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Priority areas for marine protection in the Amundsen and Bellingshausen Seas, Antarctica

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A R T I C L E   I N F O

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A B S T R A C T

Global marine environments are increasingly exposed to the stressors of climate change and human activities. International conservation agreements recommend establishing systems of Marine Protected Areas (MPAs) in each of the world’s oceans to protect marine biodiversity and ensure the sustainability of socio-ecological systems. In Antarctica’s Southern Ocean, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) are incrementally planning and implementing regional MPAs, with the aim to establish a large-scale, representative circumpolar system for the Convention Area. The Domain 9 planning region, covering the Amundsen and Bellingshausen Seas in West Antarctica, remains unplanned for and unprotected. Here, we use a Systematic Conservation Planning (SCP) approach and planning scenarios to identify a set of spatial conservation priorities for Domain 9 that meet CCAMLR MPA objectives and are robust to various planning considerations of Southern Ocean stakeholders. We show where differences in targets and data inputs influence priority area selection and their spatial relationship with areas of fisheries interest. Our results provide priority areas for a Domain 9 MPA to contribute to the ongoing development of the circumpolar Southern Ocean MPA system, with methods that are broadly applicable for MPA planning in other Areas Beyond National Jurisdiction.

1. Introduction

The extent, diversity, and intensity of human activities in ocean environments is rapidly increasing [1]. In combination with the impacts of global climate change, intensifying use of ocean resources poses a serious threat to marine biodiversity and the sustainability of socio-ecological systems [2–5]. To reduce the cumulative nature of these impacts, multilateral international conservation agreements, such as the Kunming-Montreal Global Biodiversity Framework (GBF) [6] and the new Biodiversity Beyond National Jurisdiction Agreement [7] emphasise the urgent need to implement systems of Marine Protected Areas (MPAs) across each of the world’s marine environments, including in Areas Beyond National Jurisdiction (ABNJ) [2]. Systematically designed large-scale systems of Marine Protected Areas (MPAs) can mitigate direct human impacts in these areas to support marine biodiversity conservation and sustainable resource use under current and future climates [8,9]. Currently, high seas environments are underrepresented in protected areas globally [10,11] and often lack the policy frameworks and related spatial management mechanisms needed to plan for and implement effective protection [2]. As such, areas of the high seas are particularly exposed to human threats and mechanisms to protect these areas are urgently needed.

A Systematic Conservation Planning (SCP) approach provides a framework to incorporate ecological conservation objectives and stakeholder considerations into a planning process to inform decision-making. SCP incorporates the core principles of best practice reserve design – Comprehensiveness, Adequacy, Representativeness and Efficiency (the CARE Principles) to identify priority areas for protection [12,13]. A SCP approach translates planning objectives into quantitative targets for conservation features and stakeholder interests. Using data to represent these targets, the analysis identifies contributions that existing protected areas make to targets and then identifies areas to prioritise for additional protection to meet remaining targets. It does this while minimising design costs such as area size [12,14,15]. In theory, provided the underpinning data is adequate, CARE protected area designs should represent all bioregions, habitats, and the highly interconnected
environmental processes of the high seas [2,10,16].

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is one of the first organisations to plan for and establish large-scale MPAs in international waters [5]. The CCAMLR gives effect to the CAMLR Convention, the instrument of the Antarctic Treaty System responsible for the management of Southern Ocean biodiversity [17]. The CCAMLR MPA planning approach provides a systematic framework to incrementally develop and implement a representative, circumpolar MPA system by establishing MPAs in each of the planning domains [2]. The planning domain boundaries largely match the location of Southern Ocean bioregions, and are further designed to capture the scale and location of research efforts. Domains are intended to coordinate planning and management reporting for a representative MPA system by establishing an MPA in each domain. Under this approach, the system of MPAs, if well designed and implemented, should be representative of the full range of Southern Ocean bioregions and their unique conservation values [18,19]. To date, CCAMLR MPAs have been adopted in Domains 1 (South Orkney Islands MPA) and 8 (Ross Sea region MPA), and proposals for MPAs in Domains 1 (Antarctic Peninsula), the southern part of 4 (Weddell Sea and Bouvet Maud), and 7 (East Antarctica) remain under negotiation (Fig. 1). MPAs have also been established by countries (Australia, France, and the United Kingdom) in their national waters around sub-Antarctic Islands.

Within Domains 2, 5, and 6. At this stage of the planning process, Domain 9 remains completely un-planned for.

As a result of gaps in domain planning, the circumpolar MPA system is not yet representative of all Southern Ocean bioregions or the biodiversity they contain [20]. Furthermore, current and proposed MPAs do not always include region-specific features needed for a representative circumpolar system [21]. This places additional pressure on MPAs in the remaining un-planned-for domain 9 and northern pelagic zones of Domain 4, in particular to meet circumpolar representation targets for pelagic habitats and associated highly mobile pelagic species within the Southern Ocean.

With these pelagic environments and species in mind, connectivity of MPAs is particularly important consideration [22,23]. High seas environments such as the Southern Ocean are interconnected across large spatial scales, with vertical and horizontal ecological linkages driven by a wide variety of species with broad distributions across a range of environments [10]. Protecting the requirements of wide-ranging species is critical to achieving effective and representative MPA systems [24,25] and to protect the dynamic nature of open ocean ecosystems [10,26]. Many of the proposed and established MPAs, in particular the Ross Sea Region MPA, are considered large-scale [20,27] and are designed to provide adequate protection for the persistence of many species with ranges contained within the planning region. However, wide-ranging

**Fig. 1.** CAMLR Convention Area, showing the MPA planning domains, the existing CCAMLR MPAs, National MPAs, the proposed Weddell Sea MPA, East Antarctica MPA, Domain 1 (Antarctic Peninsula) MPA and the Domain 9 MPA planning region. Planning domains: 1 = Western Peninsula-South Scotia Arc; 2 = North Scotia Arc; 3 = Weddell Sea Phase 1 and 2; 4 = Bouvet Maud; 5 = Crozet-del Cano; 6 = Kerguelen Plateau; 7 = Eastern Antarctica; 8 = Ross Sea; 9 = Amundsen-Bellingshausen. (CCAMLR MPA Planning Domains; CCAMLR Marine Protected Areas: Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) GIS 2021; National MPAs: World Database on Protected Areas 2019; Proposed MPAs: Brooks et al# 2020, Phase 2 Weddell Sea MPA Proposal: Gary Griffith (by request)).
pelagic species, such as whales and seabirds, as well as species with pelagic life history stages, such as larval toothfish, require well-designed MPA systems to provide connected protection across planning region boundaries [22,24,28,29]. The absence of protection in Domain 9 is a key gap in providing for these species, in particular between the Ross Sea and the Peninsula region [30–35]. An MPA proposal for Domain 9 would thus provide the opportunity to protect areas important for species and ecosystem processes that extend beyond the existing Ross Sea region MPA boundaries and into Domain 9, delivering much needed connectivity across MPAs.

We address this planning gap by applying a SCP process to explore planning scenarios in Domain 9 using the best available data for Domain 9 and drawing upon decision support tools, conservation targets, and data used in other CCAMLR MPA planning processes [36]. A key question raised within MPA negotiations has been the robustness of MPA plans to data limitations – either in the extent of knowledge, certainty of modelled data, or assumptions made in processing data for use in decision support tools [37,38]. It is therefore critical for CCAMLR MPA proposals to demonstrate the influence of various data inputs, conservation targets, and design criteria on the final recommended spatial priorities [19].

Our aim was to test the robustness of spatial conservation priorities within Domain 9 to these planning decisions. To this end, using the spatial prioritisation program MARXAN, we ran a range of conservation

Fig. 2. Benthic Conservation features in Domain 9 (this does not represent all conservation features considered in the analysis – see Supplementary Material for complete list of data sources for conservation features and maps). The seamount rarity data used in this study classifies seamount rarity by proximity to other seamounts and depth at mount. Where the number following SGn is the number of seamounts or seamount ridges with a specific bathome located within the seamount group, e.g. SGn1 means that there is only one seamount within that bathome within that seamount group. Further classification is provided by the number following SOn, which is the number of seamounts or seamount ridges with a specific bathome located within the CCAMLR Southern Ocean area, e.g. SGn1:SOn2 means there is only 1 seamount at this bathome in the seamount group (200 km radius) and only 2 seamounts of this bathome in the CCAMLR area. For species maps see Supplementary Material. (Antarctica: CCAMLR 2021; Penguin colony: MAPPPD 2021, Geomorphic features: Post 2016; Seamount Rarity, Polynyas: Centre for Conservation Geography 2012).
planning scenarios for Domain 9 with conservation objectives and data sources that mirror other Southern Ocean MPA planning approaches [19,39]. Our scenarios consider key planning and design questions, specifically: a) how sensitive are priority area selections to low, medium, and high targets for features?; b) how sensitive are priority area selections to choices made in processing modelled species distributions for use in planning?; c) how do protected areas designed to connect with existing protection influence priority area selections and associated targets meet?

2. Methods

2.1. CCAMLR planning Domain 9

CCAMLR MPA planning Domain 9 (defined during the 2011 CCAMLR workshop on Marine Protected Areas (in SC-CCAMLR-XXX Annex 6) [40]) comprises the Amundsen and western Bellingshausen Seas and is the third largest MPA planning domain, spanning 4.5 million km² (Fig. 1).

There are many features unique to the Domain 9 region. These include some of the deepest (De Gerlache group) and shallowest (Belgica and Lecointe Guyots) seamounts in the CCAMLR area. One of the most productive polynyas (on average per unit area) in the Antarctic, the Amundsen Sea Polynya, lies within Domain 9 and is important habitat for seals and penguins [41,42]. The shallower coastal shelf environments within Domain 9 have some of the warmest seaed temperatures within the CCAMLR area with high ice cover for most of the year [43]. The fastest melting glacier in Antarctica, the Pine Island Glacier, which is responsible for about 25 percent of Antarctica’s ice loss is also found in Domain 9. Together the Pine Island Glacier and Thwaites Glacier within Domain 9 are some of the most rapidly warming regions in Antarctica and important scientific reference areas to monitor impacts of climate change on Antarctic ecosystems (one factor in the rationale for establishing MPAs in the Southern Ocean outlined in Conservation Measure (CM) 91–04 [44])

Domain 9 contains many important breeding and foraging areas for birds and marine mammals that are a high priority for protection. The islands within Domain 9 (Peter I, Thursten, Siple and Grant Islands) support emperor and Adélie penguin colonies (Fig. 2). The region is also a known feeding ground for the only endangered population of humpback whales in the world, the Oceania Humpback (Megaptera novaeangliae), a migratory species that feeds in the Amundsen and Bellingshausen Seas [29,46]. In addition, the seafloor in Domain 9 contains a diversity of seabed habitats that support a range of benthic species. For example, seafloor surrounding Peter I Island hosts a rich diversity and abundance of invertebrates, with some of the highest mollusc abundance within the Bellingshausen Sea [47,48]. Much of this seafloor diversity is located at depth ranges vulnerable to human impacts [49]. These features represent the conservation values within Domain 9 that a representative circumpolar MPA system intends to protect. We include targets for these features in our analysis (See Table 1a Supplementary Material).

An exploratory fishery, targeting the benthico-pelagic species, Antarctic Toothfish (Dissostichus mawsoni), operates in designated CCAMLR Research Blocks and within Small Scale Research Units in Domain 9. Exploratory research fishing aims to support the development of a commercial fishery. MPA designation in areas that overlap with existing fisheries have potential implications for the development of a commercial fishery, depending on zoning requirements. We included an objective to minimise impacts on the Toothfish fishery in different planning scenarios and explored the spatial relationship between the location of CCAMLR Research Blocks/Units and priority areas selected for MPAs to provide additional information for decision-making.

### Table 1

<table>
<thead>
<tr>
<th>Conservation feature type</th>
<th>Low target</th>
<th>Medium target</th>
<th>High target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benthic and pelagic regionalisations</td>
<td>10 %</td>
<td>20 %</td>
<td>30 %</td>
</tr>
<tr>
<td>Geomorphology</td>
<td>30 %</td>
<td>40 %</td>
<td>50 %</td>
</tr>
<tr>
<td>Outputs from species distribution models (SDMs)</td>
<td>30 %</td>
<td>40 %</td>
<td>50 %</td>
</tr>
<tr>
<td>Important features: Rare and restricted environment types, Vulnerable Marine Ecosystems (VMEs), emperor and Adélie penguin colony area buffers, polynyas, shallow and rare seamounts</td>
<td>70 %</td>
<td>85 %</td>
<td>100 %</td>
</tr>
</tbody>
</table>

2.2. Scenario inputs and design

#### 2.2.1. Planning principles and objectives

To identify conservation priority areas in Domain 9, we followed the steps of a typical SCP process [12]. We applied the CARE (Comprehensive, Adequate, Representative, Efficient) principles of representative reserve system design and the requirements for CCAMLR MPA proposals outlined in Conservation Measure (CM) 91–04 [44] to develop conservation objectives for the Domain 9 region. For a Southern Ocean MPA system to achieve the CARE principles and be consistent with the requirements for MPA proposals outlined in CM 91–04, it would:

1. Comprehensively include each of the benthic and pelagic environment types and ecoregions within the planning region (CCAMLR area) [50,51];
2. Adequately represent the location and extent of key areas and environmental processes required to sustain key species, communities, and populations;
3. Represent fine scale heterogeneity within broader environment types, including restricted habitat distributions, and represent both environmental and socio-economic values and interests;
4. Achieve the above CAR principles with maximum efficiency (E) in terms of minimising area costs and impacts on resource users.

#### 2.2.2. Planning objectives

Based on these four principles, we developed five general objectives that reflect the types of objectives used in previous and current CCAMLR MPA planning processes [19,39] that are consistent with the requirements for MPA proposals outlined in CM 91–04:

1. Protect representative areas of benthic environment types and environmental processes.
2. Protect representative areas of pelagic environment types and environmental processes.
3. Protect essential habitats for top predators (as defined by [52]) and other key species.
4. Protect species, habitats, or environment types of a rare, restricted, threatened, or unique/endemic distribution (not already captured in objectives 1 and 2).
5. Achieve objectives 1–4 while minimising impacts on toothfish fisheries in area selections.

#### 2.2.3. Targets

Adequacy of protection is often expressed by the targets set for features, where the choice of target is driven by the extent or viability of a feature and its vulnerability. For example, range restricted and rare (and thus vulnerable) species may require a higher protection target than wide ranging and common species. For ecosystems or geomorphic
features where information on viability or vulnerability are absent, instead globally accepted norms of adequacy such as global targets might be used (ranging from 10% to 30%). To understand the impacts on spatial priorities from variable target levels, we collated existing data for environmental, biodiversity and biophysical features from publicly accessible databases and from private requests to authors and set targets for features (Table 1a. Supplementary Material) for three planning scenarios with low, medium and high target ranges (Table 1). There were 74 individual features based on four feature types – broadscale benthic and pelagic regionalisations, geomorphological features, outputs from species distribution models (SDMs), and important features such as rare and restricted environment types, vulnerable marine ecosystems (VMEs), and emperor and Adélie penguin colony areas. Data included in this analysis reflects data used in previous Southern Ocean planning analyses and MPA planning processes [21,53].

The targets for conservation objectives in the low targets scenario are based on the recommended minimum protection requirements for a protected area to meet conservation goals [54,55] from best practise, evidence-based conservation science and established MPAs [14,55,56] and international agreements for marine protection, such as the Convention on Biological Diversity (CBD) [57]. Targets reflect the conservation requirements of the features, based on what is known about their distribution, viability, and vulnerability [54,55]. Even in this low target scenario, important features such as rare and restricted environment types, Vulnerable Marine Ecosystem areas, areas surrounding emperor and Adélie penguin colonies, polynyas, and shallow and rare seamounts receive high targets (70%) to meet conservation requirements. The medium and high target scenarios are designed to reflect incremental adjustments to these minimum protection targets to explore the sensitivity of the scenario results (in terms of spatial distribution of priorities and costs associated with protection).

Data to represent areas likely to be important to the toothfish fishery in the MARXAN analysis was included as a cost layer. Areas likely to be important are those with exploitable toothfish habitats, including those areas outside of management areas (Research Blocks/Units) that are currently open to fishing. Therefore, we developed a data layer to reflect the likely exploitable toothfish habitats, using known information about toothfish habitat and fishability. Distribution of Toothfish species is typically driven by temperature and depth [58,59]. As these are usually correlated, depth is a good predictor of distribution and has been used as an indicator of toothfish habitat suitability in previous Southern Ocean MPA planning analyses [19]. Adult Antarctic toothfish are fished close to the seafloor using mainly demersal long-lines at targeted depths between 1200 and 1800 m [60] and exploratory fishing is prohibited in depths shallower than 550 m [61]. We intersected depth and sea ice data to represent exploitable potential toothfish habitat (see Supplementary Material Fig. 32a). We combined the modelled exploitable toothfish habitat with planning unit area for the final cost layer using the following equation: cost = area × (1 + mean toothfish value). This allowed us to control for variable planning unit sizes and ensure that MARXAN minimised all costs (both area and fisheries) when making area selections. To test the influence of the additional fisheries cost layer on scenario results, we compared results from scenarios that included the fisheries cost layer to the results from a set of scenarios without the fisheries cost layer (i.e. planning unit cost set to area) using a Spearman’s rank correlation (Table 8a. Supplementary Material).

### 2.2.4. Species distribution model (SDM) data use

The Southern Ocean is remote and thus data limited for many conservation features. Therefore, MPA planning processes are reliant on modelled species data (Supplementary Material; Table 5a). These modelled outputs typically take the form of continuous modelled probability of occurrences (from species distribution models (SDMs)) [62] for which target-based approaches may not result in appropriate targeting of habitats with errors of commission and omission likely [63, 64]. The most common approach to address this is to use thresholds to convert continuous probability layers into presence absence range maps [62,65].

Thresholds applied to SDMs should be selected that reflect the costs of false positives for the study context (such as selecting poor quality habitat over higher quality habitat). However, threshold choice is not simple and depends on the application of the SDM as well as the characteristics of the data used to build the SDM [65,66]. Ideally thresholds applied would be species specific and expert informed [65], however this is only possible when the underlying presence absence data and modelling is publicly available and appropriate expert knowledge of areas used by each species exist. Neither is available for Domain 9 or for many other regions within the Southern Oceans. We therefore relied on naïve thresholds (default of 50%) and applied these uniformly across those features represented by modelled species distributions (Supplementary Material: Table 5a). To test the robustness of this naïve threshold choice we also considered a second threshold value of 66% as a more stringent threshold reflecting a higher level of certainty of species presence and thus reducing levels of omission from planning. To test the interactions between thresholds and targets on spatial priorities we ran combined scenarios for the two thresholds and the three target sets.

#### 2.2.5. Design parameters

We divided the Domain 9 region into 7328 planning units, typically of 10 km by 10 km (100 km2) in size (Supplementary Material Fig. 1a). Features such as canyons and seamounts were considered in a single planning unit because they are most effectively conserved as a complete feature [16]. To ensure that priority areas for MPAs in Domain 9 were sufficiently connected with existing protection outside of the planning region (e.g. the Ross Sea Region MPA in Domain 8) to meet conservation objectives for highly mobile wide-ranging species, we ‘locked-in’ a single row of planning units (10 km width) on the Domain 9 boundary adjacent to the Ross Sea Region MPA into priority area selections. We also calibrated the Boundary Length Modifier (BLM) parameter in MARXAN based on methods in Stewart and Possingham [67,68] (a final value of 1.5 was selected) to force MARXAN to preferentially select adjacent planning units to produce a more clumped design.

#### 2.2.6. Scenario planning

We used the reserve design software MARXAN [69] to test a range of planning scenarios (e.g. with different targets for conservation features, different data inputs or design requirements) to produce a range of possible solutions. MARXAN uses simulated annealing to solve the minimum set reserve design problem and identify configurations of planning units that meet feature targets for the minimum costs [69]. As a first step, we ran three spatial conservation prioritisation scenarios with low, medium and high targets for conservation features (Scenarios 1–3 Table 2). Each planning scenario was run 1000 times, each with 100,000 iterations. For these scenarios (Scenarios 1–3) we used thresholds of 0.5 for SDM data (Scenarios 1–3 Table 2). MARXAN identifies 1) the contribution of any ‘locked-in’ areas to targets; 2) remaining missed targets and 3) areas to prioritise for protection to meet remaining targets for minimum costs. MARXAN selects combinations of planning units that meet targets for the minimum costs and therefore provides multiple “good solutions” to the conservation planning problem that can inform protected area designs and support decision-making.

As a second step, we ran each of the three conservation target level scenarios with thresholds of 0.66 applied to the continuous values from

| Table 2 |
|---------------------|---------------------|---------------------|
| **SDM threshold 0.5** | **SDM threshold 0.66** |
| **Low targets** | **Scenario 1** | **Scenario 1a** |
| **Medium targets** | **Scenario 2** | **Scenario 2a** |
| **High targets** | **Scenario 3** | **Scenario 3a** |
species distribution models (Scenarios 1a-3a) (Table 2). Scenario outputs are available as ‘best’ solutions (the single solution that meets the targets for the minimum costs) and ‘summed’ solutions (where each planning unit is scored according to how many times it is selected across the total number of MARXAN runs). The range of solutions can then be reviewed to assess similarities or identify if selections are sensitive to scenario inputs.

2.3. Scenario comparisons

The summed selection frequency results from each scenario show the most frequently selected areas to meet targets and indicate priority areas for protection. We compared the location of area selections shown in the summed selection frequency outputs from each of the scenarios by overlaying these results in the GIS, to identify any patterns or similarities between the solutions. Selection frequencies >800 in all scenarios indicate the locations of key features that are always selected to meet targets for the least cost, regardless of differences in scenario inputs or design requirements. We examined the influence of selected thresholds for determining the presence or suitable habitat from continuous species distribution model (SDM) outputs by comparing the selection frequency results from the scenarios with 50% thresholds to the results from scenarios with 66% thresholds (Table 2) using a Spearman’s rank correlation (Table 7a. Supplementary Material). We also compared results (the location of the priority area selections) from our analysis (which included the aim to minimise fisheries costs) to the location of the designated Research Blocks of the exploratory fishery. While we have parameterized MARXAN to meet our objectives of minimizing costs to

Fig. 3. Comparison of selection frequencies from Scenarios 1, 2 and 3. Location of key features that influence area selections – Research Blocks and Small Scale Research Unit H, Seamounts and seamount ridges, Polynyas and emperor and Adélie penguin colonies (Research Blocks and Small Scale Research Unit: CCAMLR 2021; Penguin colony: MAPPPD 2021, Seamounts and seamount ridges: Post 2016; Polynyas: Centre for Conservation Geography 2012).
such as polynyas, seamounts and emperor and Adélie (Fig. 3). Other areas frequently selected in all scenarios were the most frequently selected planning units from the low (a), medium (b) and high (c) target scenarios (Table 2, scenarios 1–3) and mapped the locations to show which areas were most frequently selected across all scenarios, under different conservation target levels (Fig. 3). These area selections are consistent to different targets. The consistency of area selections with regard to different SDM thresholds are not shown here, however selection frequencies >800 from Scenarios 1–3 were also highly correlated with high selection frequencies >800 from Scenario 1–3a (Spearman’s rank 0.912–0.952 - Supplementary Material Table 7a). Selection frequencies >800 in all scenarios included features such as polynyas, seamounts and emperor and Adélie penguin colonies (Fig. 3). Other areas frequently selected in all scenarios were selected to meet targets for features with a more limited distribution (i.e. only present in one or two planning units) such as many of the Restricted Environment Types of the Amundsen ecoregion (Cross-shelf Valley, Island Coastal Terrane, Lower Slope, Seamounts and Seamount Ridges, and Pacific Basin ecoregion (Seamounts and Seamount ridges). Areas selected in scenarios with higher targets (scenarios 2 or 3) but not selected in scenarios with lower targets (scenarios 1 or 2 respectively) likely reflect higher targets for broad-scale benthic and pelagic ecoregions.

3.2. Influence of SDM threshold choice

The locations of priority area selections were mostly unaffected by SDM threshold choice. Where the predicted probability of occurrence or suitable habitat for species was set to 50 % or 66 %, the selection frequencies were highly correlated across the scenarios (Scenarios 1–3a) (Spearman’s rank 0.912–0.952 - Supplementary Material Table 7a). Best solutions from scenarios were also mostly unaffected by threshold choice, as the total area and percentage of the domain selected in scenarios with the 66 % threshold was broadly similar to scenarios with the 50 % threshold (Fig. 4).

However, threshold choice did impact whether the analysis included targets for species with low habitat suitability values within the Domain 9 region (Dark-mantled sooty Albatross, Echinoids, the Myctophid, Protomyctophum tenisoni - see species maps in Supplementary Material). Applying a 50 % threshold to the predicted circumpolar distribution of these species meant that the low probability areas within their range were included as targets within Domain 9. However, applying a 66 % threshold meant that the low probability areas for these species were excluded from the Domain 9 region and therefore not available as targets. Even though these features were not explicitly targeted in scenarios 1a-3a, priority area selections from scenarios with 66 % thresholds incidentally included the low probability habitat range areas for these species, as MARXAN made complimentary selections to meet other targets such as seamounts. Targets for known features such as seamounts, emperor and Adélie colonies, and polynyas remained the primary influence in area selections with either 50 % or 66 % thresholds (see Fig. 3 for locations). As a final check to ensure that the SDM data was not misinterpreted through the choice of thresholds, we identified the highest and mean values selected within priority area selections from the low target scenarios and compared these values to the highest value for the feature (the value at which species are most likely to be present). We found that priority area selections included areas of high probability for species for most features (Supplementary Material, Table 6a).

3.3. Spatial overlap of priority area selections with fisheries Research Blocks/Unit

The influence of SDM threshold choice on the percentage of fisheries Research Blocks and the Small Scale Research Unit selected was negligible for the low target scenario (1a) but significant for scenarios with higher targets (2a and 3a). In the scenarios with low targets (1 and 1a), the amount of Research Blocks and the Small Scale Research Unit included in priority area selections remained similar (27 % and 31 % respectively) with either the 66 % or 50 % threshold (Fig. 4). However, in scenarios with higher targets and SDM threshold values of 66 % (scenarios 2a and 3a), priority area selections correlated with a greater area of fisheries Research Blocks and Small Scale Research Unit (57 % and 60 % respectively) than for scenarios with the same targets but with SDM thresholds of 50 % (Scenario 2, 30 %, and Scenario 3, 42 %) (Fig. 4). In the best solutions from each scenario, the total area of Research Blocks and the Research Unit selected increased from the low to high target scenarios (Scenarios 1–3) from 40 % of the study region to
464 % of the study region, proportional to the incrementally higher targets for features such as polynyas and seamounts - highly productive areas that provide important habitats for a range of species (Fig. 4).

4. Discussion

Planning for a network of Southern Ocean MPAs is ongoing: proposals for CCAMLR Planning Domains 1, 3, and 7 remain in negotiations and since 2019 there has been ongoing planning for Domains 4, 5 and 6 [45,70,71]. However, Domain 9 remains un-planned for. Here, we tested a range of conservation planning scenarios to explore how key stakeholder planning considerations, such as choices of targets and SDM thresholds, influenced the selection of priority areas for conservation, and where these areas relate spatially to fisheries Research Blocks and the Small Scale Research Unit. We found a set of spatial conservation priorities that meet CCAMLR conservation objectives, are consistent to different conservation targets and data inputs, and are therefore robust to various considerations of Southern Ocean stakeholders.

We found the conservation priority areas within Domain 9 that are robust to different target levels and SDM threshold choices. These included offshore priority areas consistently selected across all three scenarios to meet high targets for polynyas, and a range of coastal pelagic environment types of a restricted distribution, including rare and restricted benthic environment types, vulnerable marine ecosystem (VME) fine scale rectangles, rare seamounts, and geomorphology features such as canyons, ridges, fans and troughs. These areas are important for some species of myctophids, grey headed albatross, and black banded albatross. Priority area selection in all scenarios in coastal regions were influenced by high targets for small scale coastal pelagic regions, emperor and Adélie penguin colony buffer areas, polynyas, and one coastal VME risk area. These higher latitude habitats in coastal areas are likely to become increasingly important habitats for species currently found in lower latitudes as their ranges extend south [72]. Identifying where inputs influence priority area selections may help decision-makers to interpret the spatial prioritisation process and relate priority area configurations to objectives and other considerations relevant to the planning process [12,73]. For example, while coastal priority area selections (areas adjacent to the Antarctic coastline or subantarctic islands) are often well represented in other Southern Ocean MPA proposals, such as the most recent proposal for an MPA for the Weddell Sea [19], offshore pelagic areas are not well-represented in existing CCAMLR MPA proposals, and are under-represented in marine protection globally [22]. Therefore, pelagic protection in Domain 9 is particularly important relative to circumpolar and global scales [21].

Our results show that for scenarios with low targets, area selections were mostly unaffected by SDM threshold choice. However, in scenarios with medium or high targets, the selected SDM threshold did influence the locations of area selections. We found that an SDM threshold of 66 % (Scenarios 2a and 3a) correlated with a greater area of Research Blocks and the Small Scale Research Unit than selections from scenarios with medium or high targets and a SDM threshold of 50 % (Scenarios 2 and 3). An SDM threshold of 66 % restricted the areas available for selection to meet targets to the areas predicted to be most suitable for species. A higher percentage of the total area of Research Blocks and the Small Scale Research Unit were required to meet targets for these species under this threshold, which shows that fisheries areas closely overlap with the most suitable habitats for many species. In particular, Research Block 88.2.4 includes rare and restricted environment types, penguin colonies, polynyas and a range of coastal pelagic environment types. In addition, Research Blocks 88.2.2 and 88.2.1 also include emperor and Adélie penguin colonies and polynyas, and are adjacent to the Pine Island and Thwaites Glaciers, areas of immense scientific research value [74]. Small-scale Research Unit 88.2 H contains canyons, seamounts and includes identified Areas of Ecological Significance [75]. Where SDM evaluation data suggests higher thresholds are more appropriate, this will ultimately require more of Research Block areas in conservation priority selections. Allowing for a broader range of predicted species distributions to be available for selection could be seen to be a more precautionary approach where the data contains high levels of uncertainty about species true presence. However, our results show that threshold value can make a difference to area selections and therefore where a recommended threshold value is available, this should be used.

We aimed to minimise costs, or impacts, to the fishery by including the fisheries cost layer. However the cost layer was not a significant influence (Supplementary Material Table 8a: Spearman’s Rank.989) on priority areas selected for conservation. The selection of high value fisheries areas was necessary to meet priority conservation targets for features such as seamounts. As such, it wasn’t possible to minimise all impacts on the fishery. This shows that the limitations of using a cost layer in terms of rationalising both conservation and fisheries objectives. Outputs from spatial prioritisations such as presented here are potentially useful for presenting areas for specific negotiation points with the fishery, for example, where research blocks might have to be moved in order to guarantee protection for certain features. Ideally this would be presented for negotiation in a series of maps that identify the critical areas and options for moving forward. However this would require alternative tools or methods to identify options that are not possible to identify using only a cost layer.

4.1. Limitations

In all scenarios, Fisheries Research Blocks and the Small Scale Research Unit correlated with areas selected for conservation and ranged from 27 % (in Scenario 1a) to 60 % (in Scenario 3a) selected for protection. However, the amount of fisheries Research Blocks and the Small Scale Research Unit selected is likely a poor surrogate for the impact to fishers, as there are often particular locations of high value within large fishable areas [76]. Therefore, particular locations may be more desirable to fish than others for reasons that are not captured in our analysis and these locations may influence MPA proposal discussions. Further analysis to incorporate a more detailed valuation of fisheries areas would likely further refine scenarios results. This could be achieved through a refined model of fishing values or through participatory planning to allow fishing vessels to indicate areas least or most important to them for fishing. A realistic next step might be to incorporate fisheries interests into planning using a multi-zone approach to enable explicit prioritisation of areas to meet fisheries objectives alongside conservation objectives and consideration of trade-offs between conflicting objectives.

Additionally, our analysis did not consider potential interest to fish Antarctic krill in the Domain 9 region. While other areas of the Southern Ocean such as the Antarctic Peninsula are important for Southern Ocean krill fisheries, krill are not currently fished in the Domain 9 region. However, this may change as the effects of climate-change shift krill habitats and reductions in sea ice extent enable greater accessibility for vessels. There remains a strong interest, particularly from some CCAMLR members, in expanding the krill fishery into new, previously unfished areas of the Southern Ocean, for example, parts of the Weddell Sea [19]. If expansion into Domain 9 were of interest, MPA planning could consider these interests by including a cost layer for krill based on projected krill habitat potential under future climate scenarios, such as those presented in Veytia et al. [77], and could consider including a designated krill research zone as part of the MPA, similar to that included the Ross Sea Region MPA [37].

Our scenario outputs show a range of solutions to meet conservation objectives for further consideration for MPAs or other spatial conservation planning and management considerations for the Domain 9 region. A range of reserve configuration options can potentially increase flexibility in stakeholder negotiations and may help to find a workable solution for MPA design and implementation [73]. Realistic next steps might consider additional regional scale data to represent targets, and the potential for different planning approaches to incorporate more
detailed consideration of fisheries interests, and/or hypothesised or known species connectivity pathways/source-sink areas into area prioritisation. For example, all data used in our analysis to represent conservation objectives was circumpolar scale, clipped to the Domain 9 region. An important next step would be to investigate the potential to incorporate additional domain-specific scale data into the analysis, to further support and refine the priority area selections, and in particular, confirm species presence where targets are represented by SDM data. While our results show that SDMs can provide an efficient means to identify candidate (not final areas) for protection, ideally a species-specific threshold would be determined independently based on the underlying data for each species. Further sensitivity analysis to test the impact of a range of different thresholds for individual species distributions on MARXAN results would likely support the allocation species-specific threshold values and direct ground truthing efforts to focus areas to confirm species presence [62]. Identifying future research needs could inform the design of an ongoing research and monitoring plan, which is a requirement for all CCAMLR MPA proposals [44].

5. Conclusion

For the Southern Ocean MPA system to provide representative protection of all Southern Ocean bioregions and the biodiversity they contain, additional MPAs need to be established in unplanned-for domains, such as Planning Domain 9. Here, we explore a range of conservation planning scenarios for Domain 9 to show where planning considerations, such as choices of targets and data inputs, influence priority area selections, and where priority areas overlap with locations of fisheries interest. We found a set of spatial conservation priorities that meet CCAMLR conservation objectives, are consistent to different conservation targets and data inputs, and therefore respond to key considerations of Southern Ocean stakeholders. Our results provide priority areas for a Domain 9 MPA to contribute to the ongoing development of the circumpolar Southern Ocean MPA system, with methods that are broadly applicable for MPA planning in other ABNJ.

CRediT authorship contribution statement

Vanessa Adams: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. Anne Boothroyd: Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization, Writing – review & editing. Nicole Hill: Methodology, Supervision, Validation, Writing – review & editing. Karen Alexander: Methodology, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

None.

Data Availability

This study did not generate any new data. All data used to support the findings of this study is referenced and available from the original sources (Supplementary Material Table 1a)

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106232.

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