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Conservation planning in the Weddell Sea (Antarctica): A comparative analysis of decision-support tools

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Abstract

Intense human activities negatively impact marine ecosystems, creating an urgent need for effective strategies to safeguard marine biodiversity and ecosystem services. Systematic conservation planning has become a key approach to identify priority areas and design management measures. The Marxan software, based on simulated annealing (SA) algorithms, is widely used in this context. However, recent advances in integer linear programming (ILP), as implemented in the prioritizr R package, offer a promising alternative with improved optimization performance and solution quality. In this study, we compare prioritization solutions generated using SA (Marxan) and ILP (prioritizr) for the Weddell Sea Marine Protected Area Phase 1 (WSMPA P1), one of four Marine Protected Areas (MPAs) currently proposed and under negotiation by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). The planning area includes 57,077 hexagonal planning units (PUs) covering almost 3 million km^2 and 54 conservation features, alongside a cost metric reflecting potential Antarctic toothfish fisheries interests. Three conservation target scenarios–minimum, mixed, and medium–were evaluated to assess the performance of both approaches. Our results show that both methods identify largely overlapping priority areas. However, ILP solutions consistently exhibit less spatial fragmentation, smaller total area and lower costs, resulting in more compact and cost-efficient reserve designs without extensive parameter calibration. Computational times were comparable for the minimum and mixed target scenarios; for the medium scenario, prioritizr required moderately more processing time. These findings highlight the benefits of ILP for systematic conservation planning, particularly in real-world contexts where time for scenario calibration is often limited during stakeholder consultations and political negotiations. Our study suggests ILP-based methods as a valuable alternative to SA for the WSMPA P1 planning process, thereby strengthening the scientific foundation for effective marine conservation strategies.

KEYWORDS
biodiversity, CCAMLR, integer linear programming, Marxan, simulated annealing, Southern Ocean, spatial planning, prioritizr, protected areas

1 | INTRODUCTION

Human activities can have a substantial negative influence on large parts of the oceans (Halpern et al., 2008). A pressing concern today is how best to protect the world's marine biodiversity and its associated goods and services from a variety of stressors, such as overfishing and the impacts of climate change. Consequently, there has been a significant increase in initiatives, particularly over the last decade, aimed at establishing a global network of marine protected areas (MPAs). These concerted efforts are in line with the objectives of the Strategic Plan for Biodiversity 2011–2020 (CBD, 2010), the United Nations Sustainable Development Goal 14 (UN, 2020) and the new Biodiversity Beyond National Jurisdiction Agreement (UN, 2025). The impetus behind these endeavors is underscored by the growing support for the 30 × 30 target, aspiring to protect 30% of the global ocean by 2030 (Roberts et al., 2020; Waldron et al., 2020).

Systematic conservation planning (hereafter referred to as "conservation planning") is a widely applied, multistep approach for identifying priority areas for protection and developing management strategies. The process incorporates feedback, revision and iteration at each step (Kukkala & Moilanen, 2013; Margules & Pressey, 2000; Moilanen et al., 2009). In practice, conservation planning problems are often formulated as optimization problems to identify solutions that best meet predefined conservation objectives while minimizing costs. The solutions can then be presented to key stakeholders and decision makers for evaluation and negotiation. Due to the systematic, evidence-based nature of conservation planning, it can contribute to a transparent, reproducible, and more defensible decision-making process (Margules & Pressey, 2000). Trust and understanding between opposing stakeholder groups can thus be strengthened (e.g., Fernandes et al., 2005; Pressey & Bottrill, 2009).

Computer software is often used to support spatial prioritization methods, with a variety of tools currently in use (e.g., see reviews by Giakoumi et al., 2025; Sarkar et al., 2006), among which Marxan is the most widely used (Ball et al., 2009). Marxan has been extensively applied in marine contexts, including the English Channel (Delavenne et al., 2012), the Gulf of California (Airamé et al., 2003), and the Russian Arctic seas (Spiridonov et al., 2017). Generally, the algorithm used in Marxan for solving conservation planning problems is the "simulated annealing" (SA), a metaheuristic algorithm that provides not the optimal solution, but near-optimal solutions within the number of runs determined by the conservation planners (Brunel & Lanco Bertrand, 2023). However, a simulation study by Beyer et al. (2016), for example, showed that Marxan with SA could provide solutions that are orders of magnitude below the optimum. Alternative algorithms to SA, such as integer linear programming (ILP), have been around for 30 years (Önal, 2004; Rodrigues & Gaston, 2002; Underhill, 1994). However, it took some time before ILP was suitable for solving conservation problems (Beyer et al., 2016). Today, the improved performance of ILP algorithms (Schuster et al., 2020), which are able to find optimal solutions to conservation problems, seems to herald a paradigm shift that has already been recognized by the developers of Marxan (Beyer et al., 2016).

This is reflected in a gradual shift in the methods used to address conservation planning problems in Southern Ocean initiatives under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (CCAMLR, 2011). Previously, SA (using Marxan) had been used for the development of most CCAMLR MPAs, including both established MPAs (e.g., the South Orkney Islands Southern Shelf MPA) (Trathan & Grant, 2019) and those that have been proposed and discussed within CCAMLR for several years (e.g., MPAs for the Antarctic Peninsula and the Weddell Sea) (Sylvester & Brooks, 2019; Teschke et al., 2021). However, the recently proposed CCAMLR MPA east of the Weddell Sea is based on prioritization solutions derived using ILP (CCAMLR-44/27, 2025).

The Weddell Sea region is of great importance for the global climate, biosphere, and human well-being. It is considered one of the last refuges for many marine species dependent upon cold, pristine waters for their survival (Nissen et al., 2024). The Weddell Sea plays a crucial role in global marine biodiversity (Brey et al., 1994), supporting fundamental ecosystem processes such as primary and secondary production (Gutt et al., 2022), and providing important services, including carbon sequestration (Deininger et al., 2016). The region also serves as a vital breeding and foraging area for numerous bird and mammal species (Handley et al., 2021; Hindell et al., 2020). In addition, it hosts unique and vulnerable habitats, including fish spawning aggregations (Purser et al., 2022) and species-rich sponge communities (Barthel & Gutt, 1992), underscoring its value for marine conservation.

However, the growing influence of human activity in the Weddell Sea introduces both challenges and opportunities for its conservation and management. Current activities include limited fishing, scientific research, and tourism. Fisheries are restricted to exploratory longline fishing for Antarctic toothfish (*Dissostichus mawsoni*) in areas designated by CCAMLR (CCAMLR, 2025), while scientific research spans a wide range of topics, from marine biology to climate sciences (Clarke & Harris, 2003; Grant et al., 2013). Tourism, although still relatively limited compared to other parts of Antarctica (Bastmeijer et al., 2023 and references therein), is expected to grow as global warming reduces sea ice and extends the accessible season (Deininger et al., 2016). As human activity continues to expand in this ecologically significant region, careful management will be essential to balancing economic, scientific, and conservation interests.

Building on this context, our study presents the first ecosystem-based comparison of prioritization solutions derived from SA (using Marxan) and ILP (using R's package "prioritizr") in a policy-driven context, specifically for the proposed CCAMLR MPA Phase 1 in the Weddell Sea (hereafter WSMPA P1) (CCAMLR-44/23 Rev. 1, 2025). Unlike previous methodological comparisons (Beyer et al., 2016; Cavalcante et al., 2025; Schuster et al., 2020), which relied on simulated datasets or focused on single components of largely terrestrial ecosystems, our study integrates marine data across multiple taxonomic groups, including benthos, plankton, fish, birds, and marine mammals.

We hypothesize that (1) ILP solutions across different scenarios will not differ substantially from SA solutions in terms of the overlap of selected planning units (PUs), but that (2) ILP will produce more "efficient" prioritization solutions, both in terms of solution metrics and processing time. Specifically, we expect ILP to generate solutions with (i) lower spatial fragmentation, (ii) smaller total area coverage, (iii) higher cost-efficiency, and (iv) shorter computational time compared to SA.

This study is based on the dataset compiled by Teschke et al. (2020) and subsequently used by Teschke et al. (2022) to conduct univariate and multivariate statistical comparisons of reserve configurations generated with Marxan. In this study, the dataset is applied to compare the effectiveness of SA and ILP in identifying priority areas for protection, a comparison not conducted in the previous studies under the WSMPA project. The results aim to inform the potential adoption of a WSMPA P1 conservation measure, representing an important step toward achieving CCAMLR's goal of establishing a representative system of MPAs around Antarctica.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area encompasses the WSMPA P1 planning area (Figure 1) which is divided into 57,077 hexagonal planning units (PUs), each covering 50 km^2. The area extends between the Antarctic Peninsula and the prime meridian, including the Weddell Sea and a small portion of the King Haakon VII Sea. It spans from the offshore waters at 64° S in the north to the Antarctic continental margin in the south. The total area covers approximately 3.5 million km^2, with about 651,000 km^2 ($\sim$19%) permanently covered by ice shelves.

Most of the biological conservation features included in this analysis represent essential habitats for highly mobile species (e.g., fish, seals, seabirds), whose foraging typically occurs at broader spatial scales. For example, core foraging areas for breeding Adélie penguins were represented using a 50 km buffer around each colony, following CCAMLR spatial planning discussions (WG-EMM-15/42, 2015). Finer-scale patterns, particularly for less mobile or sessile species, are only locally documented and cannot reliably inform the selection of PU size. We therefore selected a PU size of 50 km^2 to capture the broad-scale ecological patterns across the study area. While this resolution may underrepresent fine-scale variation, it represents a necessary compromise given the limited availability of spatially explicit data in the data-poor Southern Ocean and the need for large-scale prioritization.

2.2 | Input data

A total of 54 conservation features were considered, including the occurrence of Antarctic krill, sponge communities, pelagic and demersal fish, seabirds, and marine mammals, as well as pelagic and benthic (eco-) regions (Table S1). The map layers for these features were generated using methods tailored to data availability: expert knowledge, deterministic interpolation, or species distribution modeling. The procedure for developing the map layers for these features is described in Teschke et al. (2020), and the maps are available from the data publisher PANGAEA (Pehlke et al., 2019a, 2019b; Pehlke & Teschke, 2019; Teschke et al., 2019a, 2019b, 2019c). The map layers for the benthic (eco-) regions were derived

FIGURE 1 Planning area of the Weddell Sea Marine Protected Area Phase 1 (WSMPA P1) and its location in the Southern Ocean (top left corner). Base layers for Antarctica and the ice shelf are derived from Quantarctica 3.2 (Matsuoka et al., 2021).

using the spatial classification approach outlined in Douglass et al. (2014).

We also used a cost metric reflecting the potential interest in the Antarctic toothfish (*Dissostichus mawsoni*) fishery at a given site. It was assumed that sites more accessible to fishing vessels (i.e., less ice-covered sites) and more suitable as habitat for Antarctic toothfish would be of higher interest to the fishery, resulting in higher relative costs. Further details on the construction of the cost metric are given in Teschke et al. (2018), and the distribution map for Antarctic toothfish is available via PANGAEA (Teschke et al., 2019a).

2.3 | Scenarios investigated

The SA problems were solved using the Marxan software, version 2.43 (Ball et al., 2009), while the ILP problems were solved using prioritizr 8.0.6.1 (Hanson et al., 2025) with the Gurobi optimizer 12.0.0 (Gurobi Optimization, LLC., 2024), one of the most powerful commercial solvers currently available.

To compare the prioritization solutions developed with SA and ILP, we focused on three scenarios, each incorporating the same cost metric for Antarctic toothfish (Table 1). The set of 54 conservation features was used for all three scenarios, but with different conservation targets, that is, varying proportions of each feature's distribution in the WSMPA P1 planning area required to be included in the solution (Table S1). The minimum target scenario (FT_{Min}) used relatively low proportions for both ecological (e.g., species and species assemblages) and environmental (e.g., benthic (eco-) regions) features' distribution (Table 1). The "mixed target scenario" (FT_{Mix}) set relatively low proportions for environmental features, but medium proportions for ecological features, providing greater protection to ecological features than to environmental ones. Finally, the "medium target scenario" (FT_{Med}) applied medium proportions for both ecological and environmental features' distributions. This scenario represents the most challenging of the three reserve-design problems when it comes to minimizing the cost of the solution while ensuring that all conservation feature targets (FTs) are met.

The conservation features and their target proportions for inclusion in the protected area (i.e., minimum versus medium) were established during an expert workshop held in Berlin in 2015. These targets were set in alignment with the targets of other Southern Ocean planning initiatives (e.g., SC-CAMLR-XXVIII/14, 2009) and beyond (e.g., Airamé et al., 2003; Grantham et al., 2011). For certain unique, rare and highly sensitive features (e.g., sponge associations, icefish nest areas), the highest conservation target of 100% was applied across all scenarios (i.e., 100% of the distribution of these features to be protected within WSMPA P1). For further details on the other conservation FTs, see Table S1.

All Marxan scenarios shared the same input parameters: (A) 10, 250, 500, 750, 1000, 1250, 1500, 1750, and 2000 runs with 10,000,000 iterations; (B) the most efficient boundary length modifier (BLM) of 0.00125; and (C) a species penalty factor (SPF) of 5.3. Parameter calibration is discussed in detail in Teschke et al. (2018). In this analysis, we used the results of the Marxan "best solution", that is, each planning unit was scored exclusively according to the best run from a series of runs.

The prioritizr scenarios were run using the most efficient boundary penalty values (which serve a similar purpose to the BLM in Marxan by penalizing spatial fragmentation): 0.0002 (FT_{Min} scenario), 0.00025 (FT_{Mix}), and 0.0005 (FT_{Med}) (see calibration in the Supporting Information). It is important to note that the BLM in Marxan and boundary penalty values in prioritizr are not directly comparable in magnitude or effect, as they are implemented differently within the respective optimization frameworks. Therefore, similar parameter values do not imply a similar degree of spatial clustering between the two approaches. Unlike Marxan, we did not need to calibrate SPFs to ensure that the targets were met, as the

TABLE 1 Overview of scenarios using Simulated Annealing (SA) and Integer Linear Programming (ILP), including costs for Antarctic toothfish (for further details on individual targets see Table S1).

Scenario	Feature targets (FT)	Abbreviation
Minimum target	Low targets for all conservation features	FT_{Min}
Mixed target	Low targets for all environmental conservation features and medium targets for all ecological conservation features	FT_{Mix}
Medium target	Medium targets for all conservation features	FT_{Med}

minimum set objective in prioritizr always returns solutions in which all FTs are met; consequently, SPFs are not required (see details in Rodrigues et al., 2000).

In this paper, we compare the best solution achieved with Marxan over 10 repeat runs (hereafter referred to as "Marxan 10 runs") with the prioritizr solution for each of the three FTs scenarios. We chose 10 repeat runs based on Schuster et al. (2020) to ensure a fair comparison between SA and ILP, focusing primarily on algorithmic differences. Additionally, for a more qualitative comparison, we also compare the overall best solution (hereafter referred to as the "Marxan near-optimal run") with the prioritizr solution for each FT scenario. The Marxan near-optimal runs were determined by performing Marxan between 10 and 2000 repeat runs, with an increment of 250 runs.

All analyses were conducted on a MacBook Pro with an Apple M3 processor, 12 cores, and 18 GB of memory, running macOS Sonoma 14.3, and R version 4.3.2 (R Core Team, 2023). All code used in the analysis and visualization as well as the underlying data are publicly available on Zenodo: https://doi.org/10.5281/zenodo.18981787.

2.4 | Comparative analyses

We visually and quantitatively assessed the spatial overlap of the selected PUs from the Marxan 10 runs and the Marxan near-optimal runs with the prioritizr solutions for each of the three FT scenarios. For the visual assessment, we mapped the solutions of each software and their overlap. For quantitative evaluation, we calculated the Jaccard similarity index between the Marxan 10 runs or Marxan near-optimal runs and the prioritizr solutions for each of the three target scenarios. The Jaccard index ranges from 0 to 1, where 0 indicates no similarity and 1 indicates complete agreement (Sokal & Rohlf, 2012). Additionally, we calculated the total area coverage of the selected PUs for each scenario to compare the spatial extent of the solutions. The associated costs were taken from the solutions outputs of each scenario.

3 | RESULTS

For the Marxan near-optimal runs, we present the overall best solution (i.e., among all the runs) that was first identified in the Marxan analyses with (i) 750 runs for the minimum target scenario (FT_{Min}), (ii) 250 runs for the mixed target scenario (FT_{Mix}), and (iii) 1500 runs for the medium target scenario (FT_{Med}). These solutions were repeatedly identified as the best solution in each subsequent Marxan analyses with higher numbers of runs (see Figure S3).

3.1 | Spatial overlap

The largest contiguous and overlapping PUs were predominantly located on the southern Weddell Sea shelf and slope (Figures 2, 3). They stretched from the southeastern ice shelves toward the eastern edge of the study area and extended along the east coast of the Antarctic Peninsula up to the study area's northern boundary.

This spatial pattern of overlap was consistent across all three conservation FT scenarios. Compared to the minimum target scenario (FT_{Min}), both the mixed (FT_{Mix}) and medium (FT_{Med}) target scenarios showed broader and more distinct overlap in these areas, as well as additional overlapping PUs, such as a prominent belt-shaped area of overlap in the southern Weddell Sea.

Spatial overlap between Marxan and prioritizr solutions showed moderate to high agreement. The degree of spatial congruence, measured using Jaccard's similarity index, was highest in the FT_{Min} scenario and decreased slightly in the more complex scenarios (Table 2). The spatial overlap between solutions derived from Marxan (both 10 runs and near-optimal run) and prioritizr was broadly comparable across all scenarios.

3.2 | Spatial fragmentation

Across all conservation FT scenarios, prioritizr consistently produced less spatially fragmented solutions compared to Marxan (Figures 2, 3). This held true both when a boundary penalty was applied (equivalent to the BLM in Marxan) and when it was omitted. Notably, even in the absence of a boundary penalty, prioritizr generated

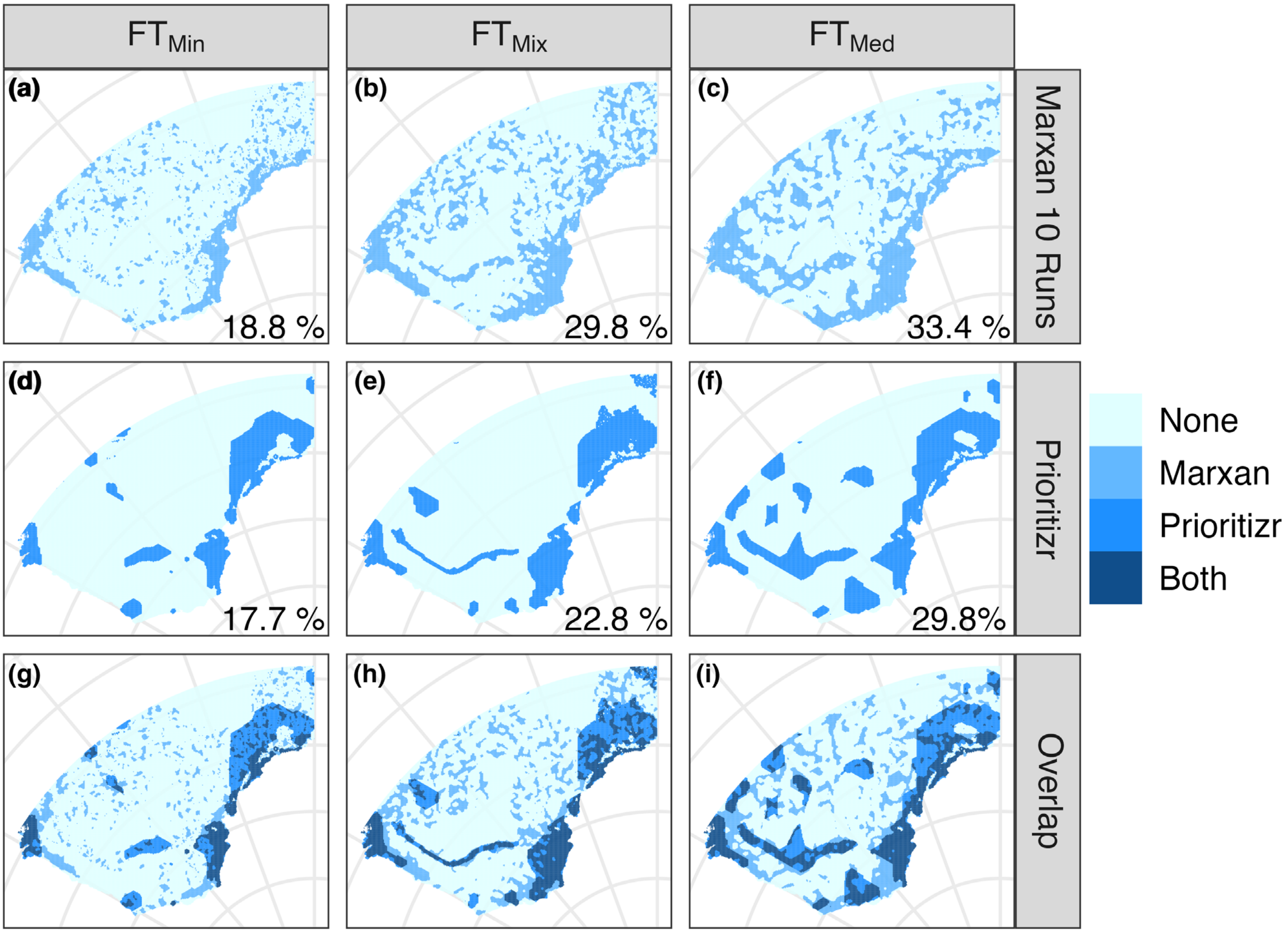

FIGURE 2 Solutions obtained from Marxan over 10 runs (panels a–c), prioritizr (panels d–f), and their overlapping areas (panels g–i) across three conservation target scenarios for WSMPA P1 features: Minimum targets (FT$_{Min}$), mixed targets (FT$_{Mix}$), and medium targets (FT$_{Med}$). The percentage shown at the bottom right of panels a–f indicates the proportion of the planning area selected in each respective solution.

more spatially cohesive solutions than Marxan (Figure S2). These differences in fragmentation were evident in both the Marxan 10 runs (Figure 2) and the Marxan near-optimal run (Figure 3).

3.3 | Total area coverage

Across all conservation FT scenarios, prioritizr consistently selected a smaller total area compared to Marxan, highlighting its spatial efficiency (Figures 2, 3, 4 and S4). This difference in total area coverage was most pronounced in the mixed (FT$_{Mix}$) and medium (FT$_{Med}$) target scenarios.

In the minimum target scenario (FT$_{Min}$), prioritizr selected a total area of 499,400 km^2, corresponding to 17.7% of the planning area. In contrast, the solutions obtained from Marxan covered larger areas: 530,550 km^2 (18.8%) in Marxan 10 runs and 517,950 km^2 (18.4%) in Marxan near-optimal run. For the mixed conservation targets (FT$_{Mix}$ scenario), the disparity became more evident. Prioritizr selected 641,250 km^2 (22.8%), while the solutions for the Marxan 10 runs and the Marxan near-optimal run covered substantially larger portions of the planning area, selecting 840,650 km^2 (29.8%) and 869,100 km^2 (30.8%), respectively. A similar trend was shown in the FT$_{Med}$, where prioritizr again produced the most spatially efficient solution by selecting 839,150 km^2 (29.8%). By comparison, Marxan selected 941,350 km^2 (33.4%) with 10 runs and 893,900 km^2 (31.7%) in the Marxan near-optimal solution.

3.4 | Cost-efficiency

Across all conservation FT scenarios, prioritizr consistently generated the most cost-efficient solutions (Figure 4 and S5). Cost differences were particularly substantial in the FT$_{Min}$ scenario, where the solution for the Marxan 10 runs resulted in the highest cost

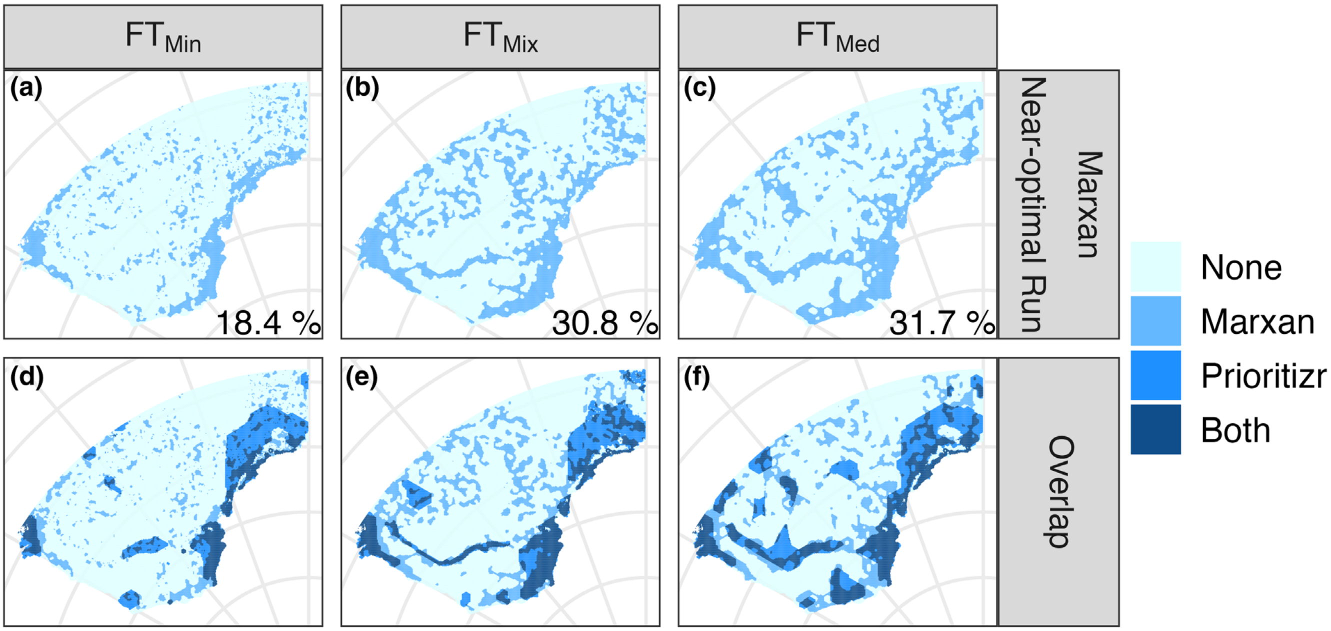

FIGURE 3 Solutions obtained from the Marxan near-optimal run (panels a–c) and their overlap with prioritizr solutions (panels d–f) for three conservation target scenarios: minimum feature targets with 750 runs (FT_{Min}; panels a, d), mixed feature targets with 250 runs (FT_{Mix}; panels b, e), and medium feature targets with 1500 runs (FT_{Med}; panels c, f). The percentage shown at the bottom right of panels a–c indicates the proportion of the planning area selected in each respective solution.

TABLE 2 Pairwise similarity scores comparing the spatial overlap between the Marxan and the prioritizr solutions.

Marxan solution	FT_{Min}	FT_{Mix}	FT_{Med}
10 runs	0.804	0.761	0.723
Near-optimal runs	0.810	0.743	0.738

Note: Values represent Jaccard's similarity index, which ranges from 0 to 1, where 0 indicates no similarity and 1 indicates complete agreement. Each column shows scores for each feature target (FT) scenario and each row shows a different Marxan solution (best of 10 runs or near-optimal run).

(>30,000 cost units), followed by the Marxan near-optimal run. In contrast, prioritizr produced the lowest-cost solution. This pattern persisted in the FT_{Mix} scenario, although the cost disparities were less pronounced. In the FT_{Med} scenario, cost differences between Marxan and prioritizr narrowed, yet prioritizr remained slightly more efficient overall.

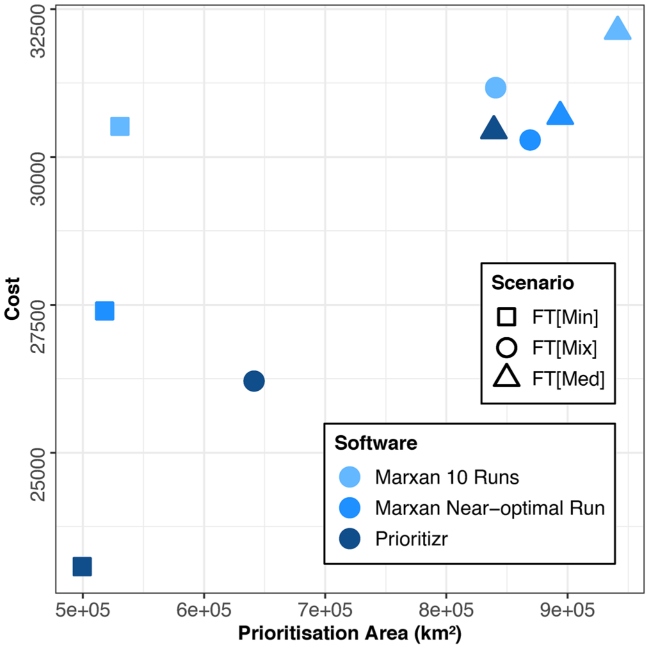

FIGURE 4 Relationship between total area coverage (km^2) and total solution cost across the three target scenarios (FT_{Min}, FT_{Mix}, FT_{Med}) for Marxan (near-optimal run and 10 runs) and prioritizr.

3.5 | Area-cost relationship

A clear positive relationship was evident, with scenarios that required larger areas generally incurring higher costs (Figure 4). The FT_{Min} scenario showed the smallest area across prioritizr and Marxan and lower costs for prioritizr and the Marxan near-optimal run. In contrast, FT_{Mix} and FT_{Med}, except for FT_{Mix} in prioritizr, required progressively larger coverage, which resulted in correspondingly higher costs. Across all scenarios, Marxan solutions, particularly the Marxan 10 runs, had higher costs and larger areas compared to the prioritizr results.

3.6 | Computational time

With respect to computational efficiency, the Marxan 10 runs solutions were the fastest to compute, due to their limited number of runs (Figure S6). Among the Marxan near-optimal runs, the FT_{Mix} scenario was resolved most quickly, requiring only 250 runs. In contrast, the FT_{Med} scenario demanded substantially more time, as the solution was derived after 1500 runs; approximately six times longer. Prioritizr's runtime was generally comparable to that of Marxan's near-optimal solutions in the FT_{Min} and FT_{Mix} scenarios. However, for the FT_{Med} scenario, prioritizr required approximately 30 additional minutes to reach its optimal solution. Given the complexity of the FT_{Med} scenario, this increase in computational time is considered acceptable, particularly in light of improved spatial coherence and cost-efficiency provided by the prioritizr solution.

4 | DISCUSSION

In this case study, we successfully addressed two central questions through the applied analytical approaches: (1) as expected, prioritizr's ILP solutions did not differ substantially from Marxan's SA solutions in terms of the spatial overlap of selected PUs across all conservation FT scenarios; and (2) prioritizr outperformed Marxan in three out of four evaluated metrics: it presented (i) reduced spatial fragmentation, (ii) smaller total area, and (iii) lower overall cost.

4.1 | Spatial overlap and fragmentation

Our results demonstrate that both algorithms identified largely overlapping priority areas with Jaccard similarity indices exceeding 0.7 across all scenarios and Marxan configurations (10 runs and near-optimal run). The highest spatial agreement occurred in the FT_{Min} scenario and the lowest in the FT_{Med} scenario, consistent with expectations that simpler conservation problems yield higher cross-method agreement. However, the increase in similarity between FT_{Med} and FT_{Min} was modest ($\sim$0.1), indicating that reducing target values alone does not sufficiently decrease conservation problem complexity. More substantial simplification may require additional reductions in planning unit numbers and conservation features (e.g., Schuster et al., 2020).

Moreover, the spatial similarity between Marxan near-optimal solutions and prioritizr solutions did not notably exceed that observed between Marxan 10 runs solutions and prioritizr. This supports previous findings that SA-based (meta-)heuristics often face difficulties in complex spatial prioritization problems (Beyer et al., 2016). Given the scale of our conservation planning problem (57,077 PUs and 54 features), it is plausible that Marxan encountered optimization challenges and was potentially trapped in local optima (Ball et al., 2009).

The highest overlap areas were located on the southern Weddell Sea shelf and slope, extending eastward along the ice shelves and the north-eastern coast of the Antarctic Peninsula. These areas have also been highlighted in previous studies (e.g., Teschke et al., 2022) as ecologically critical, due to the occurrence of numerous conservation features, including unique, rare and highly sensitive ones. In Teschke et al. (2022), the summed Marxan solution outputs showed PUs in these areas appearing in over 75% of all outputs, highlighting their irreplaceability for achieving the conservation objectives (Stewart & Possingham, 2005).

Despite broad spatial agreement, clear structural differences between the solutions were evident. Across all target scenarios, prioritizr consistently produced less spatially fragmented reserve networks. Remarkably, this was achieved even when boundary penalties in prioritizr were more than six times lower than Marxan's boundary length modifier, or were entirely omitted, with no additional connectivity constraints. These results underscore the inherent advantage of ILP approaches in producing more spatially coherent solutions (Beyer et al., 2016; Hanson et al., 2025; Williams et al., 2005), which may facilitate practical implementation. From a conservation policy perspective, the reduced spatial fragmentation observed in prioritizr solutions is relevant. More coherent reserve networks are easier to manage, enforce, and communicate. In contrast, more fragmented networks may increase edge effects (Ohayon et al., 2021), raise monitoring needs, and add to management complexity. These results underscore the value of mapping spatial fragmentation alongside traditional metrics (e.g., target achievement, area coverage) to support cost-efficient and coherent MPA designs.

4.2 | Total area coverage and cost-efficiency

Prioritizr also consistently outperformed Marxan in terms of total area and cost. Across all target scenarios, prioritizr selected fewer PUs to meet conservation FTs. Differences in total area reached up to 8%, corresponding to approximately 200,000 km^2 of additional area selected by Marxan. From a policy perspective, reducing the spatial extent of protected areas is often crucial for implementation feasibility. Larger MPAs often face political resistance due to perceived economic trade-offs, such as restricted access to fishing grounds (Davies et al., 2018). This tension is evident in ongoing discussions within CCAMLR regarding large-scale MPA proposals in the Southern Ocean (e.g., WSMPA P1), where concerns about size and fisheries impacts, among other things, have hindered progress (CCAMLR, 2022). Moreover, prioritizr provided more cost-efficient solutions than Marxan, particularly in the less complex FT_{Min} and FT_{Mix} scenarios. Given the limited financial resources typically available for MPA implementation, these results underline the practical relevance of ILP-based methods in achieving conservation goals at lower cost.

4.3 | Computational time

In terms of computational performance, both tools required comparable runtimes for FT_{Min} and FT_{Mix} scenarios. In the more complex FT_{Med} scenario, prioritizr required approximately 30 min longer to compute an optimal solution, which remains acceptable given its advantages in other performance metrics. While it is known that exact methods based on ILP can struggle with large conservation planning problems (Williams et al., 2005), the modest increase in runtime appears justifiable in this context. This is particularly relevant given that part of the computational time in prioritizr may be associated with spatial pre-processing and problem construction rather than the optimization itself, which may explain the observed similarity in runtimes with Marxan. In addition to final solution runtimes, the practical effort required for parameter calibration should also be considered. In Marxan, tuning parameters such as SPF and BLM can take several hours up to a full working day, depending on the scenario (pers. obs.), and is a necessary component of every SA-based planning process (Ardron et al., 2010). In contrast, ILP-based approaches like prioritizr typically require minimal parameter adjustment. As our results indicate, even solutions generated without boundary penalty calibration (i.e., with the boundary penalty set to 0) exhibit practically useful performance in terms of spatial and cost efficiency (Figures S1,S2).

4.4 | Conclusion and implications for the WSMPA planning process

Our results demonstrate that prioritizr can produce more spatially coherent, area- and cost-efficient solutions without extensive parameter calibration, highlighting its potential as a valuable tool for conservation planning. While this study focuses on the WSMPA case study, the demonstrated advantages of ILP-based approaches over SA-based methods, supported by findings from Beyer et al. (2016) and Schuster et al. (2020), are likely relevant for other regions and conservation planning contexts. These benefits may be particularly relevant in real-world decision-making contexts, where time and resources for scenario calibration are often limited and where spatially coherent reserve networks facilitate implementation, monitoring, and stakeholder communication.

We emphasize that Marxan and prioritizr represent only part of the methodological landscape in conservation planning, and other tools such as Zonation have also shown promising performance (e.g., Cavalcante et al., 2025). We suggest that future studies consider assessing spatial fragmentation alongside traditional performance metrics (e.g., target achievement, area coverage) to better support the design of cost-efficient and coherent MPA networks.

For the WSMPA planning process, these findings carry immediate practical relevance. They support a methodological transition toward prioritizr, especially during the ongoing CCAMLR negotiations, where stakeholder engagement and iterative refinement of the MPA design are crucial. The agreement between Marxan and prioritizr results enhances confidence in the robustness of the spatial prioritization and affirms that the WSMPA P1 planning process continues to evolve methodologically, in line with current best practices. We hope this work provides valuable technical and strategic support for the WSMPA negotiations and the eventual adoption of a comprehensive WSMPA Phase 1 conservation measure.

AUTHOR CONTRIBUTIONS

K.T.: Conceptualisation; data curation; funding acquisition; methodology; project administration; supervision; writing—original draft; writing—review and editing. R.K.: Data Curation; methodology. F.C.B.T.: Data Curation; formal analysis; methodology; resources; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The code used to generate the results and figures in this paper as well as the underlying data are publicly available on Zenodo: https://doi.org/10.5281/zenodo.18981787.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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