Polar Species'.

Global extinction risk categories were collated from the IUCN Red List (IUCN 2025). Species are assessed in one of eight categories: Extinct (EX), Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), and Data Deficient (DD) (see IUCN (2012) for definitions). Threatened species are those assessed as CR, EN, or VU.

### 2.3 | Important Shark and Ray Area (ISRA) Delineation

ISRAs are delineated through the application of four criteria incorporating seven sub-criteria: Criterion A—Vulnerability (species considered threatened on the IUCN Red List); Criterion B—Range Restricted (where a species' distribution is entirely limited to one Large Marine Ecosystem [LME], or two adjoining LMEs, or in the absence of LMEs, the equivalent area of nearby LMEs); Criterion C—Life History (Reproductive Areas, Feeding Areas, Resting Areas, Movement, and Undefined Aggregations); and Criterion D—Special Attributes (Distinctiveness [related to distinct biological, behavioural, or ecological characteristics] and Diversity [species richness]). 'Qualifying Species' are those that meet one or more of the ISRA Criteria. Species satisfying Criterion A must also meet at least one additional Criterion to be a Qualifying Species (Hyde et al. 2022).

To delineate ISRAs in Polar Waters, a regional expert workshop was held in Tirana, Albania, in May 2024. Participants contributed to preliminary Areas of Interest proposals using contemporary information (2009–2024). At the end of the workshop, 55 candidate ISRAs (cISRAs) in the Arctic and 13 cISRAs in the Antarctic were agreed upon by consensus and subsequently submitted to the ISRA Independent Review Panel for peer-review.

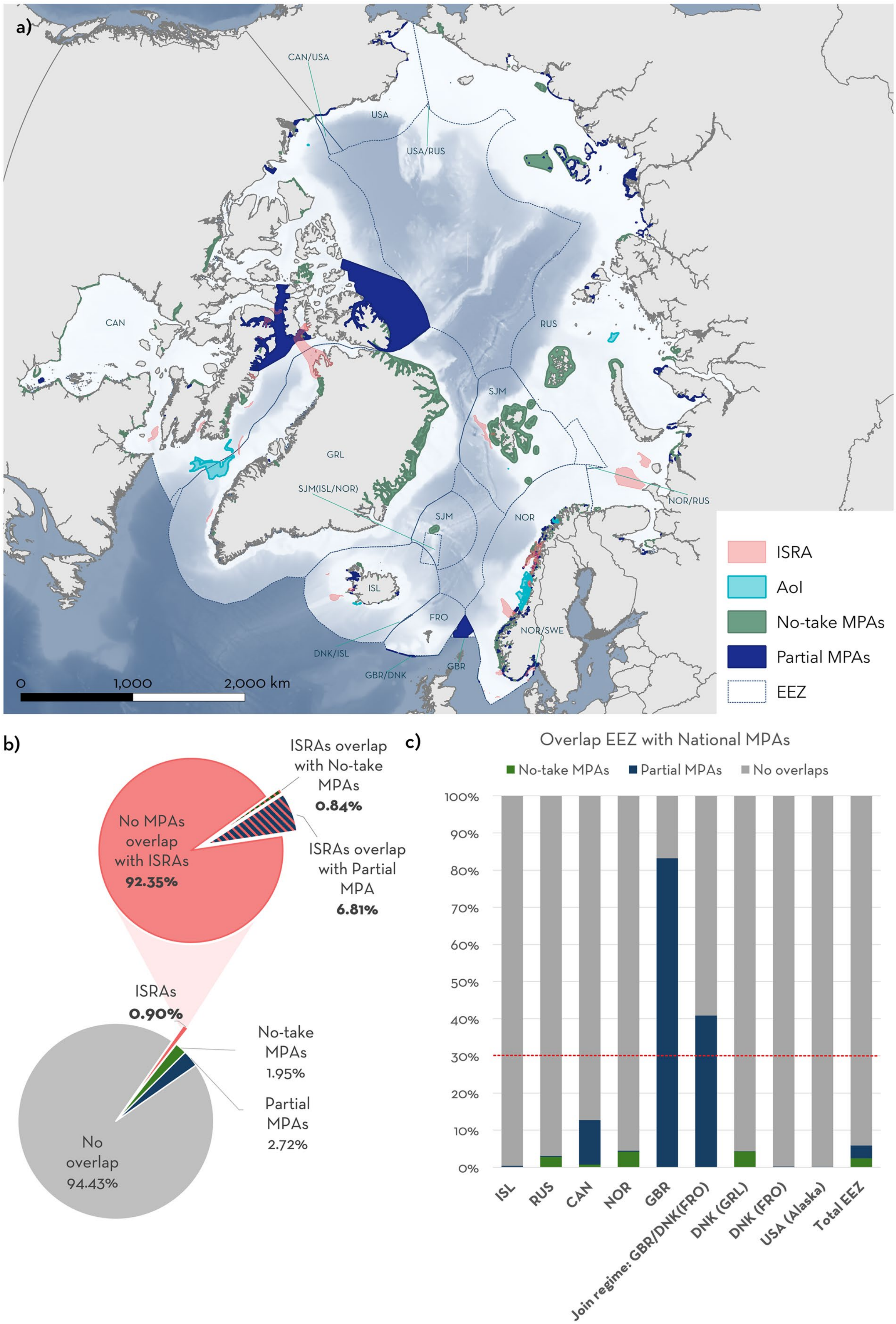


**FIGURE 1** | Legend on next page.

**FIGURE 1** | (a) Important Shark and Ray Areas (ISRAs) and Areas of Interest (AoI) delineated in Arctic Polar Waters (blue boundaries), shown in relation to nationally designated no-take or partial Marine Protected Areas (MPAs). (b) Regional overlap between ISRAs and MPAs. The bottom pie chart shows the proportion of the Arctic region that overlaps with ISRAs, and, of the remaining area, the proportion covered by no-take or partial MPAs. The top pie chart shows, within ISRA-overlapping areas, the proportion that is also covered by no-take or partial MPAs. (c) Percentage of Arctic Exclusive Economic Zone (EEZ) area within the Polar Waters region designated as no-take or partial MPAs for jurisdictions with > 0 spatial overlap with ISRAs. CAN, Canada; DNK, Denmark; FRO, Faroe Islands; GBR, United Kingdom of Great Britain and Northern Ireland; GRL, Greenland; ISL, Iceland; NOR, Norway; RUS, Russian Federation; SJM, Svalbard and Jan Mayen; SWE, Sweden; USA, United States of America.

Areas were designated as ISRAs if criteria were met or retained as Areas of Interest (AoIs) if insufficient support was available. The full ISRA delineation process is detailed in IUCN SSC SSG (2024).

Research methods (e.g., harvest fishing, scientific fishing surveys) and data types (e.g., demographic, spatial) used to support proposals were categorized following García-Rodríguez et al. (2025) and Gonzalez-Pestana et al. (2026) (Table S1).

### 2.4 | Overlay Analysis

To evaluate the spatial coverage and conservation relevance of critical chondrichthyan habitat, spatial overlays were conducted between ISRAs and three jurisdictional and management layers: (1) EEZs, (2) ABNJ, and (3) MPAs. ISRAs were also overlaid with the geographical ranges of Polar Species. When a species' current distribution did not encompass an ISRA where its occurrence was confirmed (i.e., as a Qualifying Species, the area of that ISRA was incorporated into the species' global range). EEZ and ABNJ layers were obtained from the Maritime Boundaries Geodatabase (Flanders Marine Institute 2024). All layers were clipped to the Polar Waters region boundaries using the OpenStreetMap coastline as a spatial reference (OpenStreetMap Contributors 2023), excluding permanent ice sheets in Antarctica.

MPA shapefiles were sourced from the World Database on Protected and Conserved Areas (WDPCA; UNEP-WCMC and IUCN 2025). In the Antarctic, 21 MPAs were reported only as point features; the corresponding polygons were therefore downloaded or manually digitized from official maps available through the Antarctic Protected Areas Database (SAT 2025). Polygons were filtered using WDPA attributes (UNEP-WCMC 2016) to exclude international designations, sites with *Proposed* or *Not Reported* status, terrestrial sites (*MARINE = 0*), and polygons with negligible marine spatial extent (*GIS_M_AREA* $< 1\,km^2$).

MPAs were classified as *no-take* (IUCN Categories I–III) or *partial* (Categories IV–VI and *Other*) following Day et al. (2019). No-take MPAs prohibit all extractive activities (Day et al. 2019), and partial MPAs allow some extractive activities. The resulting dataset was split to analyse National and Regional (*DESIG_TYPE = National and Regional*) MPA designations separately. Other area-based measures, including Other Effective Area-based Conservation Measures (OECMs) such as marine refuges or seasonal fishing closures, are not comprehensively reported in the WDPA and therefore not included in the MPA overlap analysis.

All spatial analyses and ocean surface area calculations were performed using the *terra* package (Hijmans 2025) in R (version 4.5.1; R Core Team 2025). Spatial layers were handled as *SpatVector* objects in the WGS84 coordinate system. Vector intersections were computed with *terra::intersect*, and surface area estimates with *terra::expanse* following recommended angular-unit procedures.

### 2.5 | Fishing Effort

Apparent fishing effort data were obtained from Global Fishing Watch (GFW) via the *gfwr* R package (GFW 2025), accessed in October 2025. We used the *Gridded Apparent Fishing Effort* dataset, which estimates fishing hours as cumulative hours that vessels are behaviourally classified as fishing based on Automatic Identification System (AIS) transmissions, rather than true gear deployment time or total time at sea.

Analyses focused on the two dominant AIS-detected gear types most prevalent in Polar Waters and detectable by AIS-based models (Taconet et al. 2019): *trawls* and *longlines* ("set_longlines" and "drifting_longlines"). Apparent fishing effort was extracted at 0.01° spatial resolution and annual temporal resolution for spatial overlays and summaries. To assess change in effort over time and allow for comparison, total apparent fishing hours were aggregated into two equal multi-year periods from the available GFW dataset (2013–2018 and 2019–2024). Aggregating fishing activity into time periods reduces interannual noise associated with variability in AIS coverage and vessel detectability, while retaining the ability to detect spatial and temporal shifts (Kroodsma et al. 2018; Taconet et al. 2019).

Fishing effort rasters were summarized for the Polar Waters region, ISRAs, EEZs, ABNJ, and MPAs using corresponding *SpatVector* polygon layers. Raster values were extracted for each polygon using the *exactextractr* R package (Baston 2023). For each polygon, we calculated: (1) total apparent fishing effort (hours; sum of raster values), (2) area of apparent fishing activity ($km^2$), and (3) apparent fishing intensity ($hours/km^2$). To estimate fishing area, GFW rasters were vectorized and intersected (*terra::intersect*) with the relevant study polygon and computed using *terra::expanse* following recommended angular-unit procedures.

### 2.6 | Sea-Ice Concentration and Apparent Fishing Effort Trends

To examine the relationship between fishing activity and sea-ice conditions, we analysed seasonal and annual trends in

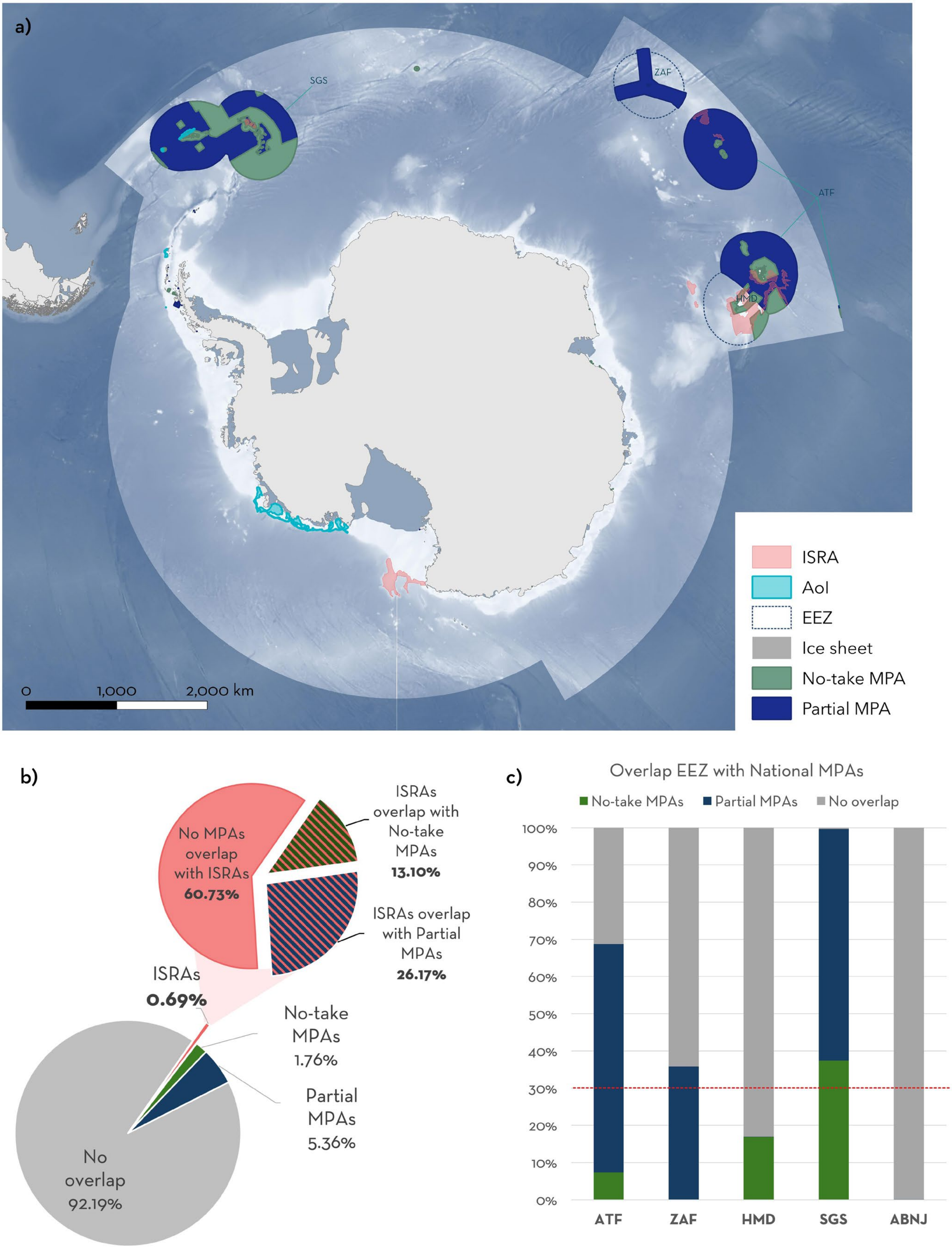


**FIGURE 2** | Legend on next page.

**FIGURE 2** | (a) Important Shark and Ray Areas (ISRAs) and Areas of Interest (AoI) delineated in Antarctic Polar Waters (blue boundaries), shown in relation to nationally designated no-take and partial Marine Protected Areas (MPAs), and jurisdictional boundaries of sub-Antarctic Exclusive Economic Zones (EEZ). (b) Regional overlap between ISRAs and MPAs. The bottom pie chart shows the proportion of the Antarctic region that overlaps with ISRAs and, of the remaining area, the proportion covered by no-take or partial MPAs. The top pie chart shows, within ISRA-overlapping areas, the proportion that is covered by no-take or partial MPAs. (c) Percentage of sub-Antarctic EEZ area designated as no-take or partial MPAs for jurisdictions with > 0 spatial overlap with ISRAs. SGS, South Georgia and the South Sandwich Islands; HMD, Heard and McDonald Islands (Australia); ZAF, Prince Edward Islands (South Africa); ATF, Kerguélen, Amsterdam and Saint Paul Islands, and Crozet Islands (France).

apparent fishing effort alongside sea-ice concentration over the period 2013–2024. Sea-ice concentration data were obtained from Copernicus Climate Change Service (C3C 2020) using the Global Sea Ice Concentration Climate Data Record (OSI-450-a) for 2013–2020 and the Global Interim Climate Data Record (OSI-430-a) for 2021–2024, both at a 25 km grid resolution (EUMETSAT Ocean and Sea Ice Satellite Application Facility 2022a, 2022b).

Monthly apparent fishing effort data for trawlers and longliners were downloaded from GFW at 0.1° spatial resolution and resampled to 25 km sea-ice grid using a sum preserving resampling approach (*terra::resample*, method = "sum"). Monthly, seasonal, and annual fishing effort totals were then derived for the entire region. Seasonal aggregations were defined as: December–February (DJF; winter in the Arctic, summer in the Antarctic), March–May (MAM; spring/autumn), June–August (JJA; summer/winter), and September–November (SON; autumn/spring).

Temporal trends in fishing effort were assessed at the regional scale using the Mann–Kendall test (*MannKendall* function; *Kendall* R package; McLeod 2022) at monthly, seasonal, and annual time scales. Evaluated parameters included total apparent fishing hours, fishing area ($km^2$), and fishing-effort intensity ($hours/km^2$).

To assess coupled spatial and temporal trends, Mann-Kendall tests were further applied at the pixel level to apparent fishing hours and sea-ice concentration at monthly and seasonal resolutions. Statistically significant trends were subsequently filtered using Kendall's $\tau$ threshold of ±0.4 to retain only consistent positive or negative trends, reducing the influence of interannual variability and episodic anomalies, and emphasizing effect size in addition to statistical significance (Cohen 1992).

## 3 | Results

### 3.1 | Species Richness, Geographic Range, and Status

Polar Waters support 86 chondrichthyan species comprising 42 sharks, 36 rays, and eight chimaeras (Table S2; S3), representing 6.8% of global chondrichthyan species richness (1266 species; Weigmann et al. 2024). Species composition was strongly divergent by pole, with species richness significantly higher in the Arctic (73 species) than the Antarctic (19 species) ($\chi^2 = 41.74$, df = 1, $p < 0.01$). Most species (72.1%) were 'deepwater', although nearly all (97.7%) had part of their depth range below 200 m (the depth threshold for the deepsea). Across Polar Waters, 28 species (32.6%) are threatened, comparable to global levels (33.3%; IUCN 2025). Extinction risk varies markedly between poles (Arctic, 37.0%; Antarctic, 15.8%). Among Polar Species ($n = 10$), three (30%) are threatened, five (50%) are LC, and two are DD (Tables S2 and S3).

### 3.2 | ISRA Delineation and Qualifying Species

Thirty-five ISRAs were delineated in the Polar Waters region (27 Arctic; 8 Antarctic), covering 397,738.6 $km^2$ (0.75% of the surface area) (Figures 1–2). Thirteen additional areas (9 Arctic; 4 Antarctic) were retained as AoIs and were not included in subsequent analyses. Details of each area are available on the ISRA e-Atlas (IUCN SSC SSG 2025). ISRAs spanned both national jurisdictions and ABNJ, with clear contrasts between poles (Figures 1–2; Table S3).

In the Arctic, ISRAs were identified within five national jurisdictions, with the largest numbers in Canada and Norway (9 ISRAs each), alongside smaller numbers in Iceland (3), Russia (2), and Greenland (1). Three ISRAs were transboundary, two of which spanned Canada–Greenland and one Denmark–Norway–Sweden. In the Antarctic, ISRAs occurred within the French EEZ (3), South Georgia and the South Sandwich Islands (1), transboundary areas between Australia–France (2), and ABNJ (2).

Across Polar Waters, 15 Qualifying Species comprising seven sharks, seven rays, and one chimaera (representing 17.4% of regional chondrichthyans, and 26% of those classified as threatened in the region) triggered ISRA delineation (Figure 3). Most ISRAs were delineated under Criterion C—Life History, particularly Sub-criteria C1—Reproductive Areas ($n = 14$) and C5—Undefined Aggregations ($n = 13$), with none under Sub-criteria C3—Resting Areas, D1—Distinctiveness, or D2—Diversity. Eight Qualifying Species are Polar Species, while no critical habitats were identified for Dark-mouth Skate and McCain's Skate (*Bathyraja maccaini*). Reproductive Areas (C1) and Undefined Aggregations (C5) were delineated for Antarctic Starry Skate (*Amblyraja georgiana*), Arctic Skate (*Amblyraja hyperborea*), Thorny Skate (*Amblyraja radiata*), and Eaton's Skate (*Bathyraja eatonii*), while ISRAs for Whiteleg Skate (*Amblyraja taaf*), Kerguelen Skate (*Bathyraja irrasa*), and Murray's Skate (*Bathyraja murrayi*) were delineated based on their restricted range (Criterion B) (Figure 3). Greenland Shark (*Somniosus microcephalus*) was the Qualifying Species included in the highest number of ISRAs ($n = 10$ Arctic ISRAs). In the Arctic, it was followed by Thorny Skate ($n = 5$ Arctic ISRAs) while in the Antarctic, Whiteleg Skate triggered the highest number of ISRAs ($n = 3$) (Figure 3).

Evidence supporting ISRA delineation derived primarily from: Scientific Fishing Surveys (8 species, 18 ISRAs) and Harvest Fishing (trawl and longline; 9 species, 10 ISRAs) (Figure 4).

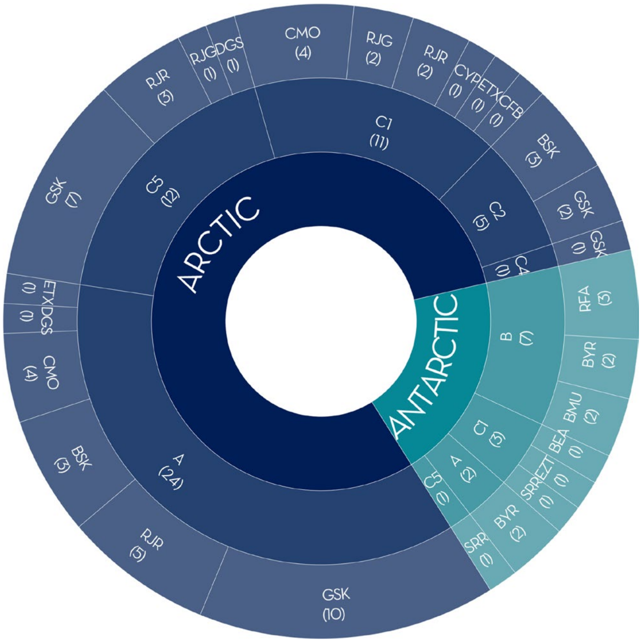


**FIGURE 3** | Number of Important Shark and Ray Areas (ISRAs) identified per species in the Polar Waters region, disaggregated by ISRA Criterion/Sub-criterion, and shown separately for the Arctic and Antarctic. Numbers in parentheses indicate the total number of ISRAs identified for each species across each Criterion/Sub-criterion in each region. Species are abbreviated as follows: *Amblyraja georgiana* (SRR), *Amblyraja hyperborea* (RJG), *Amblyraja radiata* (RJR), *Amblyraja taaf* (RFA), *Bathyraja eatonii* (BEA), *Bathyraja irrasa* (BYR), *Bathyraja murrayi* (BMU), *Centroselachus crepidater* (CYP), *Centroscyllium fabricii* (CFB), *Cetorhinus maximus* (BSK), *Chimaera monstrosa* (CMO), *Etmopterus spinax* (ETX), *Etmopterus viator* (EZT), *Somniosus microcephalus* (GSK), *Squalus acanthias* (DGS).

These methods supported criteria for 13 of 15 Qualifying Species in 29 of 35 ISRAs and were the sole evidence for ten species and 20 ISRAs. In the Antarctic, Harvest Fishing exclusively supported six of eight ISRAs and three of six Qualifying Species. Greenland Shark had the broadest evidence base: Scientific Fishing Surveys (7 ISRAs), Electronic Tracking (5), BRUVS (4), Trophic Ecology Studies (2), Local Ecological Knowledge (LEK; 2), and Harvest Fishing—Longline (1). Only two Qualifying Species (both Arctic) were supported independently of Harvest or Scientific Fishing: Basking Shark (*Cetorhinus maximus*) by Citizen Science (3 ISRAs) and Spiny Dogfish (*Squalus acanthias*) by LEK (1 ISRA).

All Polar Species overlapped with at least one ISRA, though ISRA coverage represented <10% of the distribution of most Polar Species ($n=6$), including Antarctic Starry Skate, Arctic Skate, Dark-mouth Skate, and McCain's Skate. The highest proportional overlap occurred for Whiteleg Skate (98.4% of their range within ISRAs), Kerguelen Skate (78.2%), and Murray's Skate (42.3%).

### 3.3 | MPA Coverage and Overlap With ISRAs

Across Polar Waters, MPAs covered 9.6% of the total surface area (5,083,899.4 km$^2$). Of the 1062 MPAs, no-take MPAs covered 4.2% of the region and partial MPAs covered 5.5% (Figures 1, 2, and 5). Thirty-six regional MPAs accounted for 3.3% of the region and 4.7% of ABNJ (0% of Arctic; 5.2% of Antarctic) (Table S7), while the remaining MPAs fell under national jurisdiction (Tables S7 and S8). The OSPAR Network (Arctic) included 34 MPAs covering 106,572.7 km$^2$ (0.2% no-take; 99.8% partial), and the CCAMLR area (Antarctic) contained two large MPAs covering 1,634,320.9 km$^2$ (73.5% no-take; 26.5% partial) (Figure 5). These two Antarctic MPAs accounted for 97.6% of MPA coverage in Antarctic ABNJ.

Nationally designated MPAs covered 3,446,610.5 km$^2$ (6.5% of the region; 1.9% no-take; 4.6% partial) (Table S8). In the Arctic, MPAs covered 5.8% of the total area under national jurisdiction (2.4% no-take; 3.4% partial). In contrast, 79.8% of Antarctic waters under national jurisdiction overlapped with MPAs (20.1% no-take; 59.7% partial) (Table S9). Arctic MPAs occurred across all eight EEZs and one of the six joint regime areas (the one overlapping claim area has no MPAs). Despite extensive spatial overlap with Polar Waters, six of these jurisdictions had MPA coverage well below the 30% called for under Target 3 of the GBF (Figure 1, Table S9). In the Antarctic, EEZs and overlapping-claim areas showed consistently higher levels of protection, with near-complete or complete MPA coverage in two jurisdictions and moderate coverage in two others (Figure 2, Table S9).

Overlap between ISRAs and MPAs was limited, particularly in the Arctic. Only 8.2% of the total Arctic ISRA area overlapped with MPAs (0.8% no-take; 7.4% partial), leaving 91.8% without MPA overlap. Eleven of 27 Arctic ISRAs (8.5% of total Arctic ISRA area) overlapped with MPAs, and six Arctic ISRAs (0.9%) overlapped with no-take MPAs (Table S10). In contrast, Antarctic ISRAs showed substantially greater congruence with MPAs: seven of eight Antarctic ISRAs (43.8% of Antarctic ISRA area) overlapped with MPAs, of which five included some no-take coverage (14.8%). Overlap between Polar Species' geographic ranges and no-take MPAs was <10% for five species, ranged 19.5%–31.4% for Kerguelen Skate, McCain's Skate, Dark-mouth Skate, and Eaton's Skate, and 51.4% for Murray's Skate. National partial MPAs encompassed large portions of the distributions of Whiteleg Skate (63.1%) and Kerguelen Skate (42.1%), while Arctic Skate, Thorny Skate, and Greenland Shark had <5% overlap.

### 3.4 | Fishing Effort and Overlap With Polar Species and ISRAs

Regional fishing trends differed between poles. In the Arctic, cumulative apparent trawling hours increased by 17.8% from 2013–2018 to 2019–2024, with a 26.1% increase in spatial extent (202,437 km$^2$ of newly fished area). Longline fishing effort decreased by 2.2% over the same period, but the spatial extent of fishing expanded by 34.7% with 80,620.09 km$^2$ of newly fished areas. In the Antarctic, apparent trawling hours increased by 24.7% and area fished by 22.6%. In contrast, longline fishing effort declined by 2.3%, but the spatial extent of fishing increased by 39.8%. In the Antarctic, 29,232.8 km$^2$ was newly explored by longliners and of 5073.3 km$^2$ by trawlers.

Patterns of fishing activity also differed across management zones. In the Arctic, trawling intensity declined in ABNJ and all MPAs, while spatial extent increased, primarily in ABNJ, but decreased in no-take MPAs (Figure 6). Longline intensity

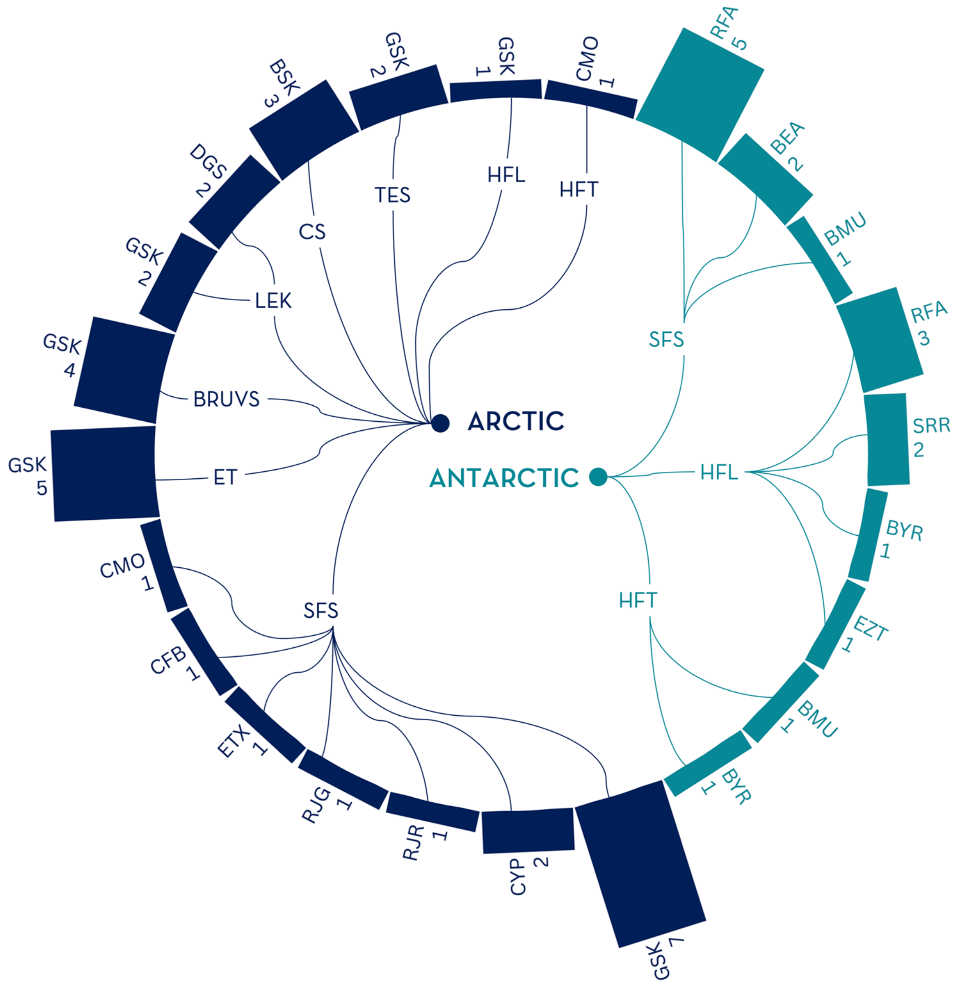


**FIGURE 4** | Evidence supporting Important Shark and Ray Area (ISRA) delineation in Polar Waters. Research methods are grouped by Arctic or Antarctic and separated by species. Research methods are abbreviated as follows: Baited Remote Underwater Video Station (BRUVS) surveys, Citizen Science (CS), Harvest Fishing—Longline (HFL), Harvest Fishing—Trawl (HFT), Local Ecological Knowledge (LEK), Scientific Fishing Surveys (SFS), and Trophic Ecology Studies (TES). Species are abbreviated as follows: Arctic—*Amblyraja hyperborea* (RJG), *Amblyraja radiata* (RJR), *Centroselachus crepidater* (CYP), *Centroscyllium fabricii* (CFB), *Cetorhinus maximus* (BSK), *Chimaera monstrosa* (CMO), *Etmopterus spinax* (ETX), *Somniosus microcephalus* (GSK), *Squalus acanthias* (DGS); Antarctic—*Amblyraja georgiana* (SRR), *Amblyraja taaf* (RFA), *Bathyraja eatonii* (BEA), *Bathyraja irrasa* (BYR), *Bathyraja murrayi* (BMU), *Etmopterus viator* (EZT). Numbers indicate the number of times in which each research method was used to support each Qualifying Species within ISRAs.

decreased in ABNJ and no-take MPAs but increased in partial MPAs, while the area under longline effort decreased in no-take MPAs and increased in partial MPAs and ABNJ. In the Antarctic, trawling intensity decreased in partial MPAs but increased in no-take MPAs, while its spatial extent decreased across all MPAs but increased in ABNJ. Longline intensity decreased in ABNJ and all MPAs, while the area under longline effort decreased in no-take MPAs and increased in ABNJ and partial MPAs (Figure 6).

Apparent fishing effort overlapped extensively with ISRAs, intersecting with 22 of 27 Arctic and all Antarctic ISRAs (Table S4). In the Arctic, the area with trawling and longlining effort increased, but intensity decreased. Arctic ISRAs with the highest trawling intensity in 2019–2024 were Skagerrak ISRA (76.23 h/km$^2$) and Rogaland Basin ISRA (21.3 h/km$^2$), while the highest longline intensities occurred in Lofoten ISRA (11.4 h/km$^2$) and Disko Shelf Break ISRA (8.5 h/km$^2$). Of 20 Arctic ISRAs experiencing trawling in 2019–2024, five had $>50\%$ of their area overlapping trawling effort (e.g., Skagerrak ISRA, 90.8%), and seven had 10%–49%. Among 14 ISRAs exposed to longlining in 2019–2024, four had 10%–49% overlap and the remainder $<10\%$.

In the Antarctic, overlap between ISRAs and longlining increased, while trawling area and intensity for both decreased. Trawling area was reduced from $<2\%$ to zero in the Eastern Del Cano, Kerguelen Islands Shelf, Eastern Kerguelen Slopes, and Heard Island & McDonald Islands ISRAs. Only the Ross Sea Slope ISRA retained trawling activity in 2019–2024 (1.8 h/km$^2$). For longlining, three of eight Antarctic ISRAs had 10%–49% overlap in 2019–2024, with the remainder $<10\%$. The highest longline intensities in Antarctic ISRAs in 2019–2024 occurred in Kerguelen Islands Shelf ISRA (3.1 h/km$^2$) and Ross Sea Slope ISRA (2.8 h/km$^2$). The largest increases in overlap between periods were observed in Ross Sea Slope ISRA (7.4% to 15.4%) and Eastern Kerguelen Slope ISRA (19.5% to 28.9%).

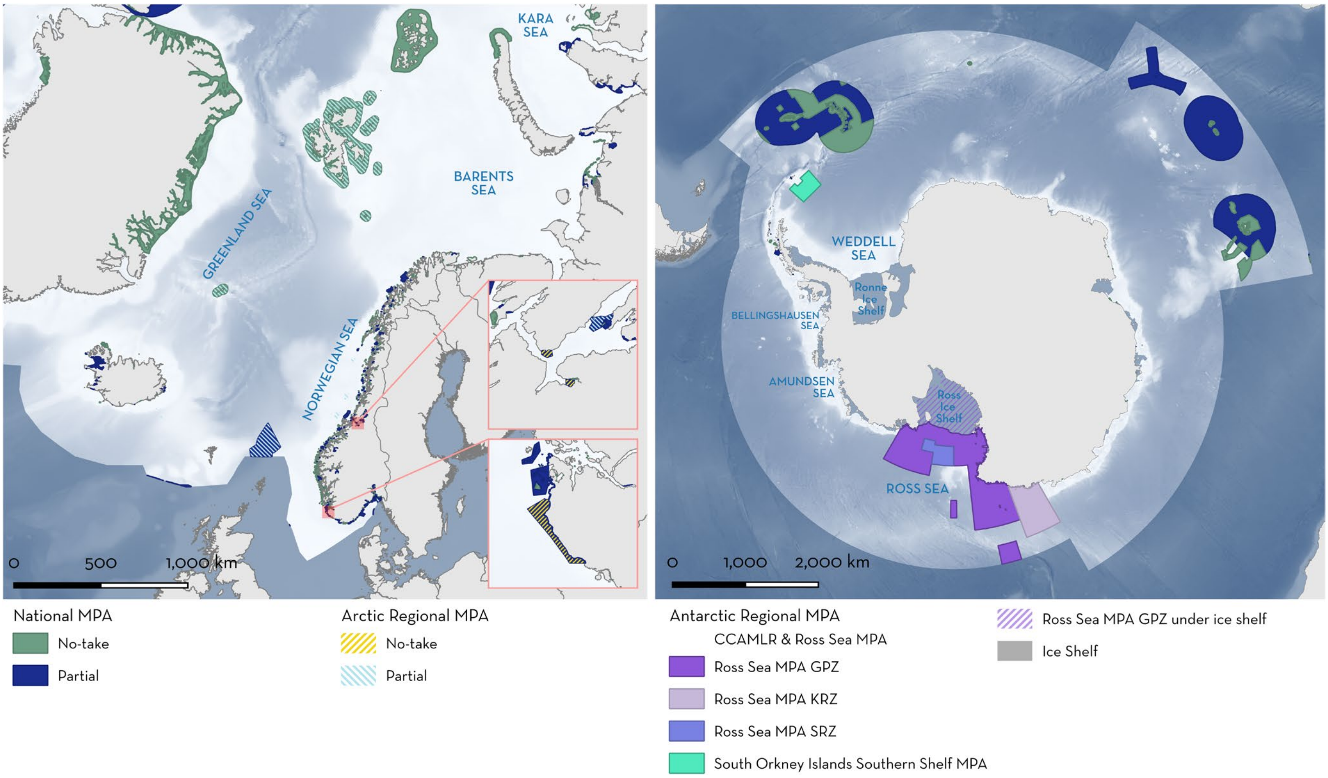


**FIGURE 5** | Coverage of regional Marine Protected Areas (MPAs) designated under regional conservation frameworks in Polar Waters, shown for the Arctic (OSPAR; left panel) and the Antarctic (CCAMLR; right panel). Polygons represent regionally designated MPAs, with nationally designated MPAs shown for comparison. Hashed polygons indicate areas of spatial overlap between nationally and regionally designated MPAs. CAT, category; GPZ, General Protection Zone; KRZ, Krill Research Zone; SRZ, Special Research Zone.

For Polar Species, the greatest overlap between their geographic ranges and trawling effort in 2019–2024 occurred for Thorny Skate (21.6%) and Greenland Shark (12.7%), while Whiteleg Skate, Kerguelen Skate, and Murray's Skate showed no overlap (Table S5). A similar pattern was observed for longlining, with Thorny Skate (9.9% overlap) and Greenland Shark (5.4%) showing the highest overlaps.

### 3.5 | Sea-Ice Concentration Trends and Overlap With Fishing Effort

Across Polar Waters, areas of significant sea-ice decline exceeded significant increases in all seasons, and were most pronounced in the Arctic during DJF (Figure 7). In Arctic DJF, significant sea-ice loss reached 1,653,081.2 $km^2$ (9.7% of the Arctic region), corresponding to a net decrease of 7.9% after accounting for areas of increase (9.7%–1.8%). In contrast, trawling activity showed greater areas of significant increase than decrease across seasons, although net increases remained $<0.5\%$ of the region, peaking in SON (310,245.9 $km^2$). For longliners, the area of significant increase exceeded those of significant decrease only in JJA (0.4%–0.3%); in all other seasons, the area of significant decreases dominated. Areas exhibiting simultaneous significant decrease in sea-ice concentration and significant increase in fishing effort were minimal in the Arctic. Pixel-wise comparisons of seasonal sea-ice concentration trends with GFW trawling activity identified a single area (15,726.6 $km^2$; 0.1% of winter fishing effort) where increased trawling overlapped with declining sea-ice ($\tau > 0.4$; $p < 0.05$), located in Greenland (11,303.6 $km^2$), Canada (2172.9 $km^2$), and Russia (2248.4 $km^2$), with no ISRA overlap. Longline fishing displayed a different pattern with the area of significant decrease exceeding that of significant increase in all Arctic seasons except JJA.

In the Antarctic (Figure 8), the largest net sea-ice declines occurred in MAM (8.8% [8.8%–0.1%]) and JJA (8.4% [9.0%–0.6%]), corresponding to 3,157,569.6 $km^2$ (8.8%) and 3,207,397.1 $km^2$ (9.0%) of significant sea-ice loss, respectively. Trawling also exhibited greater areas of significant increase than decrease during DJF, MAM, and JJA, although the net overlap remained minimal ($<0.1\%$ of the region in each season). For longline fishing, the area of significant decrease exceeded that of significant increase in all seasons. Pixel-wise analysis in the Antarctic showed no simultaneous significant decreases in ice concentration and significant increases in fishing effort, although monthly analysis identified a single pixel of overlap for longlining in December.

## 4 | Discussion

Our findings provide the first assessment of chondrichthyan conservation priorities across Arctic and Antarctic ecosystems. We identify evidence-based important areas and show strong divergence between poles in data availability, human pressures, and governance. ISRAs were shaped by ecological patterns and by substantial asymmetries in knowledge, sampling effort, and governance regimes. Despite the vast and rapidly changing

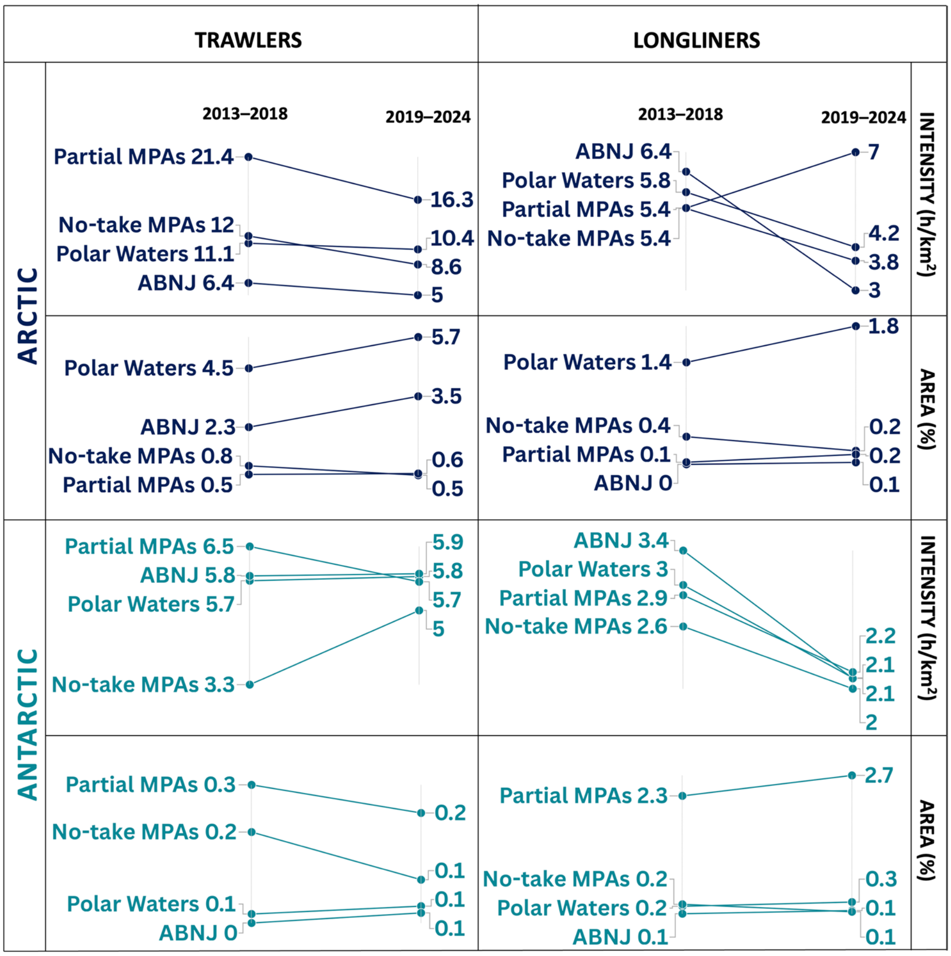


**FIGURE 6** | Apparent fishing intensity (hours/km$^2$) and the proportion of area experiencing apparent fishing activity by trawl and longline fleets within the entire Polar Waters region, areas beyond national jurisdiction (ABNJ), and Marine Protected Areas (MPAs; no-take and partial) in the Arctic (top panels) and Antarctic (bottom panels).

seascapes of Polar Waters, only a small subset of species had sufficient evidence to support the identification of critical habitats. Moreover, most Antarctic ISRAs were delineated under Criterion B—Range Restricted, reflecting locations of evolutionary endemism rather than direct evidence of life-history functions. Although spatial fishing expansion was modest to date, concerns remain about increased exposure risk associated with declining sea-ice. The largest declines in sea-ice concentrations currently occur in subarctic transition zones, and indications that similar declines may facilitate northward shifts in fishing effort constitute an early warning signal (Stroeve and Notz 2018). Protection remains sparse, uneven, limited in ABNJ, and far below the 30% stipulated under GBF Target 3; no-take MPAs reported to the WDPCA cover only 4.2% of Polar Waters. Collectively, our findings highlight key challenges for policy and conservation: (1) critical chondrichthyan habitats remain poorly resolved, especially in deepwater, ABNJ, and ice-associated environments; (2) climate-driven loss of sea-ice may enable fisheries expansion into ecologically sensitive areas faster than monitoring can track; (3) existing governance frameworks are not yet structured to incorporate species-specific habitat information such as ISRAs; (4) fishing exposure and strict protection are mismatched, with most ISRAs overlapping fishing effort but few overlapping no-take MPAs; and (5) considerable portions of both poles remain unfished and represent latent conservation opportunities that could be proactively integrated into spatial planning before fishing pressure expands. Together, these insights underscore the urgent need for coordinated research, precautionary spatial management, and integration of ISRAs into evolving polar conservation instruments.

### 4.1 | Available Evidence and Knowledge Gaps

ISRAs were delineated through synthesis of the best available information, yet critical habitat knowledge for chondrichthyans in Polar Waters remains incomplete. Species richness is relatively low in the region, with the fauna representing only 6.8% of the global diversity of chondrichthyans (Weigmann et al. 2024). Only 15 of 86 species (17.4%) had sufficient information available to be included as Qualifying Species. As a result, key life-history areas (e.g., nursery and feeding grounds) remain underrepresented or entirely unknown for most species, posing a fundamental barrier to designing effective management measures. Acute gaps persist for two Antarctic Polar Species: Dark-mouth Skate and McCain's Skate. Risk for polar chondrichthyans is exacerbated by the fact that most are deepwater, occupying depths > 200 m (Table S2), where insufficient protection (Jacquemont et al. 2024) and biological parameters (e.g., slow growth, long lifespans) confer high susceptibility to population depletion

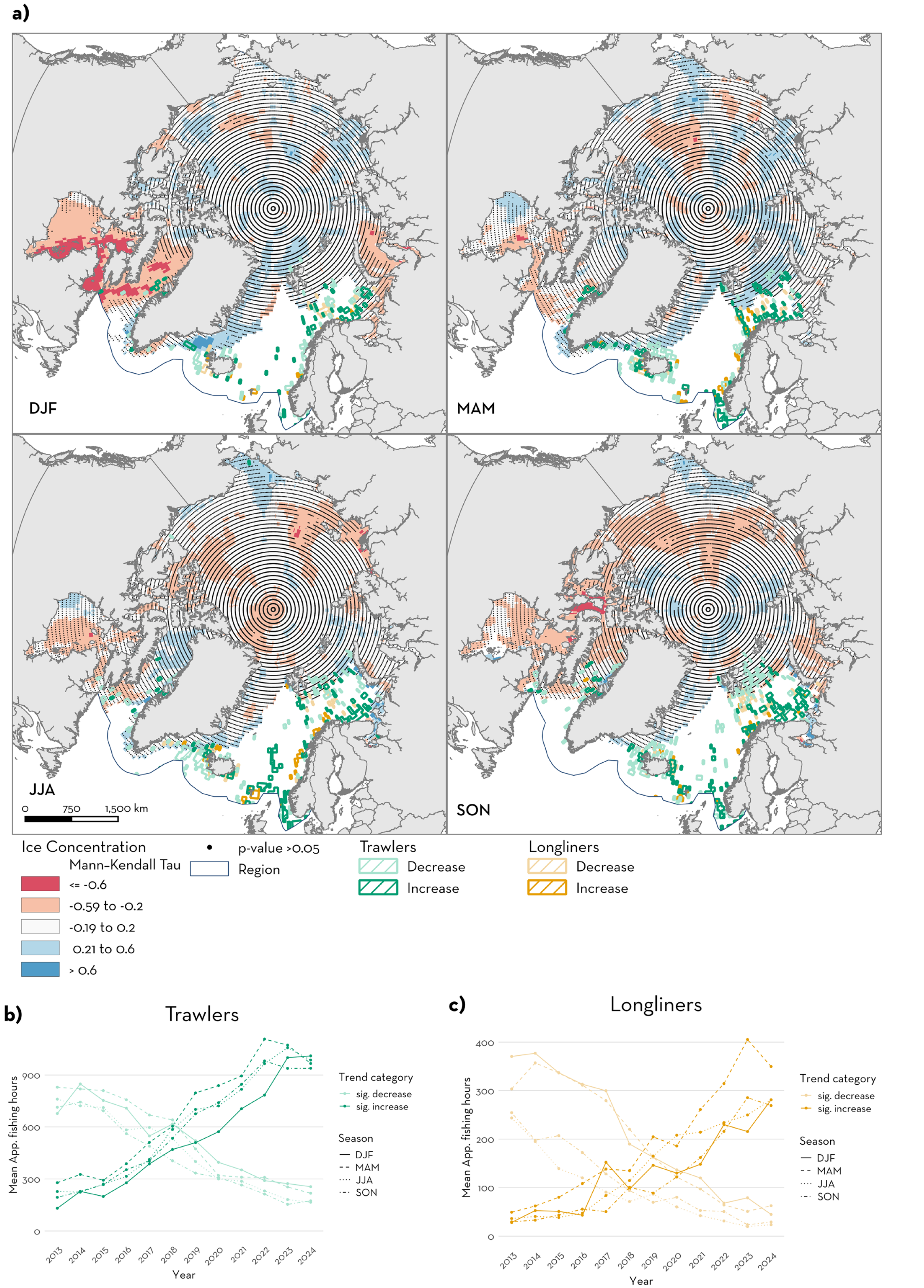


**FIGURE 7** | Legend on next page.

**FIGURE 7** | (a) Pixel-level seasonal Mann–Kendall trend results (τ, tau) for sea-ice concentration in the Arctic region (black points indicate non-significant sea-ice trends, $p$-value $> 0.05$), with overlaid polygons indicating pixels where apparent fishing hours show significant temporal trends (increasing: $\tau > 0.4$, $p < 0.05$; decreasing: $\tau < -0.4$, $p < 0.05$). Each panel represents a season: DJF, December–January–February; MAM, March–April–May; JJA, June–July–August; SON, September–October–November. (b) Mean annual apparent fishing hours (2013–2024) for trawlers calculated across pixels with significant increasing or decreasing fishing trends, shown by season. (c) Mean annual apparent fishing hours (2013–2024) for longliners calculated across pixels indicating significant increasing or decreasing fishing trends, shown by season.

(Finucci, Pacoureau, et al. 2024; García et al. 2007; Simpfendorfer and Kyne 2009). Polar chondrichthyan taxonomy and biogeography remain incompletely resolved, and evolving knowledge is likely to improve understanding of diversity, geographic ranges (e.g., taxonomic resolution of *Amblyraja* skates; Mecklenburg et al. 2018) and critical habitats (e.g., Finucci, Chin, et al. 2024), enabling updates to existing knowledge in the face of a changing seascape (e.g., shifting geographic and depth ranges).

Knowledge gaps are strongly shaped by the types of data available. In the Antarctic, most ISRAs were triggered by the application of Criterion B—Range Restricted. Further, biological information originated primarily from fisheries-dependent sources, especially incidental catch in longline and trawl fisheries, which limits documentation of reproductive condition (e.g., pregnancy, number of egg cases), early life stages (due to selectivity of fishing gear), and movement ecology. This pattern mirrors broader challenges in deep-sea and polar research, where available data frequently reflect the spatial footprint of sampling (e.g., CCAMLR observer program) rather than true ecological patterns (Finucci et al. 2022). Ship-based surveys, long-term monitoring, and electronic tracking studies remain limited due to high operational costs and remote conditions (e.g., Mallory et al. 2018; Graiff et al. 2023; Appert et al. 2025). Moreover, chondrichthyans captured in surveys or fisheries are often released with minimal biological sampling to minimize handling time, further restricting demographic inference (e.g., size, sex, maturity). Despite these constraints, scientific fishing was the most frequently used research method supporting ISRA delineation across Polar Waters. Only three Qualifying Species (Greenland Shark, Basking Shark, Spiny Dogfish) benefited from evidence independent of commercial fisheries such as electronic tagging (e.g., Hussey et al. 2015, 2018; Edwards et al. 2021, 2022; Madigan et al. 2022), BRUVS (Devine et al. 2018, 2019), or citizen science (IMR 2024). This likely reflects targeted research interest (e.g., Greenland Shark ecology), accessibility of surface-aggregating species (e.g., Basking Shark), and the presence of management and industry mechanisms that create incentives to document bycatch and improve monitoring in operational fisheries (e.g., certification-related conditions and co-management priorities in parts of the Canadian Arctic; Knapman et al. 2019).

Expanding advanced research methods in Polar Waters provides an opportunity to strengthen the existing knowledge base. Collaborative monitoring approaches that combine camera-based methods (including BRUVS) with partnerships among researchers, communities, industry, and management agencies, offers a practical pathway to expand observations in remote areas and generate nonlethal evidence of critical habitat (Forbes and Fisher 2025). Diversifying research methods (e.g., telemetry) could also strengthen the knowledge base for poorly studied taxa such as many rays and chimaeras. This is particularly important for species captured from extreme depths, where post-capture survival is low or individuals are routinely retrieved dead or severely compromised (e.g., deepwater dogfishes on longlines), limiting the utility of release-based approaches (e.g., Appert et al. 2025). Integrating empirically derived ecological observations from Traditional and Local Ecological Knowledge (TEK and LEK), including Inuit Qaujimajatuqangit (IQ), can provide complementary information on species distribution and habitat, particularly in regions difficult to access through conventional surveys. When systematically documented, and considered alongside independent scientific evidence, such observations can complement conventional datasets and strengthen the evidence base for ecological assessments while maintaining scientific rigor (e.g., Rathcke et al. 2025). Additionally, camera-based monitoring and community-led sampling can strengthen inference while maintaining relevance to co-managed decision-making and practical monitoring constraints (Forbes and Fisher 2025).

### 4.2 | Risk Of Expanding Fisheries Under Climate Change

Fishing activity in the Polar Waters region reveals a mismatch between the ecological significance of depth-structured habitats for polar chondrichthyans, which are predominantly deepwater species, and the spatial configuration of current protection and management frameworks. Apparent fishing effort overlapped 22 of 27 Arctic ISRAs and all Antarctic ISRAs, with increases in combined trawl and longline effort within ISRAs across both assessed periods. In the Arctic, fishing effort is concentrated at upper and lower bathyal depths, which also exhibit the lowest coverage by MPAs and OECMs (Jacquemont et al. 2024). Globally, fishing patterns are strongly structured by bathymetry: euphotic to upper-bathyal ecosystems experience the highest fishing pressure from mobile bottom-contact gears (e.g., trawls), whereas deeper environments are increasingly accessed by bottom-set longlines and gillnets, with some regions showing steadily expanding effort into greater depths (Jacquemont et al. 2024). These depth-specific patterns intersect directly with the physiological and life-history constraints of deepwater chondrichthyans. Maximum intrinsic population growth rates decline sharply with depth and temperature (Pardo and Dulvy 2022; Simpfendorfer and Kyne 2009), and warming increases metabolic demand (Hoegh-Guldberg and Bruno 2010), reducing surplus energy available for growth, fecundity, and survival (e.g., Coulon et al. 2026). Observed poleward range shifts of Arctic skates during warm periods (e.g., Barents Sea; Dolgov and Prozorkevich 2022), together with poleward expansions of two deepwater sharks and one chimaera and shifts in their population centers of gravity (e.g., Norwegian Sea; Jac et al. 2026) point to emerging climate-fishing interaction risks. As a result,

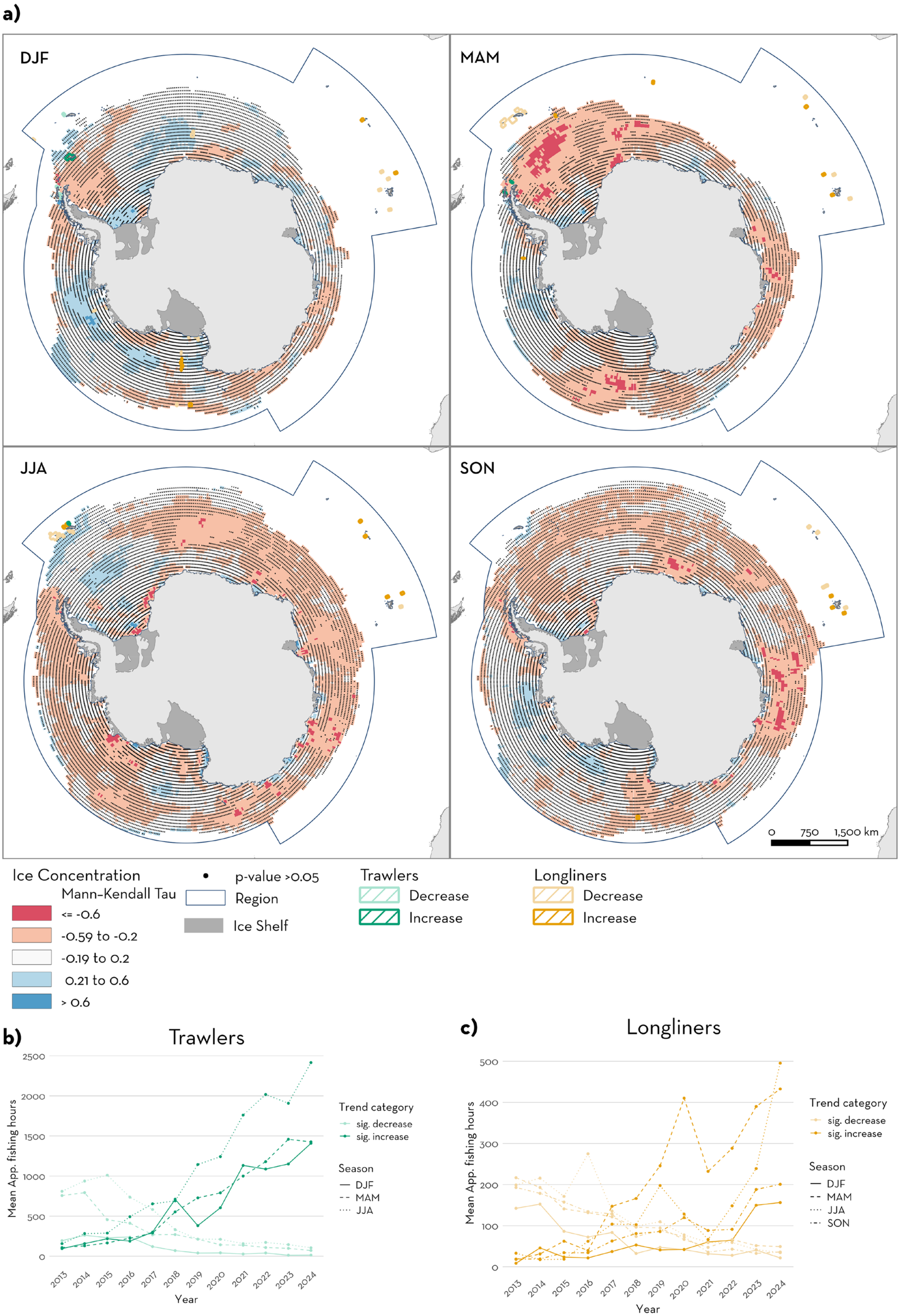


**FIGURE 8** | Legend on next page.

**FIGURE 8** | (a) Pixel-level seasonal Mann–Kendall trend results (τ, tau) for sea-ice concentration in the Antarctic region (black points indicate non-significant ice trends *p*-value $> 0.05$), with overlaid polygons indicating pixels where apparent fishing hours show significant temporal trends (increasing: $\tau > 0.4$, $p < 0.05$; decreasing: $\tau < -0.4$, $p < 0.05$). Each panel represents a season: DJF, December–January–February; MAM, March–April–May; JJA, June–July–August; SON, September–October–November. (b) Mean annual apparent fishing hours (2013–2024) for trawlers calculated across pixels with significant increasing or decreasing fishing trends, shown by season. (c) Mean annual apparent fishing hours (2013–2024) for longliners calculated across pixels indicating significant increasing or decreasing fishing trends, shown by season.

even low levels of exploitation could produce demographic impacts, with polar chondrichthyans particularly susceptible given their temperature and depth preferences. Importantly, in areas where industrial fisheries operate at high intensity, bycatch management measures for chondrichthyans should be closely linked to conservation measures for commercially targeted finfish species, recognizing that spatial and gear management for target species will often determine chondrichthyan exposure levels (e.g., Finucci, Pacoureau, et al. 2024).

Climate-driven changes further compound these pressures. Declining sea-ice alters the timing, magnitude, and spatial coupling of primary and secondary production (Dalpadado et al. 2020), with cascading effects throughout food webs. Ice-associated carbon supports a large fraction of Arctic consumers year-round (Koch et al. 2023), such that trophic responses may lag physical sea-ice decline as sympagic carbon continues to be incorporated into pelagic and benthic pathways. This temporal decoupling between sea-ice loss and trophic responses can buffer short-term ecological change but complicates detection of fisheries-climate interactions over decadal timescales. Reduced seasonal ice cover is nevertheless expected to weaken sympagic–pelagic–benthic coupling and reorganize prey fields for benthic and demersal predators (Atkinson et al. 2025). In parallel, declining ice extent facilitates boreal species incursions and community redistribution ('borealization'), exemplified by Atlantic Cod (*Gadus morhua*) predation on Polar Cod (*Boreogadus saida*) increases during low-ice years (Langangen et al. 2025). Together, these processes suggest that climate change can indirectly modify deepwater trophic dynamics, even when ice loss primarily affects surface habitats.

The reduction in sea-ice concentration is also reshaping human access to polar environments. Vessel activity, including fishing vessels, cargo ships, tankers, and icebreakers, increases markedly in ice-free waters and marginal ice zones, with higher ice concentration consistently suppressing vessel traffic (Kapsar et al. 2023). Although projections indicate the possibility of an ice-free summer before 2030 (Heuzé and Jahn 2024), fisheries tend to respond more slowly than shipping to newly accessible waters, as activity depends on the distribution of target species, regulatory constraints, and economic viability. Consistent with this, our findings showed little overlap between newly ice-free areas and recent fishing expansion, possibly reflecting lagged responses, and strong seasonality, as most fishing occurs during periods of reduced sea-ice (typically summer months). Rather than contradicting global studies of spatial fleet expansion, these results suggest that future shifts in polar fishing effort will be driven primarily by regulatory change and redistribution of commercially valuable finfish (e.g., cod), rather than ice accessibility alone (Campana et al. 2020; Christiansen et al. 2014; Mueter et al. 2021). As target species shift into higher latitudes and deeper waters, associated fisheries may follow, exposing critical habitats, including poorly resolved reproductive, foraging, resting, and aggregation areas, to disturbance before their ecological functions can be fully understood. At current latitudes, fisheries may also reconfigure through target switching as boreal species advance northward (e.g., Barents–Svalbard transition), with implications for bycatch exposure of polar chondrichthyans (Christiansen et al. 2014). Importantly, substantial portions of both polar regions, particularly in marginal shelf seas of the Arctic and higher-latitude of the Antarctic beyond toothfish (*Dissostichus* spp.) operations, currently experience limited or no fishing pressure. These areas represent important latent refugia for chondrichthyans, and proactive spatial planning drawing on ISRAs could help ensure they are not subjected to unregulated exploitation as access improves with declining sea-ice.

Monitoring limitations can add uncertainty to fishing exposure estimates. AIS-based datasets capture a small fraction ($< 1\%$) of the estimated global fleet and typically exclude vessels $< 12$ m (Kroodsma et al. 2018), creating blind spots in Arctic coastal and small-scale fisheries. These gaps lead to an underestimation of true fishing pressure, particularly in remote or seasonally ice-covered areas. Conversely, apparent fishing layers can also produce implausible signals in some regions if vessels are misclassified or research activity is interpreted as fishing (Harry and Braccini 2021). In parts of the Russian Arctic (e.g., Kara–Laptev–East Siberian sectors), commercial fishing is limited, suggesting that localized apparent fishing signals should be treated with higher uncertainty when interpreting spatial patterns and attributing drivers. Cross-validation against national statistics and Regional Fisheries Management Organization (RFMO) datasets, alongside improved data sharing, will be important to address limitations of AIS-based datasets and strengthen interpretation of exposure risk for Polar Species.

Governance responses to expanding fisheries differ sharply between the poles. The Central Arctic Ocean Fisheries Agreement (CAOFA) prohibits commercial fishing in the portion of the high seas that borders Canada, Denmark, Norway, Russia, and the United States of America, until sufficient scientific information is available, providing a strong precautionary model (Balton 2019). In the Antarctic, southward expansion of longline fleets has continued despite comparatively modest regional sea-ice decline. Still, fishing expansion is constrained by CCAMLR's precautionary framework, which includes prohibitions on shark-directed fisheries, restrictions on bottom-contact gears, depth and spatial controls for toothfish fisheries (e.g., fishing prohibited $< 550$ m), and bycatch limits with move-on rules for rays when bycatch exceeds defined limits per unit effort (CCAMLR 2024; Table 1). New and exploratory fisheries are constrained under CCAMLR research protocols and climate-driven habitat change is beginning to intersect with CCAMLR spatial planning (e.g., Special Areas for Scientific Study considered to prevent premature fishing in newly exposed habitats; Chavez-Molina et al. 2023). The combination of these measures has reduced fishing pressure and, in some cases, supported post-release survival (e.g., Whiteleg Skate in the Crozet Islands fishery; Faure et al. 2024; Faure, Péron, Jones, et al. 2025). Nevertheless, the risk to polar chondrichthyans is not fully eliminated, as many species remain highly susceptible to longline capture and exhibit low post-release survival (Campana 2016; Finucci, Pacoureau, et al. 2024). Where release is feasible, survival can be improved through species-appropriate handling, gear configuration, and release protocols (e.g., Ellis et al. 2017; Stamp et al. 2026), although taxa captured from extreme depths may be compromised regardless of handling and release practices (Appert et al. 2025).

### 4.3 | MPAs And Future Management

Protection across Polar Waters remains sparse and uneven, particularly in ABNJ, despite ABNJ comprising more than half of the study area. Our analysis revealed minimal overlap between ISRAs and existing MPAs in the Arctic, moderate overlap in the Antarctic, and limited coverage in ABNJ. However, ABNJ protection is strongly pole-specific: the Antarctic contains two large CCAMLR MPAs that account for nearly all regional MPA coverage in ABNJ, whereas Arctic ABNJ lacks comparable regional MPA coverage. This mismatch highlights a critical policy gap in which current spatial protections do not align with the depth ranges, life-history needs, or ecological sensitivities of polar chondrichthyans. This gap is particularly clear in the Arctic, where only 8.2% of ISRA area overlaps any MPA (only 0.8% no-take), leaving 91.8% of Arctic ISRA extent without MPA overlap. In contrast, Antarctic ISRAs show greater congruence with MPAs (43.8%), although only 14.8% overlap no-take zones, indicating that even the world's largest MPAs (e.g., the Ross Sea MPA) do not cover the most important habitats, which remain outside strict protection. Similarly, for some threatened species such Thorny Skate and Greenland Shark, whose distributions show the highest overlap with trawling and longlining effort, there is little overlap with national or regional MPAs.

Still, some existing governance frameworks already provide some protection for chondrichthyans (Table 1). Several ISRAs overlap with national or regional fisheries closures and marine refuges that function as OECMs and may provide meaningful protection for habitats relevant to chondrichthyans. However, these are inconsistently reported globally and are not captured in WDPCA-derived layers, highlighting both unrecognized conservation value and limitations of current global datasets. For example, the Disko Fan Conservation Area in Canada (DFO 2024) overlaps with an ISRA for Greenland Sharks, while fisheries closures implemented under Russian national regulations and industry voluntary bottom-trawl exclusion areas in the Barents Sea overlap areas important for Thorny Skate (ICES 2024). Species-specific measures can also complement protection. Despite the low overlap with MPAs and high overlap with fishing effort, Greenland Sharks are protected under North Atlantic Fisheries Organization (NAFO) conservation measures which prohibit directed fishing for this species and require the release and reporting of incidental catches (NAFO 2026, COM Doc. 22-27; Table 1). Furthermore, although the Vulnerable Marine Ecosystems (VME) closures currently implemented by CCMLR, NAFO and NEAFC do not overlap ISRAs identified in this study, they demonstrate that fisheries management bodies possess established mechanisms for implementing area-based conservation measures and could provide a practical framework for incorporating ISRAs (including species distributions, depth use, seasonality, and life-history requirements) into future management decisions (Table 1).

In the Arctic, regional governance is rapidly evolving through instruments such as the CAOFA (Balton 2019). ISRAs should be formally incorporated into its Joint Program of Scientific Research and Monitoring (NOAA 2025), a precautionary high seas framework through which ISRA spatial data could directly inform decisions about future commercial access. National spatial planning for seabirds is guided by the Protection of the Arctic Marine Environment (PAME) framework while the absence of comparable planning for sharks and rays is a recognized gap; integrating ISRAs into this process is therefore an urgent and actionable next step (PAME 2025). Coordinating these efforts through existing bodies such as the Arctic Council and ArcticNet offers a practical pathway to extend ISRA information into offshore and deepwater management. At the same time, the feasibility of broad spatial closures must be evaluated within rights-based and socio-economic contexts, particularly where Indigenous communities hold harvest rights and fisheries are governed through co-management frameworks (Swerdfager and Armitage 2023); this strengthens the case for targeted, evidence-based spatial prioritization such as ISRAs over blanket closure approaches. This framing aligns with long-standing calls to accelerate Arctic protection (e.g., Hussey et al. 2016), while recognizing that implementation pathways may differ across jurisdictions and fishing gear types.

In the Antarctic, spatial protection has advanced further but remains ecologically insufficient. The Ross Sea Region MPA and the South Orkney Islands Southern Shelf MPA are the only large-scale spatial protection designations adopted under CCAMLR (CCAMLR 2024). Because sovereignty is not recognized south of 60° S (Antarctic Treaty 1959), these are effectively high seas MPAs. Notably, the Ross Sea Region MPA entered into force in 2016, and fishing signals detected within the area during our 2013–2018 baseline partly pre-date its formal designation and should be interpreted accordingly. Three additional CCAMLR proposals, the East Antarctic MPA, the Weddell Sea MPA, and the Antarctic Peninsula MPA, would substantially increase protection if adopted (Brooks et al. 2020). These would directly benefit range-restricted Antarctic skates and other polar taxa by safeguarding benthic features that serve as foraging grounds, refugia, and potential nursery areas (e.g., Finucci, Chin, et al. 2024). ISRAs delineated in this region should be formally communicated to CCAMLR's Working Group on Ecosystem Monitoring and Management as priority reference areas for proposed MPA development. Although the Antarctic Treaty System incorporates precautionary elements that directly (i.e., chondrichthyan specific measures) or indirectly (i.e., broader measures) benefit chondrichthyans (Scully 2011), continued reliance on fisheries-dependent data constrains the resolution and completeness of habitat-related assessments. Expanded surveys,

**TABLE 1** | Recommendations for the adoption of Important Shark and Ray Areas (ISRAs) to address habitat conservation mandates of four governance bodies (agreements, commissions, or organizations) responsible for, or related to, marine management in the Polar Waters region: BBNJ, Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction ('High Seas Treaty'); CCAMLR, Commission for the Conservation of Antarctic Marine Living Resources; NAFO, Northwest Atlantic Fisheries Organization; NEAFC, North-East Atlantic Fisheries Commission.

| Governance body (relevant measures) | Existing mechanism for chondrichthyan conservation | Habitat conservation mandate | Identified gap | Recommendation for ISRA uptake |
|---|---|---|---|---|
| NAFO (COM Doc. 26-01 Rev., 2026: Article 12; Article 15; NAFO 2026) | Requires reporting of all shark catches; prohibits shark finning and retention, transshipment of detached shark fins; prohibits directed fishing for Greenland Shark; requires efforts to minimize incidental catch and mortality and release of Greenland Sharks with least possible harm; manages skates through TACs at the species complex or stock level. | Protects VMEs from bottom fishing impacts though fisheries closures and exploratory bottom-fishing provisions; calls for research on key biological and ecological parameters, life-history, behavioral traits, and migration patterns, as well as on the identification of potential mating, pupping, and nursery grounds of key shark species. | Species-specific chondrichthyan measures remain limited, with Greenland Shark the only species protected; skate management at stock level and not explicitly linked to species-specific conservation needs; existing VME closures do not overlap ISRAs identified in this study. | Submit relevant Arctic ISRAs to the Scientific Council as spatial evidence for potential mating, pupping, nursery, aggregation, and bycatch-risk areas; use ISRAs to inform future ecosystem-based spatial measures, observer/electronic monitoring priorities, species-level bycatch reporting, and handling/release protocols; where long-term fisheries closures protect ISRA-identified habitats, evaluate whether they could contribute as OECMs, where appropriate. |
| NEAFC (NEAFC Convention Arts. 4–5; Rec. 19:2004; Rec. 15:2024; NEAFC 1980, 2024) | Prohibits directed fishing for Porbeagle, Spiny Dogfish, Basking Shark, and deepwater sharks, rays, and chimaeras; requires data submission to ICES for these groups. | Establishes area management measures for the protection of VMEs, including bottom-fishing closures. | Existing measures reduce targeted fishing and protect VMEs, but do not overlap with ISRAs identified in this study related to reproduction, aggregation, movement, and other critical habitats; species-specific conservation limited to a few taxa. | Use ISRAs to inform adaptive spatial management (particularly in response to climate-driven distribution shifts), future closure proposals, monitoring priorities, and ICES advice on chondrichthyan bycatch and habitat use; strengthen species-level catch reporting, observer coverage and electronic monitoring, and handling and post-release protocols for chondrichthyans; where conservation areas overlap with ISRAs, evaluate their potential contribution as OECMs, where appropriate. |

(Continues)

**TABLE 1** | (Continued)

| Governance body (relevant measures) | Existing mechanism for chondrichthyan conservation | Habitat conservation mandate | Identified gap | Recommendation for ISRA uptake |
|---|---|---|---|---|
| CCAMLR (CM 32-18; CM 22-07; CCAMLR 2024, 1980) | Prohibits directed fishing for sharks, except for authorised scientific research; prohibits finning; requires reporting of all chondrichthyan catches; requires live release of incidentally caught sharks whenever possible, especially juveniles and gravid females; chondrichthyans are subject to bycatch limits, move-on rules, tag checks, condition assessment, and live release where survival probability is high in fisheries. | Applies an ecosystem approach to prevent irreversible changes in the marine ecosystem; has measures for VMEs, bottom fishing, and a framework for establishing MPAs; establishes precautionary management of exploratory fisheries. | Current chondrichthyan management focuses primarily on avoiding directed shark fishing and managing bycatch; identifying and protecting critical habitats supporting key life-history stages (e.g., reproductive and aggregation areas) are not explicitly incorporated into spatial management. | Communicate ISRAs to relevant CCAMLR working groups and the Scientific Committee as spatial evidence for MPA planning, VMEs/bottom-fishing considerations, and fisheries management; use ISRAs to support species-specific objectives for chondrichthyans, alongside existing bycatch measures. |
| BBNJ (Part III & IV: ABMTs & MPAs; Arts. 17–19: ABMTs; Arts. 5–7: general principles) | No taxon-specific measures for chondrichthyans; implementation relies on general biodiversity provisions, ABMTs, MPAs, EIAs, and cooperation among relevant bodies. | Provides for ABMTs, including MPAs, in ABNJ; proposals must be based on the best available science and include spatial descriptions, criteria, biodiversity information, human activities, objectives, and draft management plans; the Agreement requires cooperation and must not undermine relevant sectoral bodies. | No direct fisheries management mandate and no species-level obligations for chondrichthyans; incidental catch and spatial effort measures would need coordination with relevant fisheries bodies. | Use ISRAs in ABNJ as scientific inputs to ABMT/MPA proposals, EIA screening, and spatial planning; where proposed measures fall within the competence of fisheries or other sectoral bodies, use ISRAs to support coordinated recommendations to NAFO, NEAFC, CCAMLR, or other competent organizations. |

Abbreviations: ABMTs, Area-Based Management Tools; Arts, Articles; CM, Conservation Measure; COM Doc, Commission Document; EIA, Environmental Impact Assessment; ICES, International Council for the Exploration of the Sea; MPA, Marine Protected Area; OECMs, Other Effective Area-Based Conservation Measures; RFMOs, Regional Fishery Management Organizations; TACs, Total Allowable Catches; VMEs, Vulnerable Marine Ecosystems.

long-term monitoring, and novel research methods in deep and remote regions are required to resolve critical chondrichthyan habitats.

The BBNJ Agreement (United Nations 2025) provides an unprecedented global mechanism to bring ISRAs into decision-making beyond national jurisdiction. Through high seas MPAs, environmental impact assessments (EIAs), and Area-Based Management Tools (ABMTs), this treaty enables Parties to consider ecological significance, connectivity, and climate vulnerability, representing many of the attributes ISRAs consider. Incorporating ISRAs into the scientific and technical body under the BBNJ could ensure that chondrichthyan habitats are explicitly considered and monitored when new MPAs or ABMTs are proposed. Effective uptake will depend on coordination with existing sectoral governance and regional mandates (including CCAMLR in the Southern Ocean and relevant RFMOs). Consequently, ISRAs are likely to be most immediately actionable as a shared scientific layer informing proposals, EIAs, and monitoring priorities, rather than as standalone prescriptive designations.

### 4.4 | Concluding Remarks

Our assessment reveals that while present-day spatial overlap between ISRAs, fishing effort, and areas of rapid sea-ice loss is limited, the underlying drivers of future exposure risk are already underway. Climate-driven redistribution of boreal fishes, expanding access associated with reduced sea-ice, and depth-specific vulnerabilities of chondrichthyans create clear pathways for intensifying risk even without overt fisheries expansion. These findings underscore that the window for proactive action is narrow: precautionary, climate-responsive spatial planning integrating ISRAs is essential to prevent fishing from advancing into ecologically sensitive polar habitats faster than science and policy can respond. Spatial analyses show that delineated ISRAs are exposed to human pressure, with apparent fishing overlapping most ISRAs, while strict no-take overlap remains limited, indicating that improved monitoring and targeted risk mitigation within existing fishery footprints could yield near-term conservation benefits before new large-scale MPAs are designated.

Beyond fisheries, human activity across deep and remote polar ecosystems is expected to accelerate. Deep-sea mining is an emerging threat: seabed disturbance and sediment plumes may affect poorly understood deepwater habitats, and recovery of polar deepwater assemblages is likely to be extremely slow (Da Ros et al. 2019; Judah et al. 2025). The delineation of ISRAs provides a critical tool to enhance spatial management for polar chondrichthyans. Aligning ISRAs with emerging global and regional governance instruments, including Target 3 of the GBF, the BBNJ Agreement, CAOFA, and RFMOs, offers a unique opportunity to build representative, climate-ready conservation networks across both national waters and ABNJ. Incorporating the data and knowledge embedded within delineated ISRAs into high-seas MPA proposals, EIAs, and adaptive fisheries measures would strengthen science–policy coherence, enhance monitoring through shared research programs, and ensure that chondrichthyans, often overlooked in polar management, are explicitly considered in future spatial planning. As pressures shift from predominantly fishing to multi-sector industrialization, including shipping and resource extraction, alongside accelerating climate impacts, conservation strategies must evolve to prevent irreversible biodiversity loss in Earth's most remote, but least resilient, marine ecosystems.


#### Author Contributions

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that support the findings of this study will be made publicly available prior to publication as a repository in GitHub.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Research methods and data types used to delineate Important Shark and Ray Areas (ISRA) in Polar Waters. Definitions adapted from Gonzalez-Pestana et al. (2026) and García-Rodriguez et al. (2025). **TABLE S2:** Complete list of all shark, ray, and chimaera species recorded from the Polar Waters region. Species are listed in phylogenetic order with their IUCN Red List of Threatened Species status ('IUCN Red List status'), their occurrence by sub-region (Arctic, Antarctic), and their global depth range. Occurrence denoted by blue cells indicate 'Polar Species'. Bold species are Important Shark and Ray Areas (ISRA) Qualifying Species. IUCN Red List Categories: CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern; DD, Data Deficient. *Deepwater species; #Unresolved taxonomy (Mecklenburg et al. 2018). **TABLE S3:** Polar chondrichthyan (shark, ray, and chimaera) species richness and extinction risk. 'Polar Species' are those specialized to the polar region (outlined in Table S2); extinction risk follows the IUCN Red List of Threatened Species (IUCN 2025) where the categories are: CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern. CR, EN, and VU are the threatened categories. **TABLE S4:** Details of Important Shark and Ray Areas (ISRA) delineated in the Polar Waters region with details on jurisdiction, Qualifying Species and the ISRA Criteria they met, area size ($km^2$), and depth range (meters). ISRA Criteria: A—Vulnerability; B—Range Restricted; C1—Reproductive Areas; C2—Feeding Areas; C4—Movement; C5—Undefined Aggregations. ABNJ, areas beyond national jurisdiction. ISRA names are linked to the corresponding factsheet in the ISRA e-Atlas (https://sharkrayareas.org/e-atlas/). **TABLE S5:** Percentage overlap of Polar Species distribution ranges with the Polar Waters region; Important Shark and Ray Areas (ISRAs); national and regional no-take and partial marine protected areas (MPAs); and the proportion of the species' Polar Waters distribution exposed to apparent fishing by trawlers and longliners across two time periods: 2013–2018 and 2019–2024 according to Global Fishing Watch (GFW) data. Species in bold are ISRA Qualifying Species. Note: Some regional MPAs spatially overlap with national MPAs. **TABLE S6:** Intensity (Cumulative Apparent Fishing Hours/$km^2$) and area ($km^2$) of Apparent Fishing Effort (AFE) within each Important Shark and Ray Area (ISRA) in the Arctic and Antarctic, by gear type and period. Apparent fishing effort is derived from AIS-based Global Fishing Watch data. A value of '0' indicates no recorded fishing activity; NA, indicates values not applicable due to zero values in the input data. **TABLE S7:** List of designated regional marine protected areas (MPAs) included in the analysis for the Arctic and Antarctic based on the World Database on Protected Areas (UNEP-WCMC and IUCN 2025). Regional MPAs in the Arctic are managed by the OSPAR Commission, while those in the Antarctic are managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). 'MPA type' refers to protection levels (no-take or partial) and 'Year' to the year the MPA was established. Jurisdictions refer to: GBR, United Kingdom of Great Britain and Northern Ireland; ISL, Iceland; NOR, Norway; SJM, Svalbard and Jan Mayen; SWE, Sweden; and ABNJ, areas beyond national jurisdiction. **TABLE S8:** List of designated national MPAs included in the analysis for the Arctic and Antarctic based on the World Database on Protected Areas (UNEP-WCMC and IUCN 2025). 'Designation' and 'IUCN Category' indicate the category or type of protected area and the 'Year' of establishment. Jurisdictions refer to: ATA, Antarctica; ATF, French Southern Territories; BVT, Bouvet Islands; CAN, Canada; DNK, Denmark; GBR, United Kingdom of Great Britain and Northern Ireland; GRL, Greenland; HMD, Heard and McDonald Islands; ISL, Iceland; NOR, Norway; RUS, Russian Federation; SGS, South Georgia and the South Sandwich Islands; SJM, Svalbard and Jan Mayen; SWE, Sweden; USA, United States of America; ZAF, South Africa. For the French Southern Territories ("Terres australes françaises") of Kerguélen, Amsterdam and Saint Paul Islands, and Crozet Islands, MPA status and boundaries were updated to reflect formal designation under Decree No. 2006–1211, using updated geometries from the Inventaire National du Patrimoine Naturel. South Georgia and South Sandwich Island MPA includes the expansion of the no-take zones (SGSSI Gazette No 2 dated 22 April 2025). **TABLE S9:** Country-level area ($km^2$) and protection status of national marine protected areas (MPAs) within Arctic and Antarctic exclusive economic zones (EEZs) in Polar Waters, percentages are calculated relative to the portion of each EEZ located within Polar Waters, and total

EEZ is given as a reference. Alpha3 Codes are as follows: CAN, Canada; DNK, Denmark (Greenland and the Faroe Islands); ISL, Iceland; NOR, Norway (including Jan Mayen and Svalbard); RUS, Russian Federation, SWE, Sweden; GBR, United Kingdom of Great Britain and Northern Ireland; GBR–DNK (joint regime area of GBR and DNK, including the Faroe Islands), USA, United States of America (Alaska); ATF, French Southern and Antarctic Lands (Kérguelen, Amsterdam and Saint Paul Islands, and Crozet Islands); AUS, Australia (Heard and McDonald Islands); ZAF, South Africa (Prince Edward Islands); and SGS (South Georgia and the South Sandwich Islands). Countries not listed had zero overlap with MPAs in Polar Waters. **TABLE S10:** Important Shark and Ray Areas (ISRAs) overlap with partial and no-take Marine Protected Areas (MPAs) within Polar Waters. Percentages are calculated relative to the portion of each ISRA. Jurisdictions are as follows: CAN, Canada; DNK, Denmark (including Greenland); ISL, Iceland; NOR, Norway (including Jan Mayen and Svalbard); SWE, Sweden; GBR, United Kingdom of Great Britain and Northern Ireland; ATF, French Southern and Antarctic Lands; AUS, Australia; ATA, Antarctica; SGS, South Georgia and the South Sandwich Islands. ISRAs not listed had zero overlap with MPAs in Polar Waters.