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Exploring spatial similarity and performance among marine protected area planning scenarios: The case of the Weddell Sea, Antarctica

Katharina Teschke [a,b,*], Rebecca Konijnenberg [a], Hendrik Pehlke [a,b], Thomas Brey [a,b,c]

[a] Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar und Meeresforschung, Am Handelshafen 12, 27570 Bremerhaven, Germany
[b] Helmholtz Institute for Functional Marine Biodiversity at the University Oldenburg (HIFMB), Ammerländer Heerstraße 231, 26129 Oldenburg, Germany
[c] University Bremen, Bibliothekstraße 1, 28359 Bremen, Germany

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ABSTRACT

The world's oceans are exposed to a variety of pressures, such as overfishing and the environmental effects of increasingly dense coastal populations. Policy and science agree that a global network of marine protected areas (MPAs) will mitigate these effects. Conservation planners face the dual challenge of planning MPAs based on complex scientific information and supporting the decision-making process through clear and transparent communication with the involved stakeholders. To this end, visual comparisons of different mapped reserve configurations are a commonly used approach, while analytical approaches that assess the efficiency of different planning scenarios and trade-offs among them are still rarely used in practice. Here, we use uni- and multivariate statistics to compare reserve configurations used in the process of designing a Weddell Sea MPA (WSMPA) in Antarctica. We show that different target level settings (low, medium, mixed) for conservation features affect the configuration of the solutions significantly. The mixed-target scenario was one of the most flexible ones in that it produced the most diverse set of solutions, providing several options for consideration. At the same time, it was also the most well balanced scenario, finding relatively cost-efficient solutions while selecting an intermediate number of planning units that were most spatially clustered. Our study complements the qualitative sensitivity analysis carried out previously (mainly visual, descriptive scenario comparisons) and will hopefully further advance the WSMPA development process under CCAMLR. Furthermore, this paper adds to the growing literature advocating the application of multivariate statistics for further thorough and systematic evaluation procedures in conservation planning.

1. Introduction

Humans currently heavily influence large parts of the world's oceans (Halpern et al., 2008). One of the most urgent questions is therefore how best to protect the world's marine biodiversity and associated goods and services from the multitude of pressures, such

* Corresponding author at: Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar und Meeresforschung, Am Handelshafen 12, 27570 Bremerhaven, Germany.
E-mail address: Katharina.Teschke@awi.de (K. Teschke).

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as overfishing and the effects of climate change. Accordingly, there have been increased efforts particularly in the last decade to establish a global network of marine protected areas (MPAs) under the Strategic Plan for Biodiversity 2011–2020 (CBD, 2010) and the United Nations Sustainable Development Goal 14 (UN SDG 14, 2020). These efforts to designate MPAs continue with growing support for the 30 × 30 target (30% of the ocean protected by 2030) (Roberts et al., 2020; Waldron et al., 2020). For conservation planners, the challenge is to carefully plan priority conservation areas and ensure that stakeholders with different demands on the planning area are involved appropriately throughout the MPA development process. They also must ensure that the procedures are sufficiently transparent and that the necessary trust can be built with the stakeholders. This implies that they are able to communicate the sometimes complicated and interwoven scientific underpinnings in a way that is suitable for stakeholders and decision-makers.

Systematic conservation planning (Margules and Pressey, 2000; Moilanen et al., 2009) is a widely applied and successful approach to design effective protected areas by trying to meet user-defined conservation feature targets while minimising spatial fragmentation and user-defined costs of protected areas. Conservation planning outputs include a user-defined number of alternative 'solutions' (i.e. reserve system configurations) for a given 'scenario' that forms a specific protected area design problem.

Scenarios usually reflect conservation or management strategy and, for example, may be characterised by different feature targets, costs or probability of site destruction (Weeks et al., 2010; Harris et al., 2014; Arafeh-Dalmau et al., 2021). The different solutions can then be handed over to key stakeholders and decision-makers for evaluation and negotiation. Analytical comparisons among different solutions under different scenarios support further transparency in the negotiation process. Conservation planners can substantiate the different solutions and the resulting implications. While it is common to focus on a visual, descriptive comparison of different solutions only during the negotiation processes, procedures exist to quantify the efficiency of different spatial planning scenarios and trade-offs among them (Harris et al., 2014; Arafeh-Dalmau et al., 2021).

Systematic conservation planning has also been used to develop MPAs in the Southern Ocean under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (CCAMLR, 2011). To date, two such MPAs have been successfully established under CCAMLR: the South Orkney Islands Southern Shelf MPA (Trathan et al., 2019) and the Ross Sea MPA (Brooks et al., 2020). Further CCAMLR MPAs for the Antarctic Peninsula (Sylvester et al., 2019), East Antarctica (CCAMLR-40/18, 2021) and the Weddell Sea (Teschke et al., 2021) have been proposed. However, their approval is still pending, despite several years of scientific discussions and political negotiations.

No analytical comparisons (*sensu* Harris et al., 2014) had been carried out previously between different solutions under different scenarios in the planning of the Weddell Sea Marine Protected Area (WSMPA). Here, we present such an analysis in an effort to further enhance the transparency and trustworthiness of the ongoing WSMPA development process.

The conservation value of the Weddell Sea has been known for many years. The Weddell Sea region is, for example, an important breeding and foraging ground for birds and mammals (Hindell et al., 2020; Handley et al., 2021), inhabits benthic communities that are comparable to tropical coral reefs in terms of species richness and biodiversity (e.g. Brey et al., 1994; Brandt et al., 1994), and provides key ecosystem services (Deininger et al., 2016). Only recently, the world's largest breeding colony of Ionah icefish was discovered in the Weddell Sea (Purser et al., 2022), which, in addition to underscoring the value of the wider Weddell Sea region for marine conservation also shows how much remains undiscovered despite more than 35 years of multidisciplinary research.

Fishing in the wider Weddell Sea region is currently limited to the exploratory fishing of Antarctic toothfish (*Dissostichus mawsoni*) situated in the eastern part of the region (CCAMLR, 2021). Although the intention was expressed some years ago to conduct exploratory fisheries for Antarctic krill (*Euphausia superba*) in that same region, no krill is currently fished there. This means that the wider Weddell Sea is still a region relatively unaffected by fishing. However, this may change in the coming decades. For example, the predicted long-term effects of climate change may shift the most favourable krill habitats (currently in the Scotia Sea north of the Weddell Sea) further south into the Weddell Sea (Hill et al., 2013). Krill fisheries would have to follow, likely leading to increased competition with krill-dependent predators. Like krill, many Antarctic predators are likely to shift in similar directions as they are mostly either directly dependent on sea ice and/or have evolved such strong adaptations to polar temperatures over the last millennia that their heat tolerance is low (e.g. Antarctic silverfish, emperor penguin, crabeater seals). Their continued survival depends on human efforts to keep anthropogenic pressures to a minimum and to support the Weddell Sea's potential role as a climate change refuge. The current conservation planning in the wider Weddell Sea, which follows the precautionary principle (i.e. avoid or reduce conceivable environmental impacts as far as possible in advance), could make an important contribution here.

In this paper, we aim to compare different solutions under different scenarios, which have previously been produced in the context of WSMPA planning using the decision support tool Marxan (Ball et al., 2009). In particular, our objective was to determine how the cost and the size of the reserve systems change under the different Marxan scenarios based on different conservation feature target settings. We hypothesise that (i) the different solutions of one scenario are more similar to each other than between scenarios and (ii) the more the feature targets increase, the more planning units need to be included to achieve the conservation targets, and consequently the larger and the more costly the scenarios are. This study complements the scenario planning (incl. a scenario-design sensitivity analysis) already carried out under the WSMPA project, and we hope that it will further facilitate the WSMPA negotiation process under CCAMLR and bring us closer to the adoption of a WSMPA conservation measure. Furthermore, this paper emphasises the benefit of multivariate statistic tools for conservation planning in general.

2. Materials and methods

2.1. Study area

The study area in our case study spans the original WSMPA planning area (Fig. 1) (Teschke et al., 2021), divided into 68,816 hexagonal planning units (PUs) with a size of approximately 50 km^2 each. The area lies between the Antarctic Peninsula and 20°E, and includes the Weddell Sea, the Lazarev Sea and a small part of the Riiser-Larsen Sea. The area covers the marine region from the offshore waters at 64°S in the north to the Antarctic continental margin in the south. The entire study area is approximately 4.2 million km^2, of which about 665,000 km^2 are covered permanently by ice shelves.

2.2. Planning scenarios

The Marxan scenarios examined in our case study were taken from Teschke et al. (2018). We focus on three scenarios run with a cost metric that reflected the possible interest of the Antarctic toothfish (*Dissostichus mawsoni*) fishery at a given site (Fig. 2). It was assumed that the more accessible a site is to fishing vessels (due to sea ice cover) and the more suitable it is as habitat for Antarctic toothfish, the more likely the site is to be of interest to the toothfish fishery and the higher its relative costs. Supporting information on the construction of the cost metric is given in Teschke et al. (2018), and the habitat map for toothfish is available via the data publisher PANGAEA (Teschke et al., 2019a).

To evaluate how different targets for conservation features (CFs) affect the reserve design, three feature target scenarios were considered: low targets for all CFs (FT_{Min}), medium targets for all CFs (FT_{Med}) and low targets for all environmental CFs combined with medium targets for all ecological CFs (FT_{Mix}) (Table 1). The same set of CFs was used for all feature target scenarios, i.e. a total of 75 CFs such as Antarctic krill, sponge communities, pelagic and demersal fish, seabirds and marine mammals as well as pelagic and benthic (eco-) regions. The procedure for producing the features' distribution maps is compiled in Teschke et al. (2020) and the maps are available from the data publisher PANGAEA (Pehlke and Teschke, 2019; Pehlke et al., 2019a, 2019b; Teschke et al., 2019a, 2019b, 2019c). The distribution maps for the benthic (eco-) regions were derived from the spatial classification approach of Douglass et al. (2014). The targets for each feature (i.e. proportion of a target's distribution required to be included in the protected area) were set during an expert workshop (Berlin, 2015) - following the targets of other Southern Ocean planning initiatives (e.g. SC-CAMLR-XX-VIII/14/14/14, 2009) and beyond (e.g. Airamé et al., 2003; Grantham et al., 2011). Exceptions are the unique and rare as well as the highly sensitive CFs (e.g., sponge associations, nesting sites of demersal fish), all of which have targets of 100% for all scenarios. For other CF targets see Teschke et al. (2021).

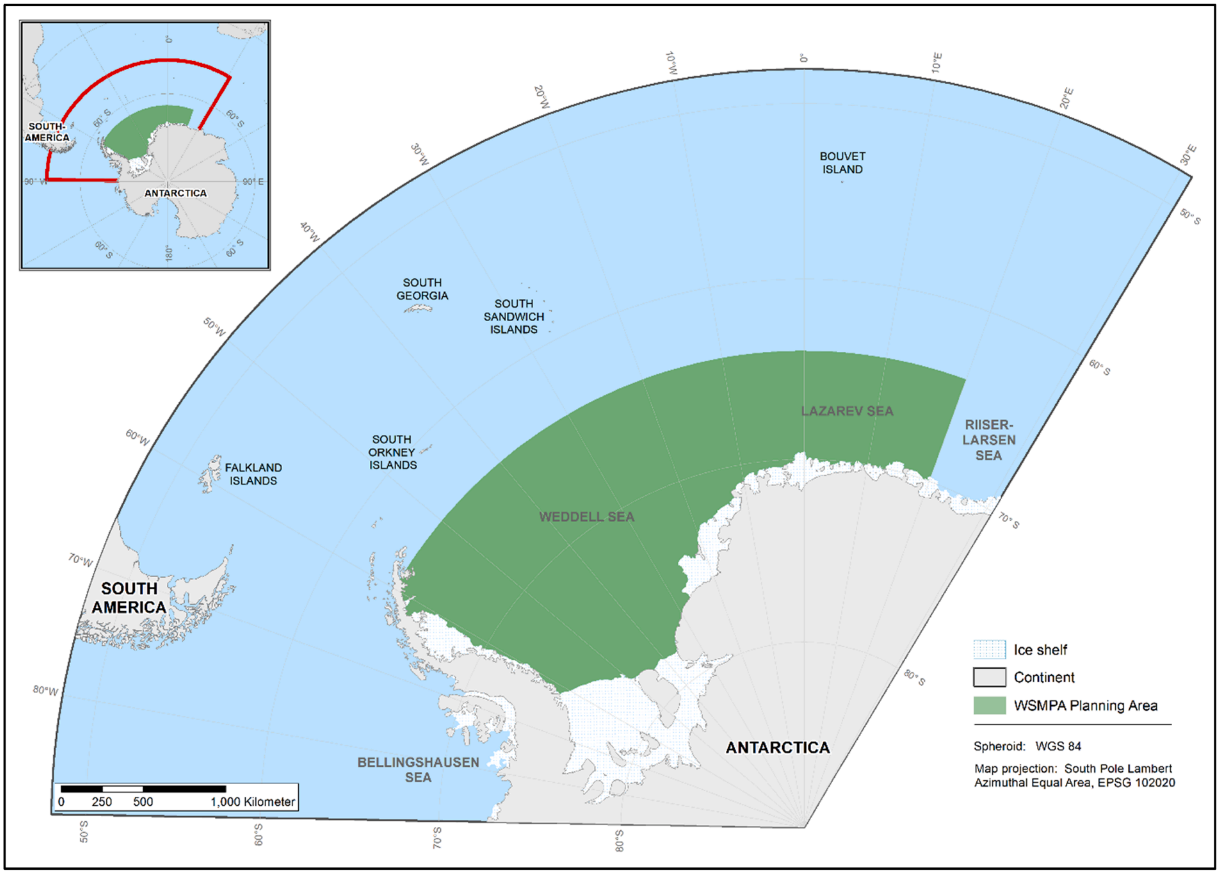

Fig. 1. Study area (green area) in the wider Weddell Sea region (Antarctica). Overview map of the study area and its location in the Southern Ocean (top left corner).

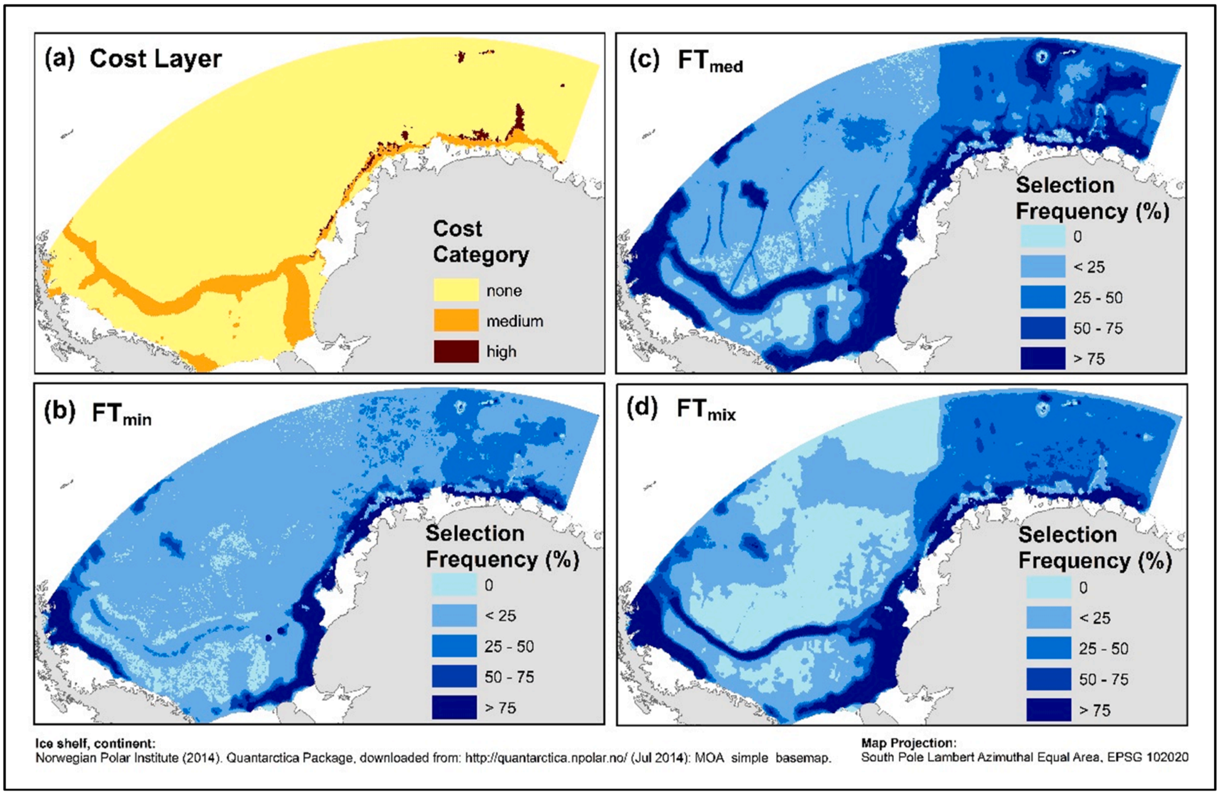

Fig. 2. (a) Cost metric and (b) - (d) selection frequency for the wider Weddell Sea region (Antarctica). Cost category expresses the interest in fisheries for Antarctic toothfish (*Dissostichus mawsoni*) at a given site. Selection frequency expresses the number of times a planning unit is selected in 250 Marxan solutions: (b) scenario with low targets for all conservation features (CFs); (c) scenario with medium targets for all CFs; and (d) scenario with low targets for all environmental CFs and medium targets for all ecological CFs.

Table 1
Overview of Marxan scenarios including costs for Antarctic toothfish.

Scenario (S)	Feature targets (FT)	Abbreviation
S1	Low targets for all conservation features	FT_{Min}
S2	Medium targets for all conservation features	FT_{Med}
S3	Low targets for all environmental conservation features and medium targets for all ecological conservation features	FT_{Mix}

To avoid possible effects of different target settings being hidden in the complexity of the interacting multi-parameter calibration, all three Marxan scenarios share the same input parameters: (1) 250 runs with 10,000,000 iterations; (2) a boundary length modifier (BLM) of 0.00125; and (3) a species penalty factor (SPF) of 5.3. The parameter calibration is discussed in Teschke et al. (2018).

2.3. Comparison of solutions

The analyses were carried out in R (version 3.6.2) (R Core Team, 2019). For the cluster and multivariate analyses, code was amended from Harris et al. (2014). All our R code is available in the Supplementary Material.

2.3.1. Spatial similarity among solutions and scenarios

A hierarchical cluster analysis was performed using the *hclust* function of the *stats* package (R Core Team, 2019) to compare similarity within and between planning scenarios. Clustering approaches originated in community ecology and have recently become of interest to conservation planners as a way to determine patterns and similarities in complex datasets (Harris et al., 2014). A traditional sample-species matrix was translated into a matrix with all 750 solutions (i.e. 250 runs x 3 scenarios) and 68,816 PUs. The PUs are either selected in the reserve design (1 = present) or not selected (0 = absent). The Jaccard similarity method was computed using the *vegdist* function (*vegan* package; Oksanen et al., 2020), as it is explicitly constructed for presence/absence data and suits the format of Marxan solution outputs. The visualisation of the cluster analysis was done by a dendrogram using the *ColorDendrogram* function of the *sparcl* package (Witten and Tibshirani, 2018), and by a principal coordinates analysis (PCoA) plot using the *wcmdscale* function of the *vegan package* (Oksanen et al., 2020).

In addition, we assessed the spatial overlap of the selection frequencies of the PUs among the planning scenarios. The selection frequency, i.e., the number of times a PU was included in the 250 Marxan solutions, is used as a proxy for PUs irreplaceability (Stewart and Possingham, 2005) and is commonly used to identify conservation priority areas. We therefore compared the summed solutions based on Cohen's kappa coefficient. This pairwise statistic (McHugh, 2012) indicates how much the selection frequencies of the PUs overlap among scenarios. Possible kappa values ranges from − 1 to + 1, though it usually falls between 0 and 1, where 0 indicates agreement no better than that expected by chance and + 1 indicates complete agreement (in contrast to −1 = complete disagreement) (Landis and Koch, 1977). We classified the PU selection frequency into five classes (0, <25%, 25%−50%, 50%−75% and >75%), following the approach of Ruiz-Frau et al. (2015). We used the *irr* package (Gamer et al., 2019) to calculate the spatial similarity among the different Marxan scenarios with respect to all five selection frequency classes and only the highest selection frequency class (>75%).

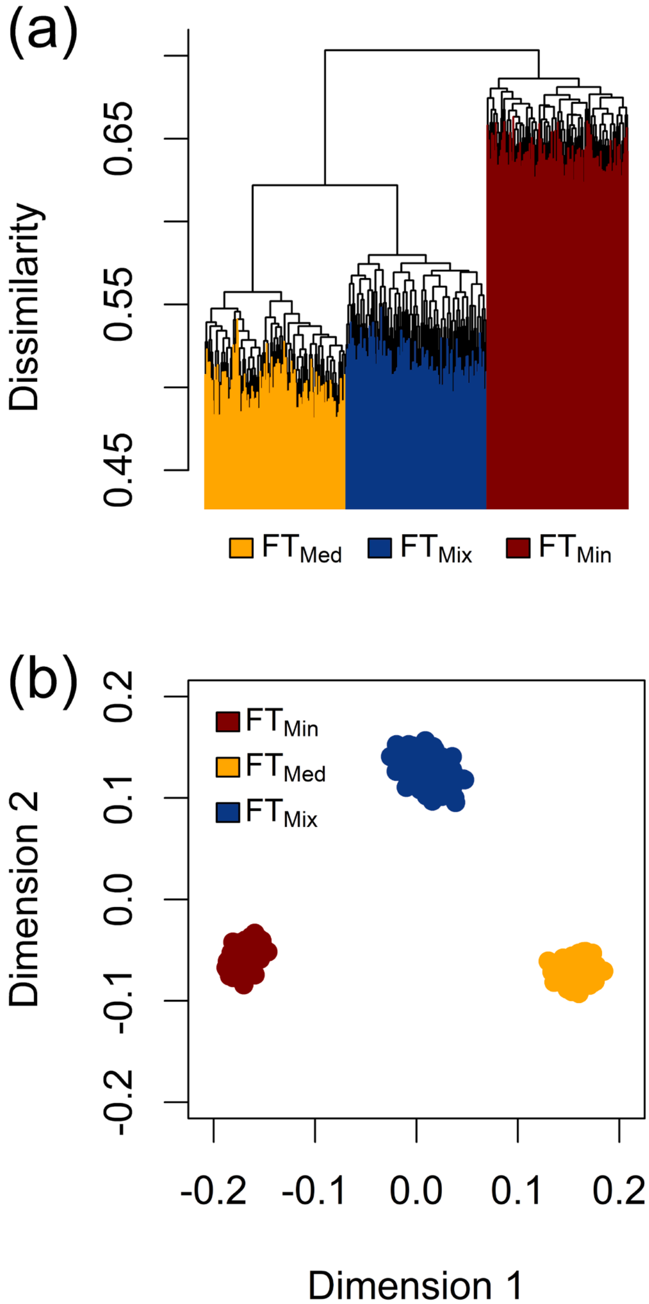

Fig. 3. Relationship among solutions and scenarios for each of the three scenarios. Data are visualised by (a) a dendrogram from a hierarchical cluster analysis and (b) a PCoA biplot based on a Jaccard resemblance matrix. FT_{Min}, FT_{Med}, FT_{Mix} refer to the three scenarios (Table 1).

2.3.2. Explanatory variables

To assess which of the explanatory variables are best correlated across the PCoA ordination, an *envfit* analysis was conducted (R *vegan* package). The explanatory variables include the continuous vectors associated with the solutions output to each scenario (Marxan summary information): total cost of the solution, number of PUs contained in the solution, connectivity (= total boundary length) of the solutions' reserve system and Marxan penalty value. Please note that this is a reduced version of the full Marxan output, reflecting the variables of interest in the case of the WSMPA. Vectors that were significantly correlated across the PCoA ordination ($p < 0.05$) were represented as GAM spline isopleths (using *ordisurf* from the *vegan* package). Collinearity between vectors was determined by Pearson's correlation coefficients using the *stats* package (R Core Team, 2019) and visualised using the *corrplot* package (Wei and Simko, 2017).

The effect of scenarios (defined by different features targets) on cost, number of planning units (PUs), connectivity (= reserve boundary length) and Marxan penalty value was tested each with a one-factorial Kruskal-Wallis test because data transformation did not eliminate heteroscedasticity (R *stats* package). Subsequently, a multiple comparison test was performed with a Wilcoxon rank sum test for post-hoc pairwise comparisons. A Bonferroni correction was used to reduce the effect of multiple comparisons testing. Approaches that combine the categorical factor "scenario" with all four continuous variables, i.e. cost, PUs, connectivity and penalty were not used due to multicollinearity of some of the variables.

3. Results

3.1. Spatial similarity among solutions and scenarios

The hierarchical clustering and the ordination technique indicated the greatest dissimilarity between Scenario FT_{Min} and the other two scenarios (FT_{Med} and FT_{Mix}), followed by the dissimilarity between Scenarios FT_{Med} and FT_{Mix} (Fig. 3). The neat clustering into three groups (i.e. grouping of solutions into individual colour bands), showed that the solutions within the scenarios were more similar than between the scenarios (Fig. 3a). Scenarios FT_{Med} and FT_{Mix} revealed higher variability among solutions compared to Scenario FT_{Min}, represented by a wider range of dissimilarity values per scenario (Fig. 3a) and a slightly larger spread of data points across the PCoA surface (Fig. 3b).

Considering all selection frequency classes of summed solutions, all scenarios showed fair spatial overlap between each other (Table 2). In contrast, Scenario FT_{Mix} had substantial spatial overlap with Scenarios FT_{Med} and Scenario FT_{Min}, while Scenario FT_{Med} showed only moderate spatial overlap with Scenarios FT_{Min} when only the highest selection frequency class > 75% was considered (Table 2).

3.2. Significant explanatory variables

All vectors chosen by us from the Marxan solution outputs (i.e., cost, PUs, connectivity, penalty) were significantly correlated with the PCoA surface ($p < 0.05$) (Fig. 4). Cost ($r^2 = 0.956$), number of PUs ($r^2 = 0.997$) and total boundary length ($r^2 = 0.929$) had high correlation coefficients (Fig. 4b, c, d), while the Marxan penalty was less correlated with PCoA ordination structure ($r^2 = 0.396$) (Fig. 4e). There was, however, a strong correlation among number of PUs and cost, suggesting that these vectors do not represent independent effects on the PCoA surface (Fig. A1).

All variables differed significantly among all scenarios ($p < 0.001$), except for Marxan penalty (Fig. 5). Scenarios FT_{Min} and FT_{Mix} had a significantly lower Marxan penalty than Scenario FT_{Med}. Scenarios FT_{Min} and FT_{Mix} were significantly less costly than Scenario FT_{Med}. Scenario FT_{Min} was the least costly, had the lowest number of PUs, but the highest boundary length. Scenarios FT_{Med} showed by far the highest costs and the highest number of PUs, but a shorter boundary length than Scenario FT_{Min}. Scenario FT_{Mix} had by far the lowest boundary length, while it showed values for cost and number of PUs between those of Scenarios FT_{Min} and FT_{Med}.

4. Discussion

For our case study, we were successfully able to derive from the analytical approaches (1) whether and how different target settings

Table 2
Spatial similarity matrix comparing the summed solutions of Marxan scenarios for all five selection frequency classes of planning units (0, <25%, 25–50%, 50–75%, >75%) (upper table section) and only for highest selection frequency class (>75%) (lower table section). Values represent Cohen's kappa coefficient ranges from − 1 to + 1, where − 1 represents complete disagreement, 0 indicates agreement no better than that expected by chance and + 1 indicates complete agreement.

Scenarios	FT_{Min}	FT_{Med}	FT_{Mix}
FT_{Min}	–		
FT_{Med}	0.27	–	
FT_{Mix}	0.28	0.39	–
FT_{Min}	–		
FT_{Med}	0.49	–	
FT_{Mix}	0.72	0.69	–

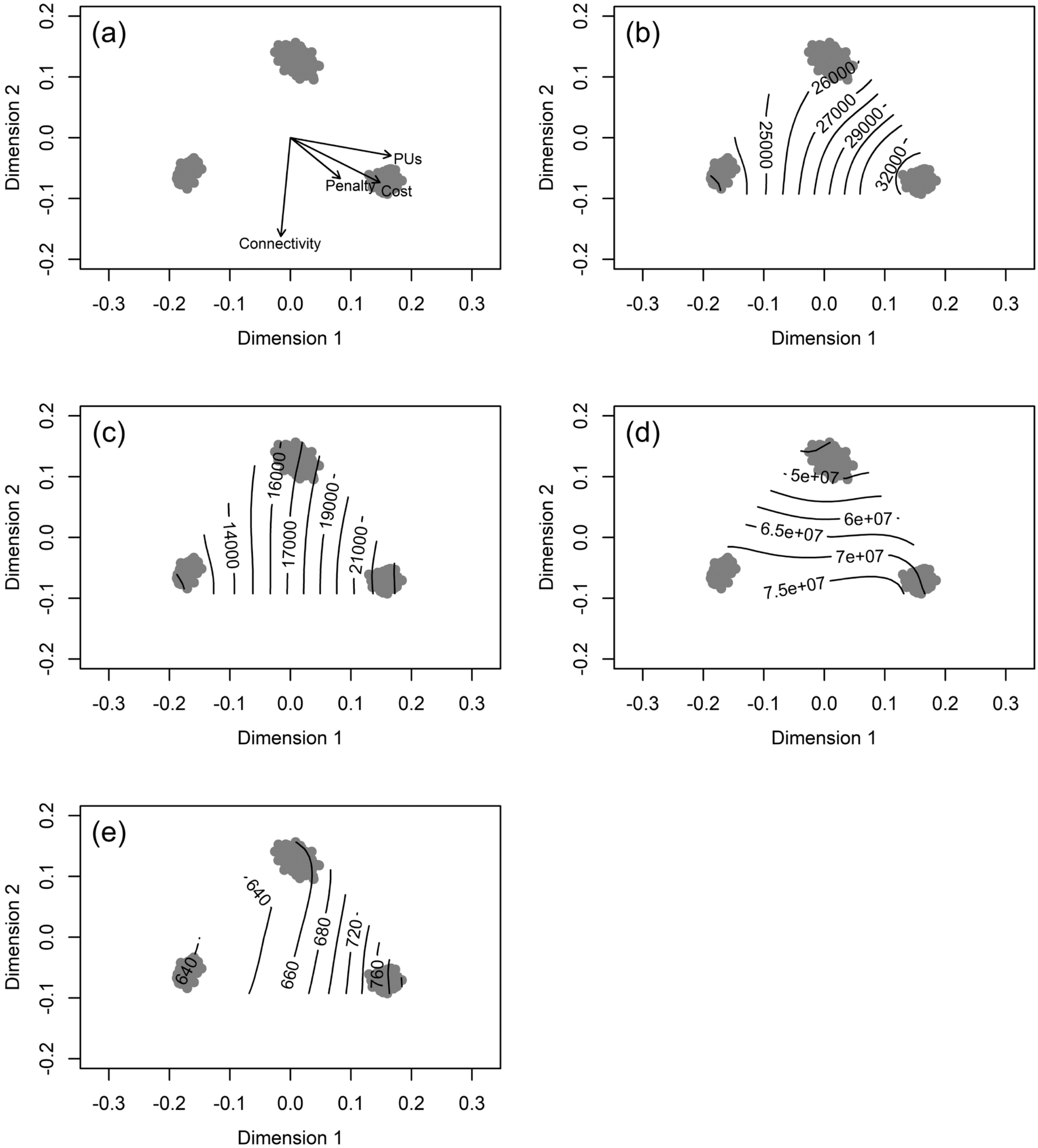

Fig. 4. A principal coordinates analysis (PCoA) plot of the solutions based on a Jaccard resemblance matrix. (a) Vectors that are significantly correlated with the PCoA surface ($p < 0.05$) are plotted. Arrows indicate the direction in which the vector increases, with the length of the arrow reflecting the relative importance of the vector. Isopleths of the vector that are significantly correlated to the PCoA surface are plotted: (b) cost ($r^2 = 0.956$, $p = 0.001$), (c) number of planning units selected ($r^2 = 0.997$, $p = 0.001$), (d) total boundary length in km ($r^2 = 0.929$, $p = 0.001$), and (e) Marxan penalty ($r^2 = 0.396$, $p = 0.001$).

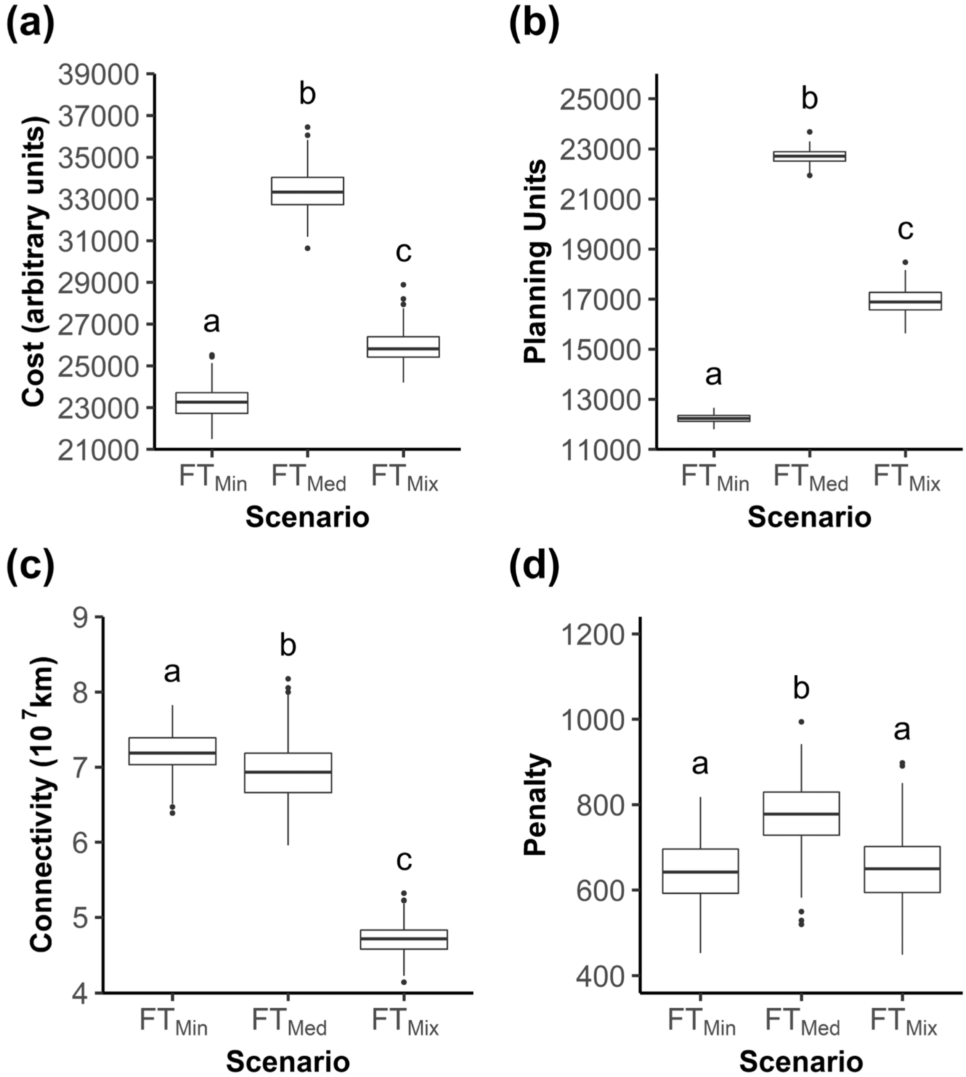

Fig. 5. Boxplots showing the differences in solution (a) cost, (b) number of planning units selected in the reserve system and (c) connectivity (= total boundary length) among scenarios. Data are presented as the median (thick black line), interquartile range (box), 25th and 75th percentiles (whiskers) and outliers (dots). Significant differences ($p < 0.001$) indicated with different letters.

have an influence on the configuration of solutions, (2) how the scenarios differ in terms of their flexibility of solutions, and (3) whether scenarios resulted in statistically different reserve systems and why.

4.1. Solutions and scenarios - Spatial similarity

As expected, the clustering approach showed a clear differentiation of solutions among the three scenarios. That targets influence the design of solutions is well known in the conservation planning literature and sensitivity analysis to determine the impact of changing targets is discussed as one of the key issues in setting up conservation planning software such as Marxan (Fischer et al., 2010; Levin et al., 2015).

Greater similarity between the solutions of the medium- and mixed-target scenario also suggests that the reserve configurations were directly triggered by raising the ecological features targets from low (Scenario FT_{Min}) to medium targets (Scenarios FT_{Med} and FT_{Mix}), further highlighting the effect of the target settings. The greater spatial overlap of these two scenarios seemed to be mainly driven by the selection of PUs in the western Weddell Sea region (Fig. 2). PUs in this region were selected less frequently in the reserve configuration of the low-target scenario. When considering only the PUs selected in > 75% of all solutions, all Marxan scenarios showed a moderate to high spatial overlap. The ‘highly selected’ PUs occurred on the shelf and slope areas from the southern Weddell Sea along the southeastern and eastern ice shelves up to the eastern border of the study area and along the east coast of the Antarctic Peninsula from the northern border of the study area deep into the southern Weddell Sea (Fig. 2). A visual inspection showed that these areas are particularly rich in many conservation features. At first glance, this might suggest that the different targets play only a minor role in the configurations of the highly selected PUs, seemingly overridden by the presences of conservation features. However, it should be noted that the effect of scenario targets is partly undermined by the fact that targets of unique, rare and/or highly sensitive conservation features were always set to 100% (regardless of the scenario). The locations of several highly selected PUs are consistent with the location of these special features (Fig. A2). The proportion of PUs containing at least one feature with a 100% target, out of the number of highly selected PUs (selection frequency >75%) is 21.4% in the low-target scenario, 13% in the mixed-target scenario and 8.1% in the medium-target scenario. The higher spatial overlap of highly selected PUs across all scenarios, compared to PUs selected less frequently, therefore appears to be a result of the combination of the 100% features as well as the high presence of other features. Both appear to make the selection of PUs in this area more likely regardless of the scenario's targets.

Furthermore, we identified that the medium-target scenario, followed closely by the mixed-target scenario, was the most flexible, i.e., had the highest variability among the solutions. This suggests that the flexibility of the solutions is not associated with a relaxation of the target values as could easily be assumed, but rather that the increase in targets seems to cause greater variation in reserve configurations. It appears that the higher the targets, the more different solutions have to be found to achieve the targets. In our case study, this is especially evident with the medium- and mixed-target scenario, where different reserve configurations emerged and Marxan selected a greater number of less costly areas in the western Weddell Sea region (FT_{Med} and FT_{Mix}) and, in addition, more costly areas in the eastern part of the Weddell Sea region (FT_{Med}) to achieve the targets (Fig. 2). In contrast, lower variability among the solutions emerged in the low-target scenario, as the low targets required fewer PUs located in less costly areas to meet the targets.

4.2. Performance of scenarios

The results do not confirm our initial assumption that higher target levels lead to a larger number of selected PUs and therefore larger and more costly scenarios. While the low-target scenario was the most cost-efficient and had the best performance with regard to minimising the number of PUs (Table 3), it was outperformed by the medium- and mixed-target scenarios in terms of boundary length of the reserve systems. It seems that the low target setting led to spatially dispersed PUs selected in the reserve systems, while the mixed targets in particular drove more spatially compact reserve systems where the selected PUs connect. It should be noted that this unimodal pattern, i.e. increasing total connectivity with increasing targets, could be broken when conservation feature targets are set particularly high or exceed a certain threshold of targets, such as reported Levin et al. (2015). The results highlight that the performance of the low-target scenario could be improved by a better balance between cost and boundary length. By using a higher value of the boundary length modifier (BLM), a more compact reserve system could be achieved, but this would at least involve a slight increase in costs. The mixed-target scenario best balances finding cost-efficient solutions while selecting an intermediate number of PUs that is spatially clustered (Table 3). Moreover, it is most flexible among solutions (along with medium-target scenario) and therefore offers the greatest number of different approaches to the conservation problem. In contrast, the medium-target scenario is unable to find cost-efficient solutions. An improvement in medium-target scenario performance by optimising the BLM cannot be expected, as the BLM for this case study is already close to zero, which means that there is no clear emphasis on minimising the total boundary length of the reserve system relative to the reserve system cost (Ardron et al., 2010). Note also that all solutions achieved all conservation feature targets (within a margin of 5%), except for two solutions (one from the low-target scenario and one from the mixed-target scenario). Here, the target of one conservation feature was not achieved.

Given these results, the mixed-target scenario emerges as the Marxan approach that shows the best performance of the three scenarios with respect to the addressed variables associated with the Marxan solution outputs.

4.3. Evaluation of tools employed

The clustering and ordination tool used proved to be valuable for visualising the total set of reserve configurations (solutions) and indicating which scenarios differ from others. This is consistent with other studies in the conservation planning context that emphasise the use of multivariate approaches to explore spatial similarities among conservation planning software-derived solutions (e.g., Linke

Table 3
Performance assessment of the three scenarios developed to protect the wider Weddell Sea region. Flexibility is the variability among the solutions within each of the scenarios.

Scenarios	Cost	Planning Units (PUs)	Connectivity	Flexibility	Recommendations
FT_{Min}	Best	Best	Worst	Worst	Has the lowest costs and lowest number of PUs. Requires trade-off analysis between cost- and reserve size-efficient (boundary length) solutions. Performance could be improved by optimising Boundary Length Modifier (BLM). Planners can explore this if they can afford an increase in cost.
FT_{Med}	Worst	Worst	Intermediate	Best	Not recommended, in particular as it fails to minimise cost in terms of interest of the Antarctic toothfish fishery.
FT_{Mix}	Intermediate	Intermediate	Best	Best	Recommended scenario because it best balances finding cost-efficient solutions while selecting an intermediate number of PUs that are spatially clustered. Moreover, it is most flexible among solutions (along with Scenario FT_{Med}).

et al., 2011; Harris et al., 2014; Christodoulou et al., 2021).

Exploratory representations of Marxan solutions using clustering and ordination methods can support the evaluation of scenarios in conservation planning by showing how spatially similar one scenario is to another and which scenario is the most flexible in terms of greatest variability among solutions (Ardron et al., 2010; Harris et al., 2014;). Identifying different reserve solutions provides insights that can help to more clearly delineate options during negotiations with stakeholders and find a workable solution that can ultimately be used to facilitate MPA implementation (Linke et al., 2011; Timonet and Abecasis, 2020). Analyses of explanatory variables (i.e. scenario-design factors and/or vectors associated with the solution outputs to each scenario), in turn, are particularly useful for examining the causes and effects of different reserve configurations and evaluating the performance of different scenarios and possible trade-offs between them (Appolloni et al., 2018). For example, reserve solutions/scenarios can be identified that have similar costs but differ spatially in the size or compactness of the reserves. The analyses are also useful as they can reduce the complex data sets with their variety of features, targets and socio-economic information to the essentials (Harris et al., 2014). Creating transparency through appropriately communicated statistical comparisons of scenarios seems particularly important for planning processes where trust and understanding need to be built between opposing stakeholders (e.g., Fernandes et al., 2005; Pressey and Bottrill, 2009).

4.4. Implication for WSMPA planning process

To date, the WSMPA planning has used only visual, descriptive scenario comparisons using two Marxan outputs to communicate results: 1) the single 'best solution' across all runs and 2) the 'summed solution' where the selection frequency for each PU is derived (Ball et al., 2009). The decision-making process regarding scenario selection conducted on this basis, including a nature conservation assessment, led to selection of the medium-target scenario for the further WSMPA development (SC-CAMLR-XXXVII/BG/15). The additional analytical approach presented in this paper provides a more quantitative assessment of the WSMPA spatial planning scenarios. It compares the scenarios statistically and carves out the spatial similarities and efficiencies of the different spatial planning scenarios, documenting the superiority of the mixed-target scenario. Whereas the earlier scenario selection had a strong focus on conservation assessment, the scenario selection presented here is based exclusively on variables associated with the Marxan solution outputs. Thus, it is important to note that the different scenario choices do not contradict each other. Rather, this assessment contributes a new, more economically nuanced angle and underscores the importance of working with the stakeholder community. In our opinion, this paper significantly increases the transparency regarding the Marxan scenario options used in the WSMPA spatial planning process. We hope that it can be used to assist the WSMPA negotiation process that is still ongoing.

Author contributions

KT led the writing of the paper. RK, KT and HP did the analyses. RK and TB contributed to the writing of the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared the R code for the analysis presented in the article in the supplementary material. PANGAEA links to the respective spatial data layers (open access) are provided in the article itself.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02238.

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