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Scientific background document in support of the development of a CCAMLR MPA in the Weddell Sea (Antarctica) – Version 2018 – Reflection on the recommendations by WG-EMM-17 and SC-CAMLR-XXXVI

K. Teschke, H. Pehlke and T. Brey

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Scientific background document in support of the development of a CCAMLR MPA in the Weddell Sea (Antarctica) – Version 2018

- Reflection on the recommendations by WG-EMM-17 and SC-CAMLR-XXXVI -

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Content

Abstract

The CAMLR Scientific Committee in 2017 reviewed the scientific background document SC-CAMLR-XXXVI/BG/28. Germany was asked to carry out further work, in particular as regards the issues and questions raised at WG-EMM-17 and SC-CAMLR-XXXVI with respect to the WSMPA proposal (SC-CAMLR-XXXVI, Annex 6, §§ 5.1-5.14).

Chapter 1 reflects on the recommendations concerning the suitability of some data layers for Marxan analyses, such as the data layer representing the distribution of Antarctic krill larvae (SC-CAMLR-XXXVI, Annex 6, §§ 5.9 - 5.10). **Chapter 2** discusses the recommendations concerning the suitability of the cost layer developed for the WSMPA Marxan analysis (SC-CAMLR-XXXVI, Annex 6, §§ 5.10 and 5.12) and presents the updated cost layer. **Chapter 3** provides a new data layer on juvenile Antarctic toothfish, and **Chapter 4** presents a robustness testing of the WSMPA Marxan model.

1) The suitability of some data layers for Marxan analyses

This chapter reflects on the recommendations concerning the suitability of some data layers for Marxan analyses, such as the data layer representing the distribution of Antarctic krill larvae (SC-CAMLR-XXXVI, Annex 6, §§ 5.9 - 5.10). Due to their sparse data basis and/or spatially clustered data distribution in the WSMPA Planning Area the exclusion of the respective layers from Marxan analyses was recommended by Norway.

We are well aware that the reliability of any distribution model is a function of data quantity and quality. Our larval Antarctic krill data set consists of approx. 300 samples that has been collected rather opportunistically over several years and that do not cover the planning area evenly. Similar is the case with the data on larval Antarctic silverfish: the data sets consist of approx. 250 samples gathered in 1983 and 1985 and concentrated on a few areas within the WSMPA Planning Area (see maps on the spatial distribution of data points for the WSMPA conservation features in CCAMLR e-group "Weddell Sea MPA"; publishing date: Oct 6, 2017).

We tried to take into account these modest data bases by applying an interpolation model that is restricted to a buffer around each sampling point. However, the Norwegians have correctly stated that the larval Antarctic krill data set cause Marxan to select a specific region to the west of the prime meridian based on the krill data only. That is not the case for larval Antarctic silverfish data as these data were sampled in areas where data on several other conservation features were gathered, too, and thus Antarctic silverfish sampling areas were not selected based on the silverfish data only.

Nevertheless, we revised the data layer representing the distribution of Antarctic silverfish larvae. We combined the data layer on Antarctic silverfish larvae with the data layer on adult Antarctic silverfish assuming similar habitat preferences for both life history stages. This assumption is based on our previous analysis that shows similar spatial distribution patterns of larvae and adults (see maps on the spatial distribution of WSMPA conservation features in CCAMLR e-group "Weddell Sea MPA"; publishing date: Oct 6, 2017). For more details on the metadata description and the interpolation approach see supplementary material in the Appendix. Finally, we developed a data layer representing Antarctic silverfish distribution (see Figure 1), independently from different life history stages (i.e.

larvae and adults), that is based on more than 1000 samples and has a quite good temporal resolution, i.e. a sampling almost every second year on average from 1983 to 2011 (time interval between two consecutive samples: 1-4 years).

Both conservation features, the Antarctic krill and the Antarctic silverfish, are important prey species for top predators in the Southern Ocean (Siegel 2016, Vacchi et al. 2017); and a pivotal role of both species can also be assumed in the Weddell Sea food web (e.g. Descamps et al. 2016, Mintenbeck 2008). Therefore, we refrain from excluding both data layers altogether from our Marxan analyses. In order to address this issue, however, we set a lower Species Penalty Factor (SPF) for both conservation features to give these data layers less impact on the Marxan scenarios presented in Chapter 4.

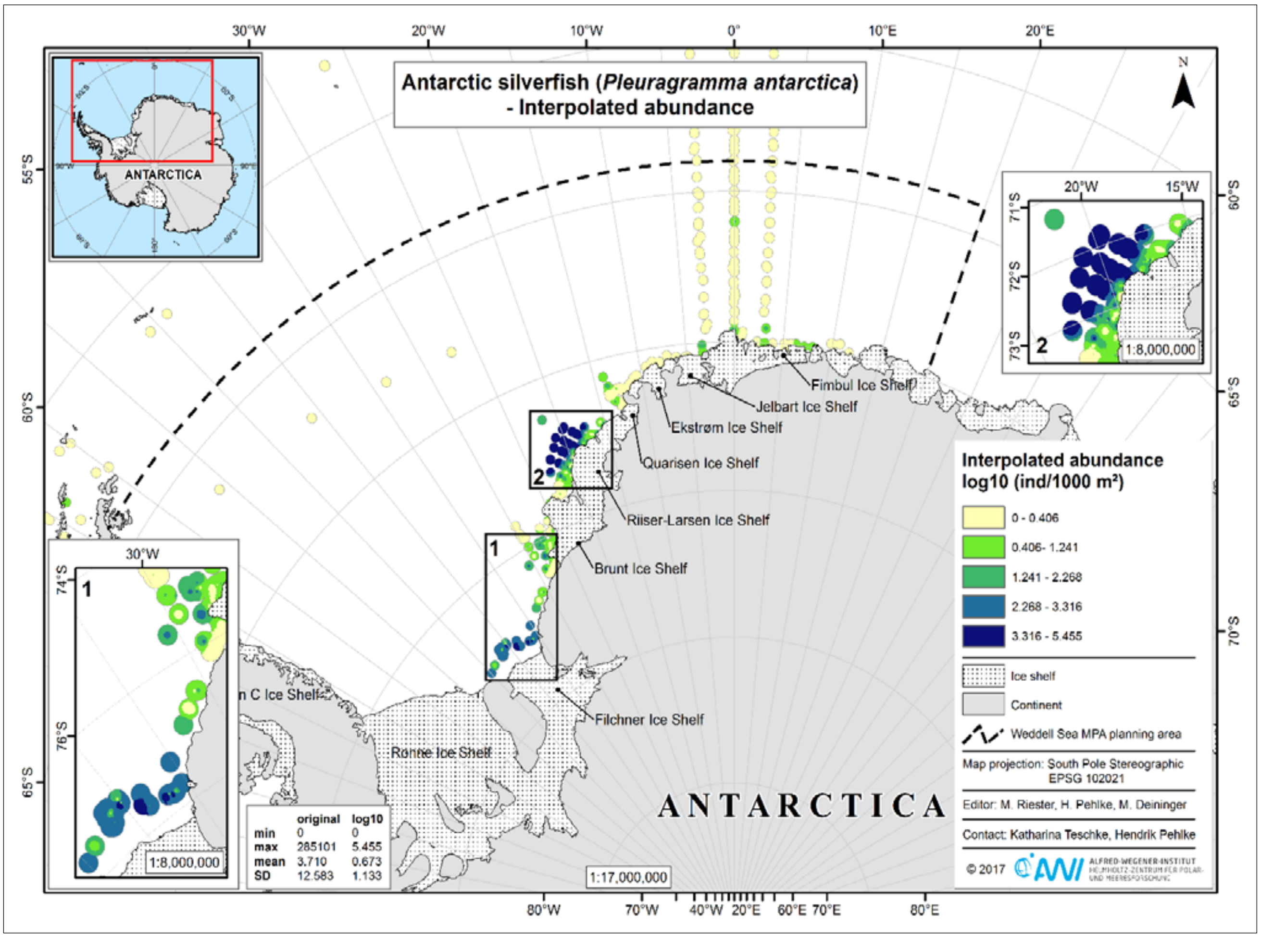

Figure 1 Data layer representing the Antarctic silverfish (*Pleuragramma antarctica*) distribution in the Weddell Sea (WS) MPA Planning Area. The log-transformed data are plotted as densities (individuals/1000 m²) for a 10 nautical mile radius around each record. Black dashed box: WSMPA Planning Area.

2) The suitability of the cost layer for Marxan analyses

This chapter reflects on the recommendations concerning the suitability of the cost layer developed for the WSMPA Marxan analysis (SC-CAMLR-XXXVI, Annex 6, §§ 5.10, 5.12). The main suggestions made by Norway are:

- Sensitivity tests to establish weighting factors for the cost layer capable of exerting an adequate influence on the Marxan results
- Multiplicative cost layer model
- Two cost layers representing the individual opportunity cost to toothfish and krill fisheries.

In the framework of a sensitivity analysis of the protection-level for Antarctic toothfish (*Dissostichus mawsoni*) and other demersal fish we evaluated the influence of the cost layer on the Marxan results (please see SC-CAMLR-XXXVI/BG/28, chapter 3.2.). We showed that the cost layer as described in SC-CAMLR-XXXV/BG/13 and SC-CAMLR-XXXVI/BG/28 (i.e. additive model, six weighting categories) has considerable influence on the Marxan results. Particularly the two-factor Marxan scenarios analysed exclusively with *D. mawsoni* and demersal fish showed visible differences in the scenarios with and without the cost layer.

Therefore, we continue to adhere to a cost layer instead of incorporating fishing interest in the WSMPA planning process at a later stage. However, we adjust our cost layer by using *(i)* a multiplicative model, *(ii)* two separate cost layers for Antarctic toothfish and krill, and *(iii)* a revised accessibility layer.

Our previous cost layer was based on an additive model, comprised of three layers and used following equation:

$C_i = a_i + b_i + c_i /2; 0 \leq C_i \leq 2.5$

where C_i is the cost assigned to planning unit *i*,

a_i = the accessibility value of planning unit *i*; the accessibility layer representing areas accessible for fishery vessels based on ice cover,

b_i = the toothfish occurrence value of planning unit *i*; the toothfish occurrence layer indicating areas suitable for *D. mawsoni* occurrence based on a model combining CPUE and depth data, and

c_i = the krill occurrence value of planning unit *i*; the krill occurrence layer presenting areas suitable for Antarctic krill occurrence based on a habitat suitability model for adult krill.

By the additive model potential fishing areas are considered regardless of whether they are accessible, i.e. areas predicted to have high probability of target species occurrence but which are inaccessible due to ice cover are weighted quite high. Thus, this model takes into account that potential fishing areas which are currently still inaccessible, bur could be accessible in future times due to changes in ice conditions and thus could also provide fishing opportunities. As however sea ice cover in Antarctic waters is likely to remain stable, or even increase, for decades (e.g. Comiso & Nishio 2008), we switched to a cost layer based on a multiplicative model instead of an additive model. By using the multiplicative model (see equation (1) and (2)) we assure that only accessible potential fishing areas are considered, i.e. areas predicted to have high probability of target species occurrence but which are inaccessible due to ice cover are very low weighted (see Figure 2 and 3).

We now use two separate cost layers for Antarctic toothfish and Antarctic krill (instead of one combined cost layer) in the revised WSMPA Marxan analysis (see chapter 4). By separating these two fishing activities we do not have the situation anymore where overlapping potential fishing areas are assigned to higher cost than non-overlapping areas regardless of whether the impact of MPA implementation on individual fisheries may be greater in non-overlapping areas. Additionally, we also revised the accessibility layer by using a sigmoid function to describe the accessibility of a planning unit due to sea ice cover instead of using a threshold for the likely accessibility for fishing operations. For more details on the revision of the accessibility layer see supplementary material in the Appendix.

Finally, the following equations were used for the cost calculations:

$$C_{TFi} = a_i * b_{TFi};\ 0 \leq C_{TFi} \leq 1 \quad (1)$$

$$C_{Ki} = a_i * b_{Ki};\ 0 \leq C_{Ki} \leq 1 \quad (2)$$

where C_{TFi} and C_{Ki} is the cost assigned to planning unit *i* for the Antarctic toothfish and Antarctic krill cost layer, respectively,

a_i = the accessibility value of planning unit *i*; the accessibility layer representing areas accessible for fishery vessels based on ice cover (see Figure 2a),

b_{TFi} = the toothfish occurrence value of planning unit *i*; the toothfish occurrence layer indicating areas suitable for *D. mawsoni* occurrence based on a model combining CPUE and depth data (Figure 2b), and

b_{Ki} = the krill occurrence value of planning unit *i*; the krill occurrence layer presenting areas suitable for Antarctic krill occurrence based on a habitat suitability model for adult krill (Figure 2c).

All values were scaled between 0 and 1 for comparability among the accessibility value and the respective fishing value.

Please refer to SC-CAMLR-XXXVI/BG/28 (Antarctic toothfish) and SC-CAMLR-XXXV/BG/13 (Antarctic krill) for more information on the data base and the model approaches.

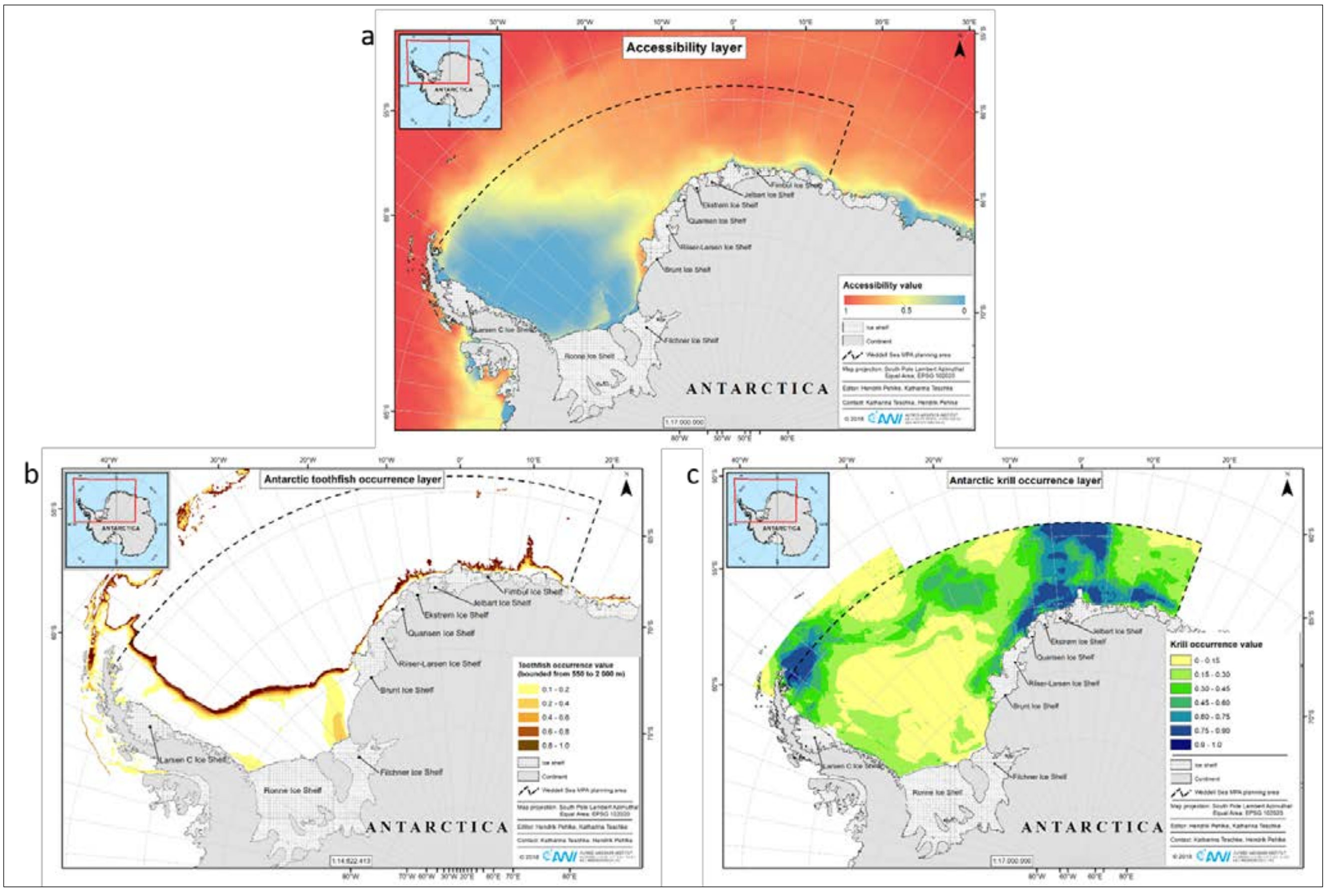

Figure 2 Accessibility layer based on the assumption that the accessibility for fishing operations relates to ice cover with a sigmoid pattern (a); Antarctic toothfish (*Dissostichus mawsoni*) occurrence layer indicating areas suitable for *D. mawsoni* occurrence based on a model combining CPUE and depth data (b); and Antarctic krill (*Euphausia superba*) occurrence layer presenting areas suitable for Antarctic krill occurrence based on a habitat suitability model for adult krill (c).

As for our previous cost layer the cost values for C_{TF_i} and C_{K_i} were classified into six classes and were reclassified by assigning new cost values for each class to guarantee effects on the Marxan results (see Tab. A3). Please note that for the Antarctic toothfish cost layer we assigned a cost factor of 0.1 to all planning unit grid cells *i* with depths 550 m or shallower and depths > 2000 m according to CCAMLR regulations (CM 22-08, 2009) and fishing practice as recommended by the EMM Working Group 2016 (WG-EMM-16 report, paragraph 3.6). In order to ensure that Marxan runs technically flawless we have refrained from using a cost factor of zero for these grid cells.

The revised cost layer of the Antarctic toothfish shows high cost areas on the slope along the eastern and south-eastern coast and around Maud Rise, i.e. in areas of the adult Antarctic toothfish habitat which are accessible for fisheries vessels regarding ice cover (see Fig. 3). The new cost layer of the Antarctic krill shows particularly high cost areas east of 20°W offshore.

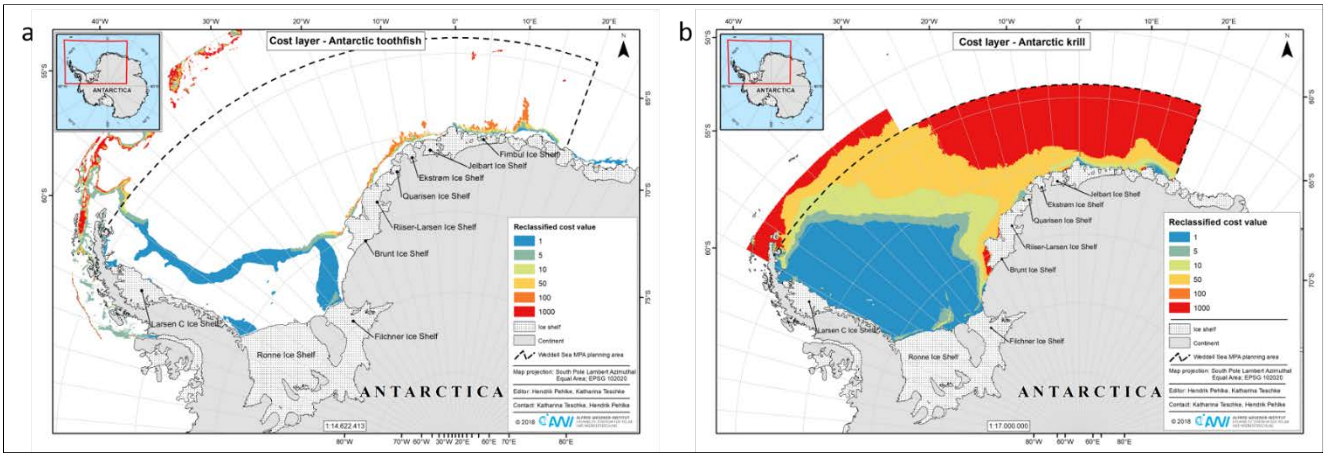

Figure 3 Cost layer for Antarctic toothfish (i.e. accessibility layer combined with toothfish occurrence layer) (a) and cost layer for Antarctic krill (i.e. accessibility layer combined with krill occurrence layer) (b). Areas in red are relatively easy to access for fishery vessels based on ice cover and represent suitable Antarctic toothfish and Antarctic krill habitats, respectively. Please note that the Antarctic toothfish cost layer is bounded from 550 to 2 000 m according to CCAMLR CMs and fishing practise. Black dashed box: WSMPA Planning Area.

3) New data layer on juvenile Antarctic toothfish

The workshop for the development of an Antarctic toothfish (*Dissostichus mawsoni)* population hypothesis for Area 48 was held in Berlin, Germany, in February 2018. During the three-day workshop information on spawning times and locations, as well as the locations where juvenile and adult fish are recorded, was brought together and was used to generate different population hypotheses of *D. mawsoni*. In the WSMPA planning process we only took into account the habitat model of adult Antarctic toothfish so far. To develop now a data layer for the juvenile fish, we used the information that was brought together during the Workshop. This means that we georeferenced a raster showing the potential habitats of juvenile fish in Area 48 (see Figure 4), and digitised the areas along the eastern and south-eastern ice shelves within the WSMPA Planning Area as a polygon shape file. Consequently, in the current Marxan analyses two data layers regarding the Antarctic toothfish were incorporated, i.e. one layer for the adult and one layer for the juvenile fish.

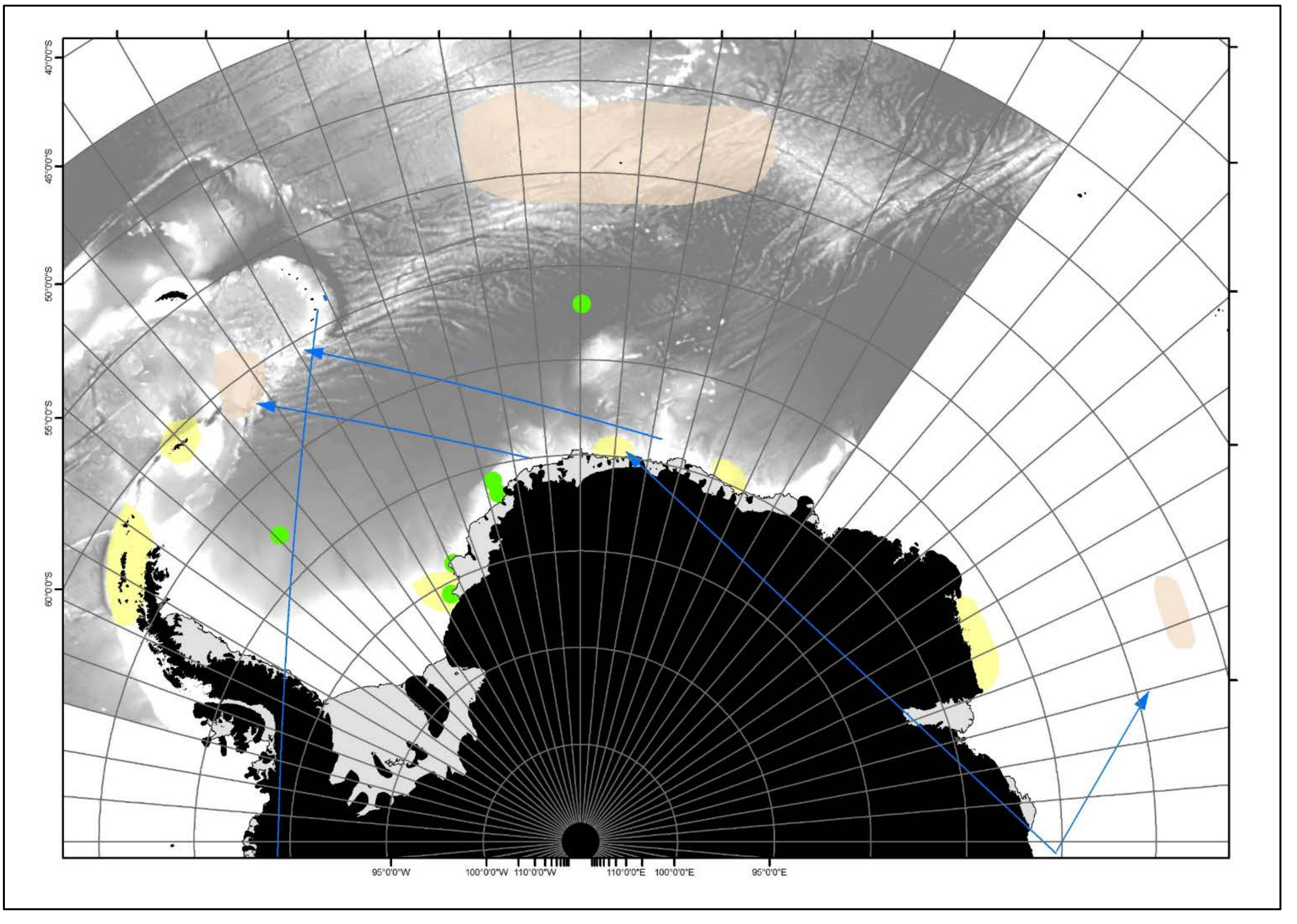

Figure 4 Records of Antarctic toothfish (*Dissostichus mawsoni)* larvae (green circles), potential habitats of juvenile fish (yellow areas), spawning locations (light brown), and long-distance movements of tagged *D. mawsoni* (blue arrows) in CCAMLR Statistical Area 48. The preliminary map was developed during the CCAMLR Workshop for the development of *D. mawsoni* population hypothesis for Area 48 (Berlin, Germany, 19 - 21 February 2018).

4) Robustness testing of WSMPA Marxan model

In general, robustness of the Marxan solution outputs can be tested at three levels: (a) the Marxan internal parameters such as the Boundary Length Modifier (BLM), (b) the set of conservation features and (c) the target levels.

a) Marxan internal parameters

In this chapter we evaluate the effects of a range of values of the Species Penalty Factor (SPF) and the Boundary Length Modifier (BLM) on the Marxan solution output. The SPF contemplates penalties for not meeting conservation features with their target levels, i.e. a higher SPF gives a greater penality for not meeting conservation targets. The BLM controls the level of fragmentation of the Marxan solutions, i.e. a higher BLM results in a more compact reserve system.

The Marxan scenarios for SPF and BLM calibration were run with the following setup:

- Single, non-recursive restart approach - as recommended by Bristow and Godø at the EMM Working Group Meeting in 2017 (WG-EMM-17/42) - to increase the understandability and clarity of the Marxan analysis
- Equal-area projection (EPSG: 102020) for all spatial data - as recommended by Bristow and Godø at the EMM Working Group Meeting in 2017 (WG-EMM-17/42) - to ensure accuracy of areal calculations and minimisation of areal distortion
- Conservation features and their targets according to Marxan Scenario S_{Med} (see Appendix, Tab. A4)
- Antarctic toothfish cost layer (see Chapter 2)
- Number of runs = 100
- Number of iterations = 10,000,000
- BML = 0 (for the SPF calibration)
- SPF = 5.3 (for the BLM calibration)

First, we calibrated the SPF according to the Marxan Good Practices Handbook (Fischer et al. 2010). We set 60 different levels for SPF values (see Appendix, Tab. A5). The range of selected SPF values is based on preliminary analyses with arbitrary values for SPF (results not shown) showing that an appropriate SPF value is roughly between 1 and 10, and most likely between 0 and 6.0. For each level, the SPFs were defined for all conservation features the same. Subsequently to the Marxan analyses, we computed for each scenario in how many runs (out of 100 in total) all conservation features were being met and calculated the mean number of missed conservation targets. We examined the distribution of solution quality among those runs, and defined the SPF as appropriate if for the first time 100 % of runs meet all conservation targets. Our calibration analysis suggests that a SPF value of 5.3 is most appropriate (see Appendix, Tab. A5).

Subsequently, we calibrated the BLM with a SPF value of 5.3 (see selected range of BLM values in Tab. 2). We applied three calibration techniques (see Tab. 3) as described in the Marxan Good Practices Handbook (Fischer et al. 2010), and recommended by Bristow and Godø at the Working Group Meeting EMM in 2017 (WG-EMM-17/42). First, we visually assessed the best solution as representative and the summed solution per Marxan scenario. In addition, as a second calibration method, we set the BLM such that Boundary Lengths (BL) scale to a similar order of magnitude as Planning Unit (PU) costs (allocated by the cost layer), i.e. BLM x BL ~ PU cost. Furthermore, we explored the cost-boundary length trade-off using minimum cost and boundary length solution.

No clear preference on a Scenario from S_{BLM} 001 to S_{BLM} 016 could be set by the visual inspection for the best as well as summed solution, as this BLM selection is subjective to a certain extent (Fig. A3 - A6). The two objective techniques showed a most appropriate BLM at 0.00125 (see Tab. 2 and 3, Fig. 5). In general, both the best and the summed solutions showed relatively similar results across the range of different values of BLM. In particular, however, it was found that the higher the BLM value, the more frequently the areas east of the 0 meridian are selected, especially in the very cost-intensive areas of the Antarctic toothfish habitat. I.e. that high BLM values produce high "boundary costs" (i.e. BLM x BL) that are given priority over PU costs allocated by the cost layer.

Table 2 Effects of Boundary Length Modifier (BLM) on best and mean Marxan solution costs and boundary length.

		Cost		Boundary length	
Scenario	BLM	Best solution	Mean solution	Best solution	Mean solution
S_{BLM} 001	0	22,730	24,810	249,719,665	250,379,092
S_{BLM} 002	0.00125	32,898	33,357	61,473,922	69,070,431
S_{BLM} 003	0.0025	33,372	34,762	60,928,352	69,727,407
S_{BLM} 004	0.005	39,763	39,233	62,365,363	72,368,705
S_{BLM} 005	0.0075	59,727	59,869	66,613,479	73,808,718
S_{BLM} 006	0.01	59,387	62,632	66,806,170	74,131,470
S_{BLM} 007	0.02	85,591	85,340	66,317,303	73,310,247
S_{BLM} 008	0.04	89,108	92,544	66,015,677	72,773,496
S_{BLM} 009	0.06	94,299	101,293	66,010,847	72,642,468
S_{BLM} 010	0.08	101,937	103,362	66,098,244	72,683,542
S_{BLM} 011	0.1	121,974	107,865	65,279,923	72,236,111
S_{BLM} 012	0.25	131,417	130,090	66,216,497	72,225,787
S_{BLM} 013	0.5	141,741	138,202	64,363,576	72,238,185
S_{BLM} 014	1	132,747	137,265	63,145,377	72,069,339
S_{BLM} 015	10	133,691	137,330	60,781,052	71,778,899
S_{BLM} 016	100	145,096	137,474	65,414,528	71,814,776

Table 3 Overview of BLM calibration methods and results.

	Calibration method	**Calibration result**
1	Visual inspection of the best and summed solution per scenario	No clear preference (choice is subjective to a certain extent)
2	Set BLM such that "boundary lengths" scale to similar order of magnitude as "PU costs" in the Marxan objective function	Scenario S_{BLM} 002 (BLM = 0.00125)
3	Exploration of cost-boundary length trade-off using minimum cost and boundary length solutions	Scenario S_{BLM} 002 (BLM = 0.00125)

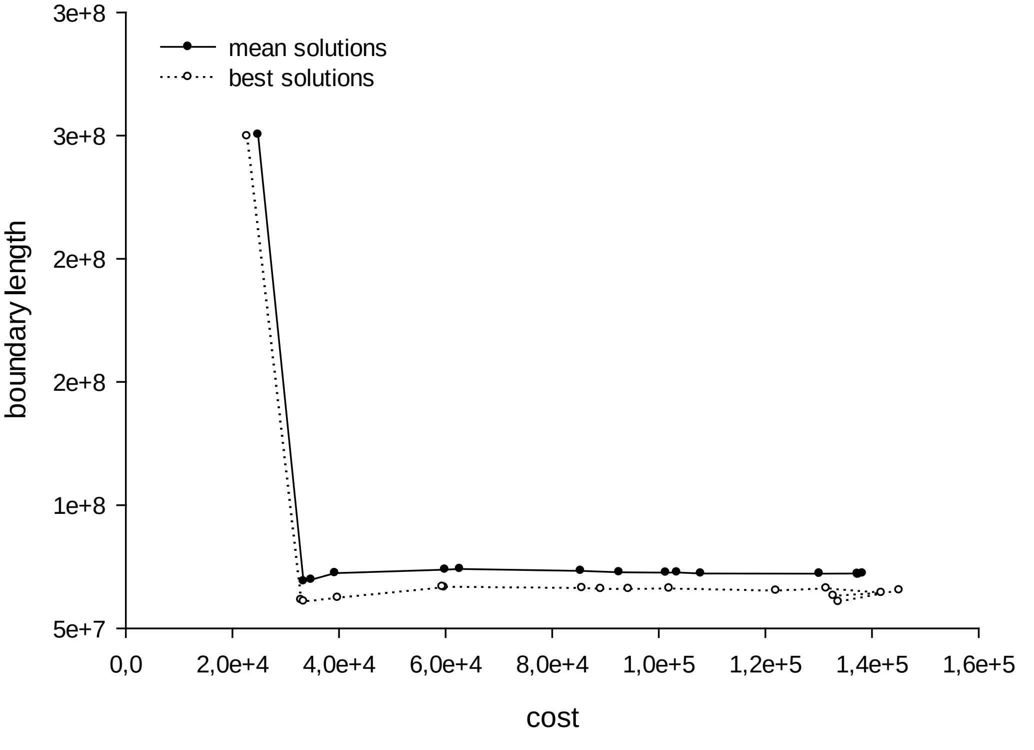

Figure 5 Relationship between best and mean Marxan solution cost and boundary length. Minimum cost and boundary length solutions are reached with a Boundary Length Modifier (BLM) of 0.00125.

b) Set of conservation features

The significance of a particular conservation feature could be analysed by an exclusion analysis, i.e. running as many Marxan analyses as conservation features but excluding one particular feature in each run. This approach would constitute an enormous effort and may provide little useful information for MPA planning. Therefore, we refrain from running an exclusion analysis for the WSMPA model.

However, there are ways to approximate the overall significance of a feature: On the one hand, significance is proportional to spatial extension x target level, and this information is available in the background document SC-CAMLR-XXXVI/BG/28 (see Table A2-1). Additionally, we recently showed the spatial distribution of each conservation feature in a standardized way. These maps were made available via the CCAMLR e-group “Weddell Sea MPA” (publishing date: Oct 6, 2017). On the other hand, the spatial distribution of a conservation feature in relation to the distribution of all other features is indicative of its significance, too. An analysis of the spatial overlap between the ecological features was presented in the background document SC-CAMLR-XXXV/BG/13 (see Table 2-4) and the spatial relationship between all conservation features (i.e. next to the ecological, also the environmental features) were made available through the CCAMLR e-group “Weddell Sea MPA (publishing date: Jun 30, 2016).

c) Different target levels

We already explored different target levels for features that are of key importance to the planning process, i.e. demersal fish and toothfish, as requested by EMM-16 (WG-SAM-17/30, SC-CAMLR-XXXVI/BG/28). In this context, it is important to note that target levels of conservation features were not chosen arbitrarily by us, but that target levels for each individual feature were discussed at the 2nd International WSMPA Expert Workshop (see workshop report published via CCAMLR e-group "Weddell Sea MPA" on July 7, 2015). Finally, the experts agreed on a range of target levels (from low to high targets) for each individual feature. Already at the time of the workshop, three Marxan scenarios had been calculated based on low, medium and high targets for all conservation features. The results of the robustness testing of the 2015 WSMPA Marxan model showed that some area, such as the shelf and slope in the eastern and southern part of the WSMPA Planning Area and an area at the tip of the Eastern Antarctic Peninsula, were selected with high frequency independently of the target levels.

Nevertheless, we again explored target level ranges based on our current Marxan model in the following way: *(i)* Scenario S_{Med} based on medium targets for all features, *(ii)* Scenario S_{Low} based on low targets for all features, and *(iii)* Scenario S_{Mix} based on low targets for all the environmental features and medium targets for all the ecological features (for the exact targets per conservation feature see Table A4). Exceptions were the unique and rare features (i.e. shallow water area on the Norsel Bank, buffer area around Adélie penguin colonies) and the highly sensitive areas (i.e. sponge associations, nesting sites of demersal fish); here, we used target values of 100 % for all Scenarios. Scenario S_{Med}, S_{Low} and S_{Mix} were run each with the Antarctic toothfish cost layer and the Antarctic krill cost layer, respectively (see Tab. 4).

All Marxan scenarios listed in Table 4 - for evaluating the effects of a range of target values on the Marxan solution output - share the following setup:

- Single, non-recursive restart approach - as recommended by Bristow and Godø at the EMM Working Group Meeting in 2017 (WG-EMM-17/42)
- Equal-area projection (EPSG: 102020) for all spatial data - as recommended by Bristow and Godø at the EMM Working Group Meeting in 2017 (WG-EMM-17/42)
- Number of runs = 250
- Number of iterations = 10,000,000
- BML = 0.00125
- SPF = 5.3, except of conservation feature (a) larval Antarctic krill, (b) Antarctic silverfish, and (c) juvenile Antarctic toothfish that got a lower SPF of 1.0 to give it less impact of the data layers on the Marxan scenarios (see Chapter 1 for justification of the selection of a lower SPF value).

Table 4 Overview of the Marxan scenarios.

Scenario	Description	Cost layer
S_{Med}-T	Medium targets for all features	Antarctic toothfish
S_{Low}-T	Low targets for all features	Antarctic toothfish
S_{Mix}-T	Low targets for all environmental features and medium targets for all features ecological features	Antarctic toothfish
S_{Med}-K	Medium targets for all features	Antarctic krill
S_{Low}-K	Low targets for all features	Antarctic krill
S_{Mix}-K	Low targets for all environmental features and medium targets for all features ecological features	Antarctic krill

The results of the exploration of a range of targets show that some areas are always selected with high frequency, apparently independently of the target levels and the chosen cost layer. This result fits quite well with the result of the robustness testing of the 2015 WSMPA Marxan model, although there were considerable differences (e.g. regarding the Marxan approach, the data layers developed) between our previous and the current Marxan model. For example, areas such as the area along the ice shelves from the eastern to the southern part of the WSMPA Planning Area or the area near the tip of the Antarctic Peninsula are selected frequently (see Fig. 6, 7). On the other hand, different scenarios cause distinctly different selection frequency for particular areas. Especially in the inner Weddell Sea the selection frequency of areas reduces from Scenario S_{Med} over S_{Mix} to S_{Low}. These changes are related to the cost layer. While in Scenario S_{Med} and S_{Mix} particularly low cost areas in the inner Weddell Sea must be selected to achieve the targets, the cost layers in Scenario S_{Min} no longer shows such a strong influence due to the low target levels that are reached faster.

The calculation of the achievement of conservation targets shows that all conservation features (i.e. 18 ecological and 57 environmental features) with their medium targets are met completely for the revised 2018 WSMPA proposal (see WG-SAM-18/16 for details on the main differences between the 2016 and the 2018 version of the draft WSMPA proposal). However, if the area of CCAMLR research block 48.6_3, 48.6_4 and 48.6_5 is excluded from the revised 2018 WSMPA proposal, ten conservation features with their medium targets will no longer be fully met (see Figure 8). The three ecological features concern the sponge associations (S5: Important areas for unique and diverse suspension feeding assemblages), the shallow water area on the Norsel Bank (S6: Rare and unique habitats) and a nesting site of demersal fish (S7: Important areas for demersal fish) and are situated in research block 48.6_5 mainly shallower than 550 m. As outlined in WG-SAM-18/16, this area is supposed to be included in the Special Protection Zone in the 2018 WSMPA proposal. In addition, seven environmental features, i.e. depth classes in the geomorphic features Margin Ridge, Plateau, Plateau Slope, Seamount Ridge and Seamount (see Fig. 8E, F), are no longer fully met. While the geomorphic features of Margin Ridge are in the area of research block 48.6_4, all other, not fully achieved geomorphic features occur in near Maud Rise where research block 48.6_3 is installed.

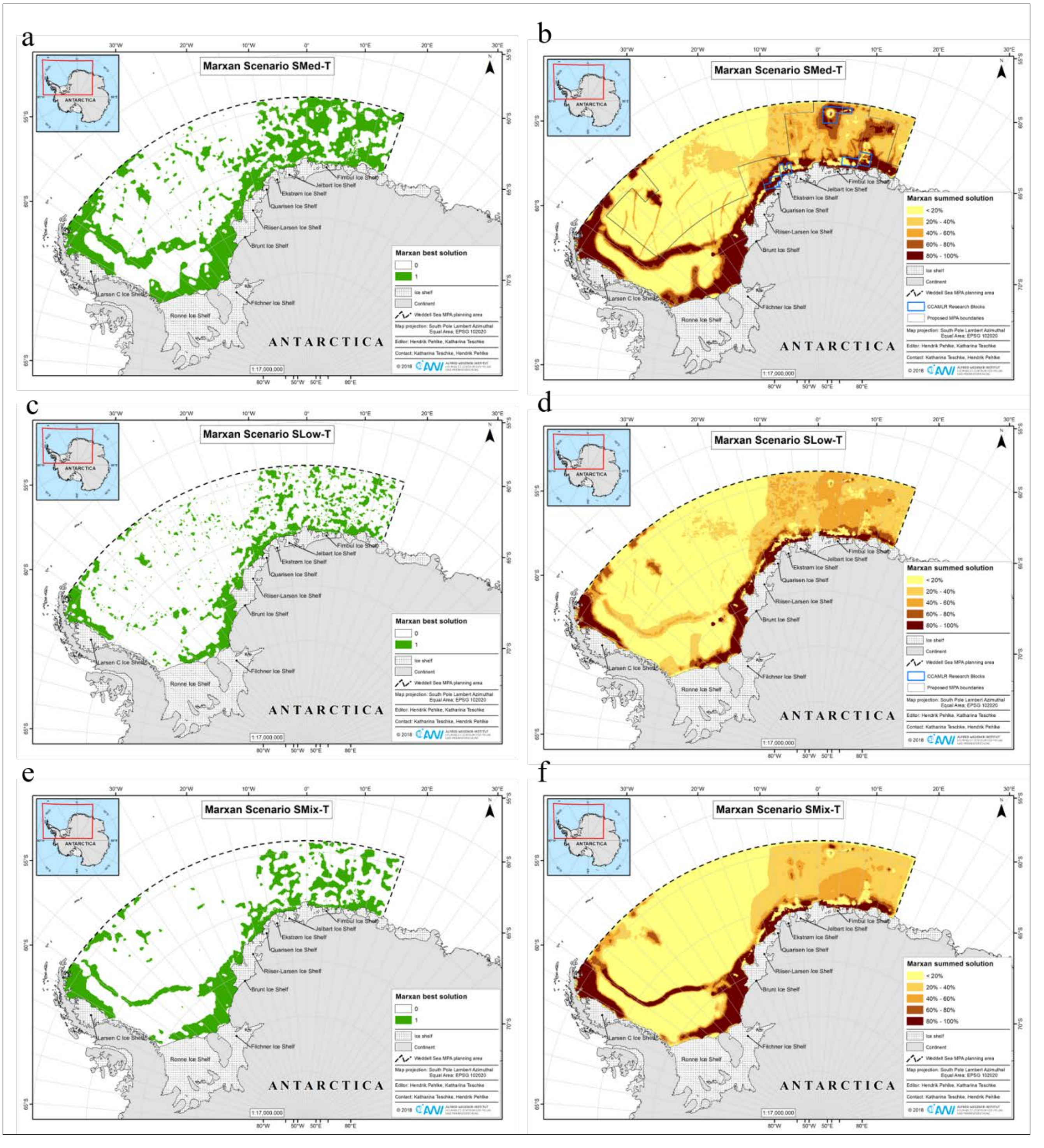

Figure 6 Best (a, c, e) and summed solutions (b, d, f) from the exploration of conservation targets, where Scenarios S_{Med}-T, S_{Low}-T and S_{Mix}-T (with Antarctic toothfish cost layer) each used different target levels for the conservation features to assess its effect on the Marxan solution outputs. All Scenarios used an identical setup (in terms of Marxan input parameters), except for the targets that took medium (a, b), low (c, d) and a mixture of medium and low values (e, f). Green areas indicate areas of selection (a, c, e). Dark brown areas indicate areas of highest selection frequency, and yellow areas indicate areas of low selection frequency.

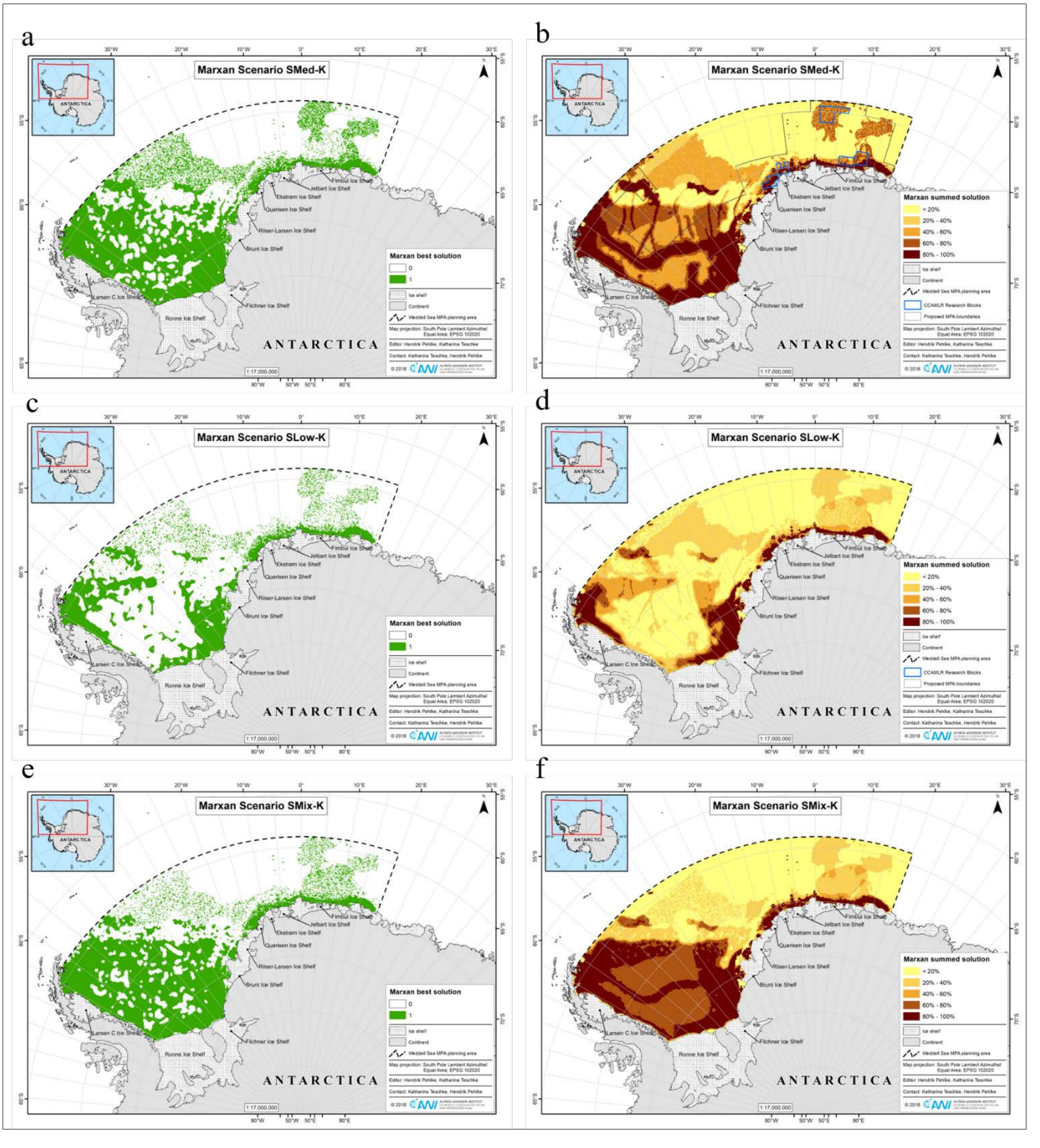

Figure 7 Best (a, c, e) and summed solutions (b, d, f) from the exploration of conservation targets, where Scenarios S_{Med}-K, S_{Low}-K and S_{Mix}-K (with Antarctic krill cost layer) each used different target levels for the conservation features to assess its effect on the Marxan solution outputs. All Scenarios used an identical setup (in terms of Marxan input parameters), except for the targets that took medium (a, b), low (c, d) and a mixture of medium and low values (e, f). Green areas indicate areas of selection (a, c, e). Dark brown areas indicate areas of highest selection frequency, and yellow areas indicate areas of low selection frequency.

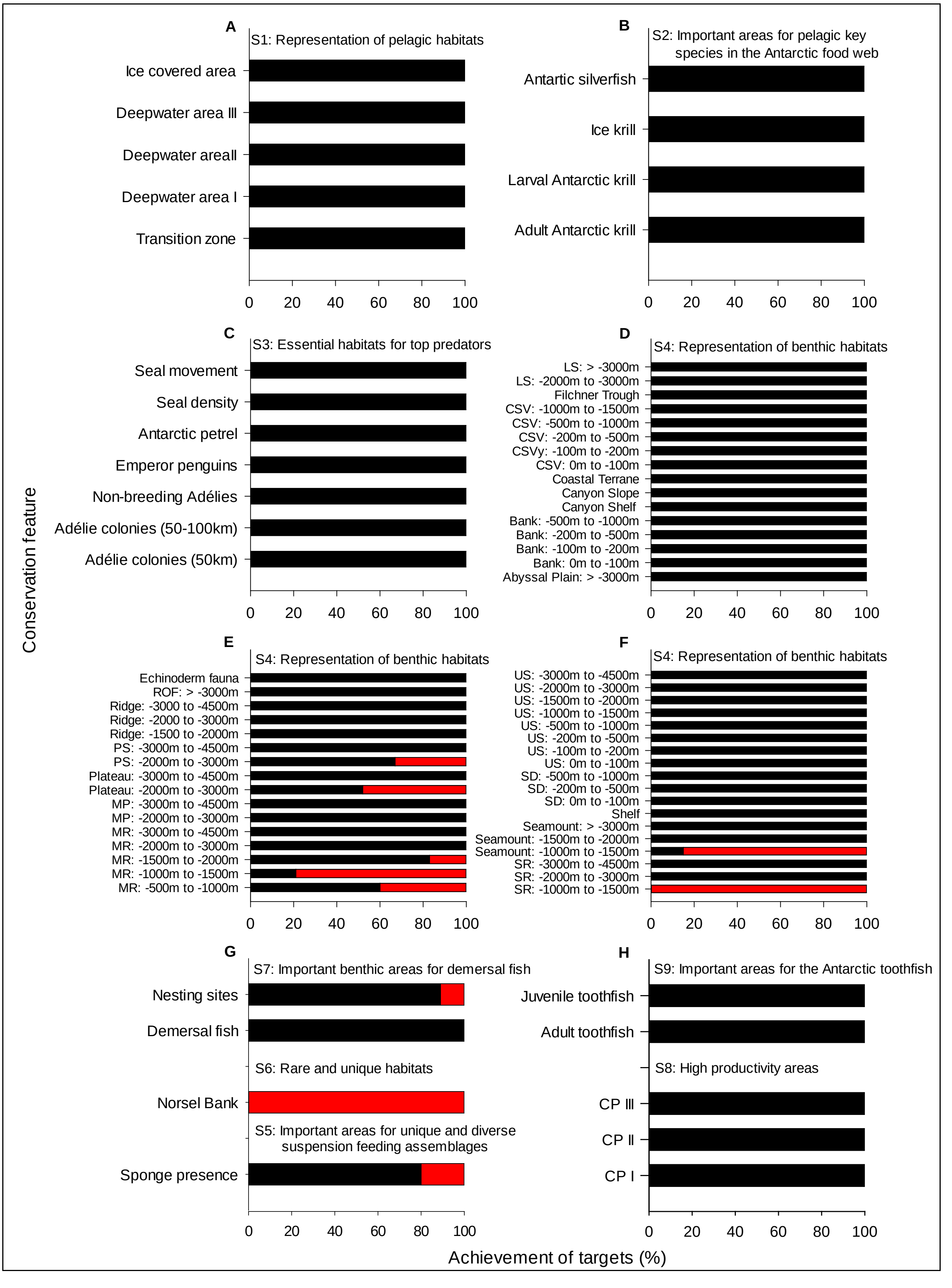

Figure 7 Achievement of medium conservation targets (in %) for the revised 2018 WSMPA proposal excluding the area of CCAMLR research block 48.6_3, 48.6_4 and 48.6_5. Black bars represent the percentage of target met. The features were arranged by their corresponding specific objective (S1 - S 9). Abbreviations: LS: Lower Slope, CSV: Cross Shelf Valley (**D**); ROV: Rugose Ocean Floor, PS: Plateau Slope, MR: Margin Ridge (**E**); US: Upper Slope, SD: Shelf Deep, SR: Seamount Ridge (**F**); and CP: Coastal Polynya (**H**).

5) References

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Appendix

1) *Pleuragramma antarctica* - Metadata & interpolation approach

Table A1 Data sets that were used for developing a data layer representing the Antarctic silverfish (*Pleuragramma antarctica*) distribution in the WSMPA Planning Area.

Cruise Name	Primary data set / Contact	Reports	Publications
Predominately pelagic surveys			
ANT-I/2	Volker Siegel volker.siegel@thuenen.de	- Drescher et al (1983) hdl:10013/epic.10012 - Hempel et al. (1983) hdl:10013/epic.10014	Boysen-Ennen & Piatkowski (1988)
ANT-III/3		- Hempel (1985) hdl:10013/epic.10025	Hubold et al. (1988)
Lazarev Sea Krill Survey (LAKRIS) data: ANT-XXI/4, ANT-XXIII/6, ANT-XXIV/2	Hauke Flores Hauke.Flores@awi.de Anton van de Putte anton.vandeputte@naturalsciences.be	- Smetacek et al. (2005) hdl:10013/epic.10505 - Bathmann (2008 and 2010) hdl:10013/epic.30948, hdl:10013/epic.34024	Flores et al. (2014)
Predominately benthic surveys			
ANT-XIII/3, ANT-XV/3, ANT-XVII/3, ANT-XIX/5, ANT-XXI/2, ANT-XXIII/8, ANT-XXVII/3	Rainer Knust Rainer.Knust@awi.de	- Arntz & Gutt (1997) hdl:10013/epic.10252 - Arntz & Gutt (1999) hdl:10013/epic.10304 - Arntz & Brey (2001) hdl:10013/epic.10407 - Arntz & Brey (2003) hdl:10013/epic.10467 - Arntz & Brey (2005) hdl:10013/epic.22180 - Gutt (2008) hdl:10013/epic.28679 - Knust et al. (2012) hdl:10013/epic.39114	
ANT-I/2, ANT-III/3, ANT-IX/3, ANT-V/3, ANT-VII/3, ANT-XXIII/8	PANGAEA (https://pangaea.de) - Drescher et al. (2012) - doi:10.1594/PANGAEA.786877 - Ekau et al. (2012a) - doi:10.1594/PANGAEA.786883 - Ekau et al. (2012b) - doi:10.1594/PANGAEA.786884 - Hureau et al. (2012) - doi:10.1594/PANGAEA.786886 - Kock et al. (2012) - doi:10.1594/PANGAEA.786888 - Wöhrmann et al. (2012) - doi:10.1594/PANGAEA.786887	- Drescher et al (1983) hdl:10013/epic.10012 - Hempel et al. (1983) hdl:10013/epic.10014 - Hempel (1985) hdl:10013/epic.10025 - Ekau (1988) hdl:10013/epic.10051 - Schnack-Schiel (1987) hdl:10013/epic.10039 - Bathmann et al. (1992) hdl:10013/epic.10100 - Arntz et al. (1990) hdl:10013/epic.10068 - Gutt (2008) hdl:10013/epic.28679	

The Inverse Distance Weighted (IDW) interpolation was used by means of ArcGIS Spatial Analyst (see for more details e.g. Burrough & McDonnell 1988, Lu & Wong 2008). IDW was performed using log-transformed data, and the interpolated data were finally expressed as densities of *Pleuragramma antarctica* (individuals/1000 m²) for a 10 nautical mile radius around each record according to Conservation Measure 22-09 (Annex 22-09/A) (2012). The IDW settings were chosen as follows:

- Z value: The calculated log10-transformed *P. antarctica* density per 1000 m²
- Output cell size (x, y): 1000 m

- Distance coefficient power P: 2
- Search radius setting, number of points: 10.

For our MARXAN scenarios the interpolated values (log-transformed data) were grouped into five classes (defined by natural breaks) representing the density of Antarctic silverfish (individuals/1000 m²) for a 10 nautical mile buffer around each record (Tab. A2). The arithmetic mean of each group was computed and a weighting factor for each class was calculated by following formula:

Weighting factor = (10/max)*mean (class i) / ((10/max)*mean (class 1))

where *max* (maximum value) is 5.5.

Table A2 Calculated mean and corresponding weighting factor of the five classes representing the final interpolated density of Antarctic silverfish. The values in the table are rounded; the calculation of the weighting factor is based on three decimals.

Class	Interpolated density log10 (individuals/1000 m²)	Mean	Weighting factor
1	0 – 0.4	0.2	1.0
2	0.4 – 1.2	1.0	5.1
3	1.2 – 2.3	2.4	11.7
4	2.3 – 3.3	3.9	19.3
5	3.3 – 5.5	6.0	29.8

2) Revision of cost layer

Table A3 Classification and reclassification of original cost values for Antarctic toothfish in the WSMPA Planning Area. Mean value (MV) +/- standard deviation (SD) of original cost values is 0.21 +/- 0.26.

Class	Class of original cost value	Basis of classification	Reclassified cost value
1	0 - 0.08	0 to (MV - 0.5 * SD)	1
2	0.08 - 0.21	(MV - 0.5 * SD) to MV	5
3	0.21 – 0.35	MV to (MV + 0.5 * SD)	10
4	0.35 – 0.48	(MV + 0.5 * SD) to (MV + (2 * 0.5 * SD))	50
5	0.48 – 0.61	(MV + 2 * 0.5 * SD) to (MV + (3 * 0.5 * SD))	100
6	> 0.61	> MV + (3 * 0.5 * SD)	1000

Revision of accessibility layer

For our previous accessibility layer we used 60 % ice cover (IC) as a threshold for the likely accessibility for fishing operations, i.e. ≤ 60 % IC were defined as 1 (accessible/“ice-free”) and > 60 % IC were defined as 0 (inaccessible for fishery vessels) according to Parker et al. (2014). Finally, the mean maximal sequence of ice-free days was calculated over 10 years from 2002 to 2011 (for more details on the data set SCCAMLR-XXXV/BG/12).

To better describe the accessibility of areas for fishery vessels based on ice cover we revised our accessibility layer by assuming that the accessibility for fishing operations relates to IC with a sigmoid pattern modelled by the following *tanh*-function (see Figure 1A):

$$a_i = 1 - \frac{\tanh\left(\pi * \left(c1 * \left((IC/100) - c2\right)\right)\right) + 1}{2}$$

where a_i = accessibility value of planning unit grid cell *i*,
c1 = steepness of the sigmoid curve was set at a value of 2.5,
c2 = midpoint of the curve (y = 0.5) was set to 0.4 according to Parker et al. (2014).

The accessibility value a_i was calculated for each planning unit *i* per day during the austral summer (Dec - Mar) from 2002 to 2017. Finally, the mean accessibility values over time were standardised to a range between 0 and 1 for comparability among the other cost value, i.e. the toothfish fishing value and the krill fishing value, respectively.
A comparison of the previous and revised accessibility layer shows that the different calculations to describe the accessibility of areas for fishery vessels based on ice cover match rather well (see Figure 2A).

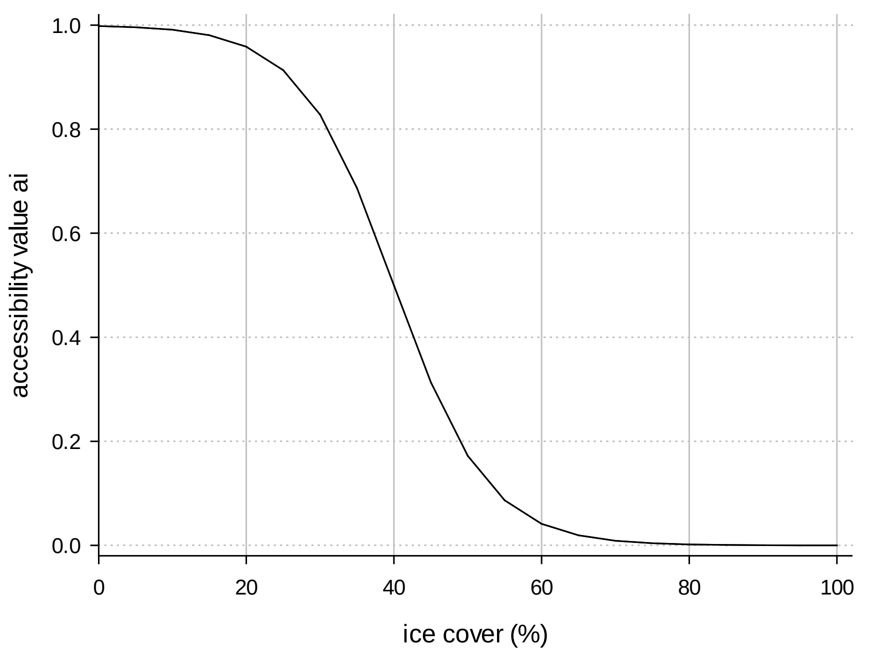

Figure A1 *Tanh*-function of the ice cover to describe the accessibility of areas for fishery vessels.

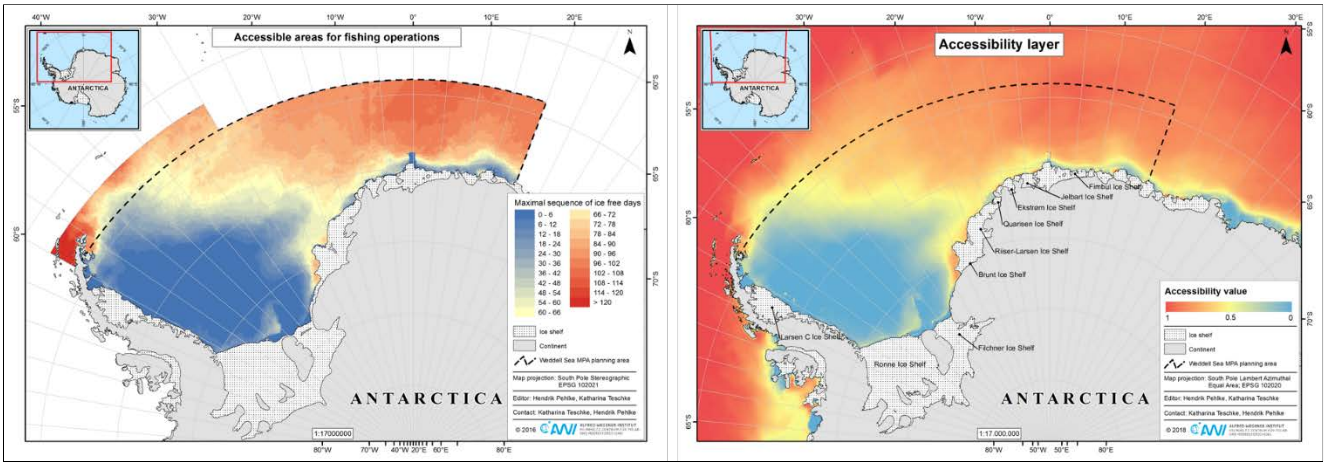

Figure A2 Previous (left) and revised (right) accessibility layer. Both accessibility layers based on ice cover. The previous accessibility layer based on the assumption that 60 % ice cover is a threshold for the likely accessibility for fishing operations; while the revised accessibility layer based on the assumption that the accessibility for fishing operations relates to ice cover with a sigmoid pattern.

3) Robustness testing of WSMPA Marxan model

Table A4 Systematic overview of the specific conservation objectives for the WSMPA, the corresponding conservation features, and their targets for each Marxan scenario. For Scenario S_{Med} and S_{Low} medium and low target levels, respectively, assigned to the conservation features, while for Scenario S_{Mix} low targets were given to all environmental features and medium targets to all ecological features. An exception were the unique and rare features (i.e. shallow water area on the Norsel Bank, buffer area around Adélie penguin colonies) and the highly sensitive areas (i.e. sponge associations, nesting sites of demersal fish); here, we used target values of 100 % for all three Scenario (S_{Med} - S_{Mix}).

Conservation feature		**Marxan scenario with different combination of target level**		
Feature type	**Feature name**	**Scenario S_{Med} (medium target level)**	**Scenario S_{Low} (low target level)**	**Scenario S_{Mix} (mixed target level)**
Specific conservation objective S1: Representation of pelagic habitats				
Pelagic regions (Habitat classification of five pelagic regions)				
Environmental feature	Transition zone	20 %	10 %	10 %
Environmental feature	Deepwater area I	20 %	10 %	10 %
Environmental feature	Deepwater area II	20 %	10 %	10 %
Environmental feature	Deepwater area III	20 %	10 %	10 %
Environmental feature	Ice covered area	20 %	10 %	10 %
S2: Important areas for pelagic key species in the Antarctic food web				
Ecological feature	Adult Antarctic krill	35 %	20 %	35 %
Ecological feature	Larval Antarctic krill	50 %	20 %	50 %
Ecological feature	Ice krill	35 %	20 %	35 %
Ecological feature	Antarctic silverfish	35 %	20 %	35 %
S3: Essential habitats for top predators				
Ecological feature	Adélie penguin colonies (50 km buffer around each colony)	100 %	100 %	100 %
Ecological feature	Adélie penguin colonies (50-100 km ring buffer around each colony)	50 %	50 %	50 %
Ecological feature	Non-breeding Adélie penguins	20 %	10 %	20 %
Ecological feature	Emperor penguins	40 %	30 %	40 %

Conservation feature		Marxan scenario with different combination of target level		
Feature type	**Feature name**	**Scenario S_{Med} (medium target level)**	**Scenario S_{Low} (low target level)**	**Scenario S_{Mix} (mixed target level)**
Ecological feature	Antarctic petrel	40 %	30 %	40 %
Ecological feature	Seal density	20 %	15 %	20 %
Ecological feature	Seal movement	20 %	15 %	20 %
S4: Representation of benthic habitats				
Environmental feature	Abyssal Plain: > -3000m	20 %	10 %	10 %
Environmental feature	Bank: 0m to -100m	20 %	10 %	10 %
Environmental feature	Bank: -100m to -200m	20 %	10 %	10 %
Environmental feature	Bank: -200m to -500m	20 %	10 %	10 %
Environmental feature	Bank: -500m to -1000m	20 %	10 %	10 %
Environmental feature	Canyon Shelf Commencing	60 %	30 %	30 %
Environmental feature	Canyon Slope Commencing	60 %	30 %	30 %
Environmental feature	Coastal Terrane	20 %	10 %	10 %
Environmental feature	Cross Shelf Valley: 0m to -100m	20 %	10 %	10 %
Environmental feature	Cross Shelf Valley: -100m to -200m	20 %	10 %	10 %
Environmental feature	Cross Shelf Valley: -200m to -500m	20 %	10 %	10 %
Environmental feature	Cross Shelf Valley: -500m to -1000m	20 %	10 %	10 %
Environmental feature	Cross Shelf Valley: -1000m to -1500m	20 %	10 %	10 %
Environmental feature	Filchner Trough (incl. parts of Cross Shelf Valley)	60 %	30 %	30 %
Environmental feature	Lower Slope: -2000m to -3000m	20 %	10 %	10 %
Environmental feature	Lower Slope: > -3000m	20 %	10 %	10 %
Environmental feature	Margin Ridge (= Astrid Ridge): -500m to -1000m	60 %	30 %	30 %
Environmental feature	Margin Ridge (= Astrid Ridge): -1000m to -1500m	60 %	30 %	30 %
Environmental feature	Margin Ridge (= Astrid Ridge): -1500m to -2000m	60 %	30 %	30 %

Conservation feature		Marxan scenario with different combination of target level		
Feature type	**Feature name**	**Scenario S_{Med} (medium target level)**	**Scenario S_{Low} (low target level)**	**Scenario S_{Mix} (mixed target level)**
Environmental feature	Margin Ridge (= Astrid Ridge): -2000m to -3000m	60 %	30 %	30 %
Environmental feature	Margin Ridge (= Astrid Ridge): -3000m to -4500m	60 %	30 %	30 %
Environmental feature	Marginal Plateau: -2000m to -3000m	60 %	30 %	30 %
Environmental feature	Marginal Plateau: -3000m to -4500m	60 %	30 %	30 %
Environmental feature	Plateau: -2000m to -3000m	60 %	30 %	30 %
Environmental feature	Plateau: -3000m to -4500m	60 %	30 %	30 %
Environmental feature	Plateau Slope: -2000m to -3000m	60 %	30 %	30 %
Environmental feature	Plateau Slope: -3000m to -4500m	60 %	30 %	30 %
Environmental feature	Ridge: -1500 to -2000m	20 %	10 %	10 %
Environmental feature	Ridge: -2000 to -3000m	20 %	10 %	10 %
Environmental feature	Ridge: -3000 to -4500m	20 %	10 %	10 %
Environmental feature	Rugose Ocean Floor: > -3000m	20 %	10 %	10 %
Environmental feature	Seamount Ridge: -1000m to -1500m	60 %	30 %	30 %
Environmental feature	Seamount Ridge: -2000m to -3000m	60 %	30 %	30 %
Environmental feature	Seamount Ridge: -3000m to -4500m	60 %	30 %	30 %
Environmental feature	Seamount: -1000m to -1500m	60 %	30 %	30 %
Environmental feature	Seamount: -1500m to -2000m	60 %	30 %	30 %
Environmental feature	Seamount: > -3000m	60 %	30 %	30 %
Environmental feature	Shelf	60 %	30 %	30 %
Environmental feature	Shelf Deep: 0m to -100m	60 %	30 %	30 %
Environmental feature	Shelf Deep: -200m to -500m	60 %	30 %	30 %
Environmental feature	Shelf Deep: -500m to -1000m	60 %	30 %	30 %
Environmental feature	Upper Slope: 0m to -100m	60 %	30 %	30 %

Conservation feature		Marxan scenario with different combination of target level		
Feature type	**Feature name**	**Scenario S_{Med} (medium target level)**	**Scenario S_{Low} (low target level)**	**Scenario S_{Mix} (mixed target level)**
Environmental feature	Upper Slope: -100m to -200m	60 %	30 %	30 %
Environmental feature	Upper Slope: -200m to -500m	60 %	30 %	30 %
Environmental feature	Upper Slope: -500m to -1000m	60 %	30 %	30 %
Environmental feature	Upper Slope: -1000m to -1500m	60 %	30 %	30 %
Environmental feature	Upper Slope: -1500m to -2000m	60 %	30 %	30 %
Environmental feature	Upper Slope: -2000m to -3000m	60 %	30 %	30 %
Environmental feature	Upper Slope: -3000m to -4500m	60 %	30 %	30 %
Ecological feature	Echinoderm fauna	35 %	20 %	35 %
S5: Important areas for unique and diverse suspension feeding assemblages				
Ecological feature	Sponge presence	100 %	100 %	100 %
S6: Rare and unique habitats				
Ecological feature	Shallow water area - Norsel Bank	100 %	100 %	100 %
S7: Important benthic areas for demersal fish				
Ecological feature	Demersal fish	75 %	65 %	75 %
Ecological feature	Nesting sites	100 %	100 %	100 %
S8: High productivity areas				
Environmental feature	Pelagic region - Coastal polynya I	75 %	50 %	50 %
Environmental feature	Pelagic region - Coastal polynya II	75 %	50 %	50 %
Environmental feature	Pelagic region - Coastal polynya III	75 %	50 %	50 %
S10: Important areas for the Antarctic toothfish				
Ecological feature	Adult Antarctic toothfish	60 %	20 %	60 %
Ecological feature	Juvenile Antarctic toothfish	30 %	20 %	30 %

Notes: Specific conservation objectives S9 and S11-S12 are not mentioned. S9 is reflected by all the conservation features listed above, rather than a unique feature, and we wanted to prevent a repeated listing of features. S11 and S12 defining research objectives which are not directly reflected by one of the above listed conservation feature data layers.

Table A5 Calibration of Species Penalty Factor (SPF). Marxan solution quality among Scenario S_{SPF} 001 to S_{SPF} 060.

Scenario	SPF	% of runs meet all conservation targets	Mean number of missed conservation targets	Scenario	SPF	% of runs meet all conservation targets	Mean number of missed conservation targets
S_{SPF} 001	0	0	79.0	**S_{SPF} 031**	3.0	0	1.1
S_{SPF} 002	0.1	0	65.0	**S_{SPF} 032**	3.1	0	1.1
S_{SPF} 003	0.2	0	59.0	**S_{SPF} 033**	3.2	0	1.1
S_{SPF} 004	0.3	0	48.4	**S_{SPF} 034**	3.3	0	1.0
S_{SPF} 005	0.4	0	38.9	**S_{SPF} 035**	3.4	0	1.0
S_{SPF} 006	0.5	0	34.6	**S_{SPF} 036**	3.5	0	1.0
S_{SPF} 007	0.6	0	33.3	**S_{SPF} 037**	3.6	0	1.0
S_{SPF} 008	0.7	0	30.6	**S_{SPF} 038**	3.7	0	1.0
S_{SPF} 009	0.8	0	23.4	**S_{SPF} 039**	3.8	0	1.0
S_{SPF} 010	0.9	0	12.3	**S_{SPF} 040**	3.9	0	1.0
S_{SPF} 011	1.0	0	8.3	**S_{SPF} 041**	4.0	0	1.0
S_{SPF} 012	1.1	0	7.7	**S_{SPF} 042**	4.1	0	1.0
S_{SPF} 013	1.2	0	6.8	**S_{SPF} 043**	4.2	0	1.0
S_{SPF} 014	1.3	0	6.7	**S_{SPF} 044**	4.3	0	1.0
S_{SPF} 015	1.4	0	5.6	**S_{SPF} 045**	4.4	0	1.0
S_{SPF} 016	1.5	0	5.6	**S_{SPF} 046**	4.5	0	1.0
S_{SPF} 017	1.6	0	4.6	**S_{SPF} 047**	5.0	59	0.4
S_{SPF} 018	1.7	0	1.5	**S_{SPF} 048**	5.1	88	0.1
S_{SPF} 019	1.8	0	1.4	**S_{SPF} 049**	5.2	96	0.0
S_{SPF} 020	1.9	0	1.5	**S_{SPF} 050**	5.3	100	0.0
S_{SPF} 021	2.0	0	1.4	**S_{SPF} 051**	5.4	100	0.0
S_{SPF} 022	2.1	0	1.3	**S_{SPF} 052**	5.5	100	0.0
S_{SPF} 023	2.2	0	1.3	**S_{SPF} 053**	5.6	100	0.0
S_{SPF} 024	2.3	0	1.3	**S_{SPF} 054**	5.7	100	0.0
S_{SPF} 025	2.4	0	1.2	**S_{SPF} 055**	5.8	100	0.0
S_{SPF} 026	2.5	0	1.2	**S_{SPF} 056**	5.9	100	0.0
S_{SPF} 027	2.6	0	1.2	**S_{SPF} 057**	6.0	100	0.0
S_{SPF} 028	2.7	0	1.3	**S_{SPF} 058**	8.0	100	0.0
S_{SPF} 029	2.8	0	1.2	**S_{SPF} 059**	10	100	0.0
S_{SPF} 030	2.9	0	1.1	**S_{SPF} 060**	100	100	0.0

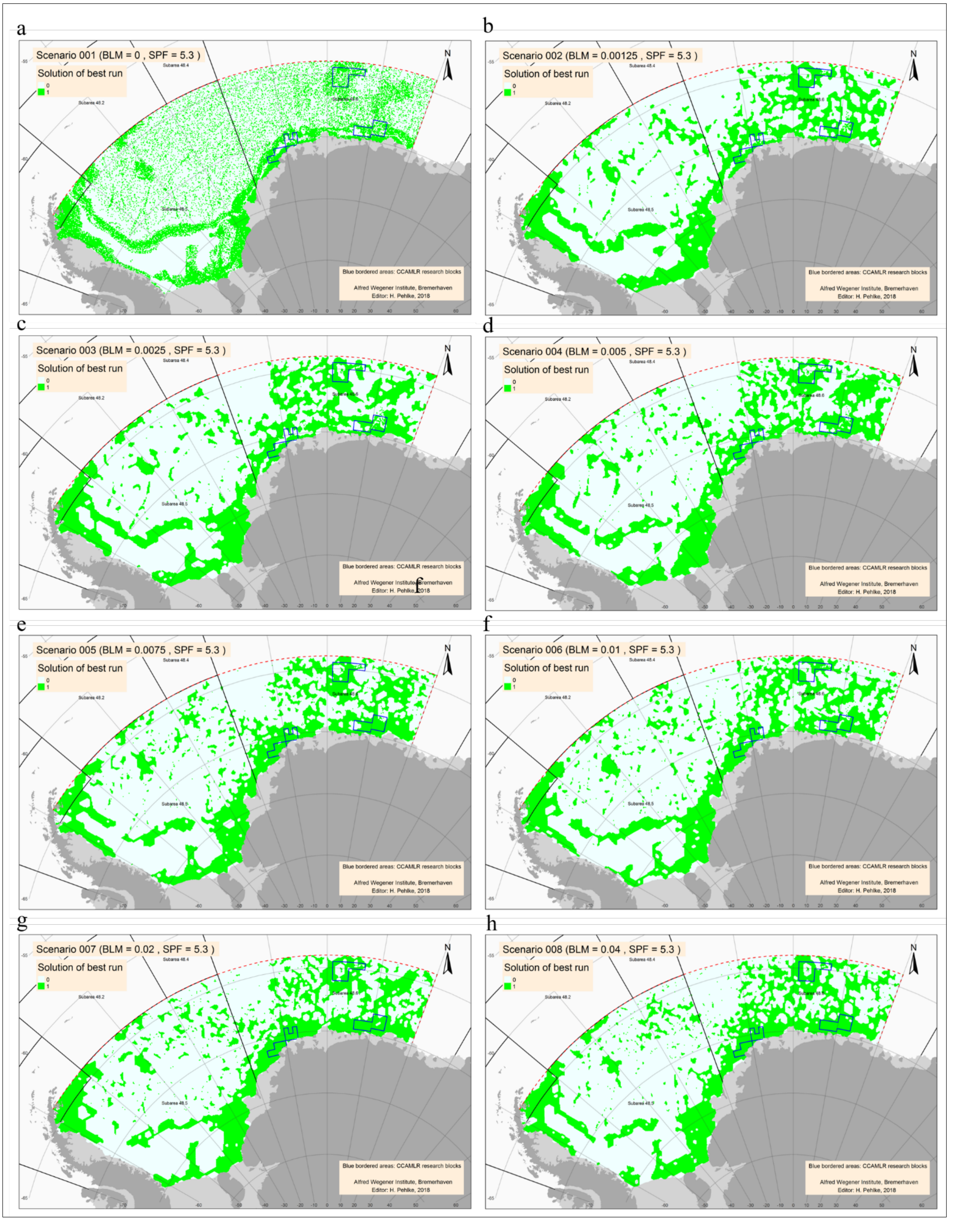

Figure A3 Best solutions from Boundary Length Modifier (BLM) calibration, where Scenarios S_{BLM} 001 to S_{BLM} 008 each used a different BLM to assess its effect on the Marxan results. All Scenarios used an identical setup (in terms of Marxan input parameters), except for the BLM that took values 0 (a), 0.00125 (b), 0.0025 (c), 0.005 (d), 0.0075 (e), 0.01 (f), 0.02 (g) and 0.04 (h). Green areas indicate areas of selection.

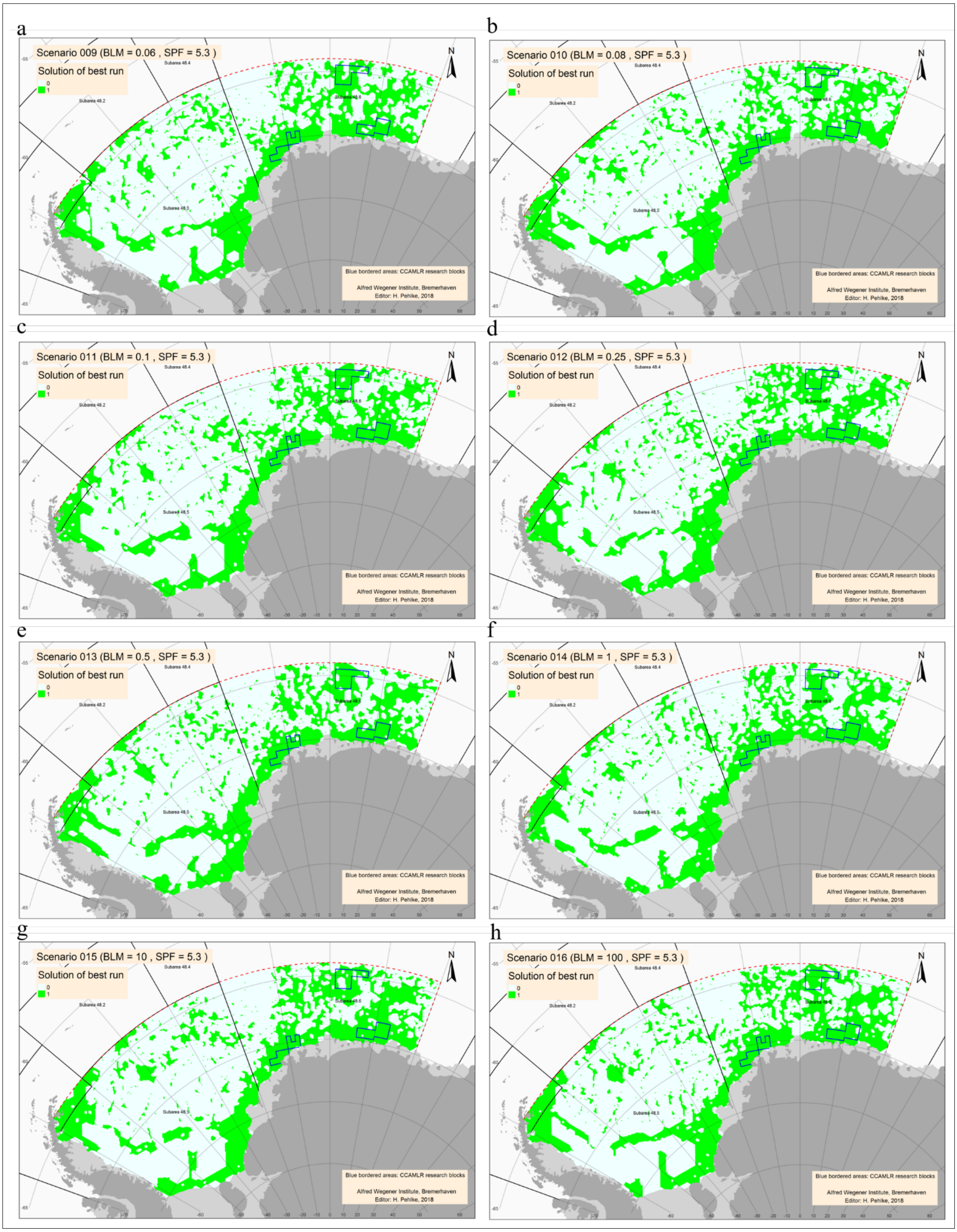

Figure A4 Best solutions from Boundary Length Modifier (BLM) calibration, where Scenarios S_{BLM} 009 to S_{BLM} 016 each used a different BLM to assess its effect on the Marxan results. All Scenarios used an identical setup (in terms of Marxan input parameters), except for the BLM that took values 0.06 (a), 0.08 (b), 0.1 (c), 0.25 (d), 0.5 (e), 1 (f), 10 (g) and 100 (h). Green areas indicate areas of selection.

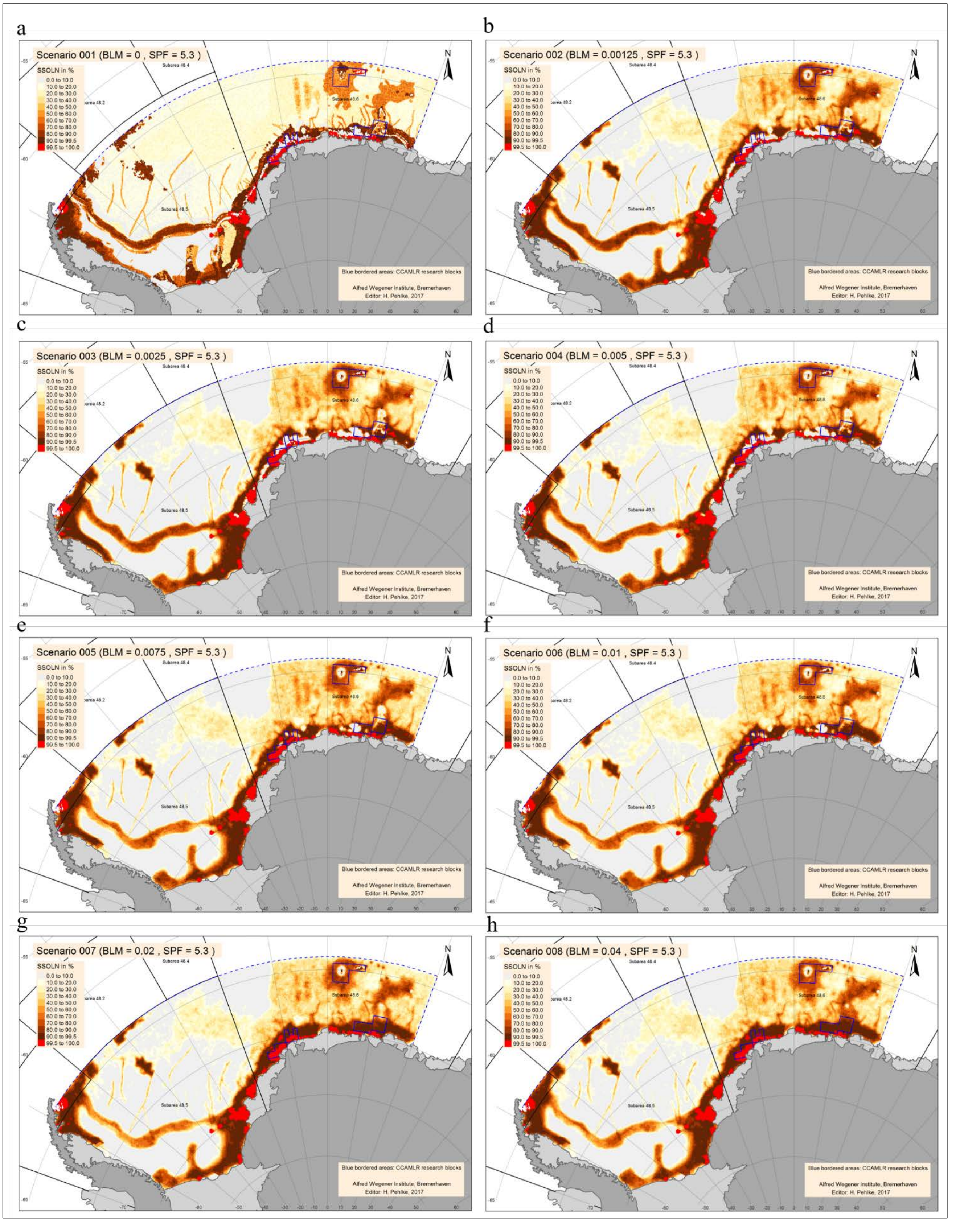

Figure A5 Summed solutions from Boundary Length Modifier (BLM) calibration, where Scenarios S_{BLM} 001 to S_{BLM} 008 each used a different BLM to assess its effect on the Marxan results. All Scenarios used an identical setup (in terms of Marxan input parameters), except for the BLM that took values 0 (a), 0.00125 (b), 0.0025 (c), 0.005 (d), 0.0075 (e), 0.01 (f), 0.02 (g) and 0.04 (h). Red areas indicate areas of highest selection frequency; dark brown areas indicate areas of high selection frequency, and yellow to grey areas indicate low selection frequency.

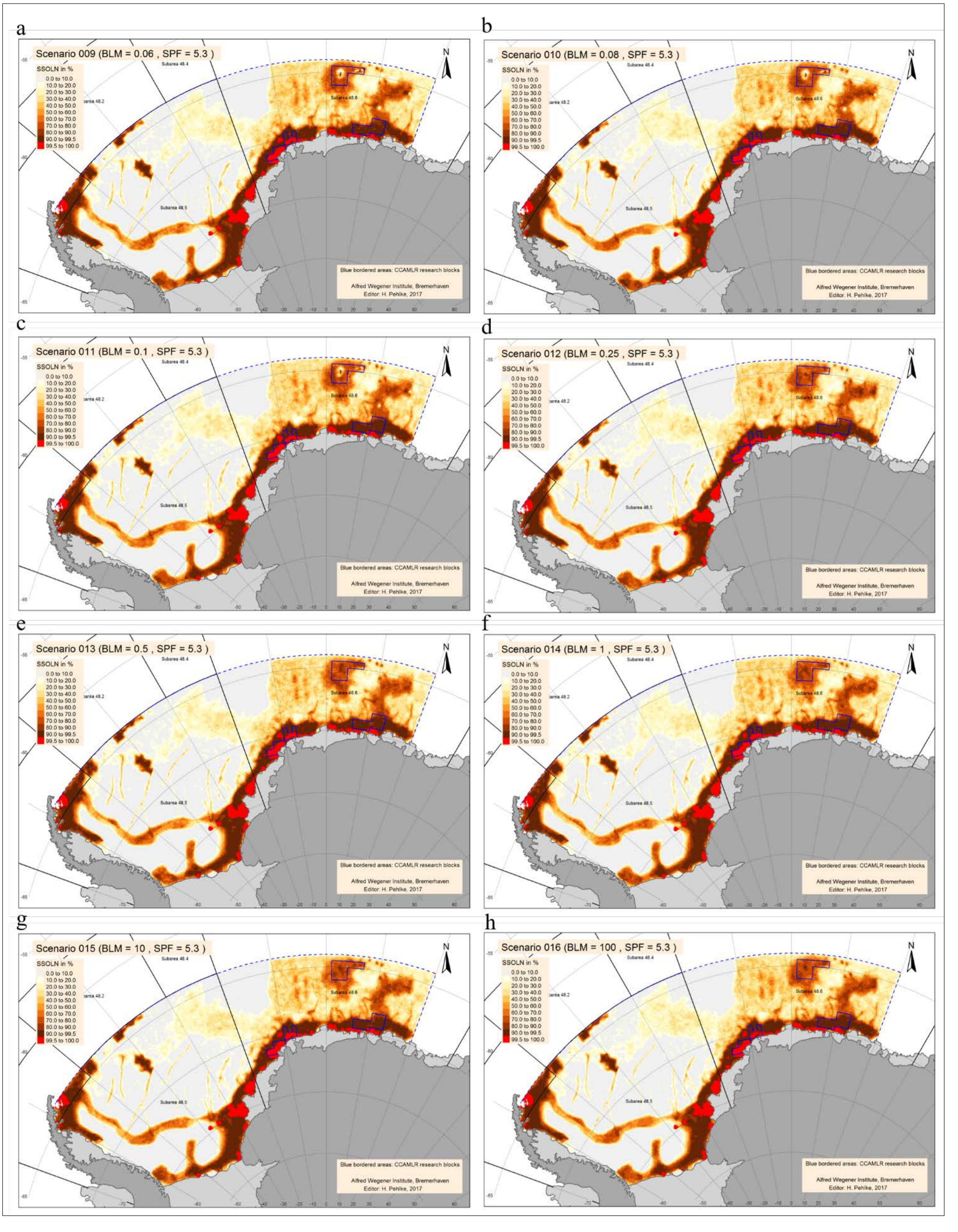

Figure A6 Summed solutions from Boundary Length Modifier (BLM) calibration, where Scenarios S_{BLM} 009 to S_{BLM} 016 each used a different BLM to assess its effect on the Marxan results. All Scenarios used an identical setup (in terms of Marxan input parameters), except for the BLM that took values 0.06 (a), 0.08 (b), 0.1 (c), 0.25 (d), 0.5 (e), 1 (f), 10 (g) and 100 (h). Red areas indicate areas of highest selection frequency; dark brown areas indicate areas of high selection frequency, and yellow to grey areas indicate low selection frequency.