Searching spatial-temporal changes in intrinsic productivity of Antarctic Krill (Euphausia superba) in a fishery management context

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# ABSTRACT

One approach to understanding the dynamics of krill populations in the Antarctic Peninsula of the Southern Ocean is through the analysis of empirical data, such as size compositions obtained from fishery monitoring. By studying this data over multiple years and considering life history parameters, we can assess the intrinsic productivity of krill and how it has changed over time and in different areas. To achieve this, we have employed a method known as the Length-Based Spawning Potential Ratio (LBSPR). This method allows us to estimate the reproductive potential of the population based on current exploitation levels, as well as in comparison to a virgin condition. By identifying reference points specifically related to reproductive potential, the LBSPR method provides insights into the state of the krill population. Recognizing spatial and temporal changes in the intrinsic productivity of krill, as indicated by their reproductive potential, is crucial in understanding the unique characteristics of this species. Moreover, these findings have important implications for management strategies within the context of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). By integrating knowledge of krill dynamics and their reproductive potential, we can give advise to ensure the sustainable management of krill populations in the Antarctic Peninsula.

*Keywords: Length Structure, Intrinsic productivity, SPR, spatial-Temporal changes, Krill, 48.1 SubArea*

# 1. INTRODUCTION

The northern Antarctic Peninsula ecosystem is a critical region of the Southern Ocean for populations of Antarctic krill (*Euphausia superba*; hereafter krill) serving as a major spawning and recruitment area and as an overwintering hotspot, especially within Bransfield Strait. Over the last 40 years, climate driven changes have resulted in warming waters, declines in seasonal sea ice extent and duration ([Sharon E. Stammerjohn et al., 2008](#ref-Stammerjohn2008a); [S. E. Stammerjohn et al., 2008](#ref-Stammerjohn2008)), changing trends phytoplankton productivity ([Saba et al., 2014](#ref-Saba2014); [Siegel et al., 2013](#ref-Siegel2013)).

Additionally, changes have impacted the population dynamics of krill, resulting in distribution changes with consequent contraction of the population in the southwest Atlantic Ocean toward the peninsula ([A. Atkinson et al., 2009](#ref-Atkinson2009)). These changes in the population structure have been verified in krill for the last years also ([Reiss et al., 2020](#ref-Reiss2020); [Siegel et al., 2013](#ref-Siegel2013)). This changes (temporal and spatial) has implications for the reproductive potential of the species and this, in turn, for intrinsic productivity.

One way to understand and measure changes in intrinsic productivity is through assessing the ratio of krill reproductive potential. There are many length-based assessment methods to understand this changes between years ([Canales et al., 2021](#ref-Canales2021); [Froese et al., 2018](#ref-Froese2018); [A. R. Hordyk et al., 2016](#ref-Hordyk2016); [Rudd & Thorson, 2017](#ref-Rudd2017a)). On the other hand, one of the advantages of these methods is to use one of the most reliable and abundant sources in the sampling of fishing activities, such as size structures ([Canales et al., 2021](#ref-Canales2021)).

This changes in spatial and temporal structure of krill population has tried to be considered in management that performed CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources), but does not consider reference points that can help in making decisions with scientific rigor. We propose to identify the differences in the reproductive potential of krill on the spatial and temporal scale, propose a species-specific reference point and thereby provide recommendations for the sustainable management of this fishery trough Spawning Pontential Ratio (SPR) from krill population catch in SubArea 48.1 in Antarctic Peninsula in Southern Ocean.

# 2. METHODOLOGY

## 2.1. Study area

The study area includes one of the sectors where today the largest amount of krill fishing is concentrated. In this case, the analyzes include the entire subarea 48.1. In order to have a better spatial definition of the behavior of krill dynamics, we will analyze the differences between the management strata defined in WG-EMM-2021/05 Rev. (WG-EMM-2021/05 ([2021](#ref-Dornam2021))), namely Brainsfield Straith, Elephant Island, Extra, Joinville Island and South West (Figure 1).

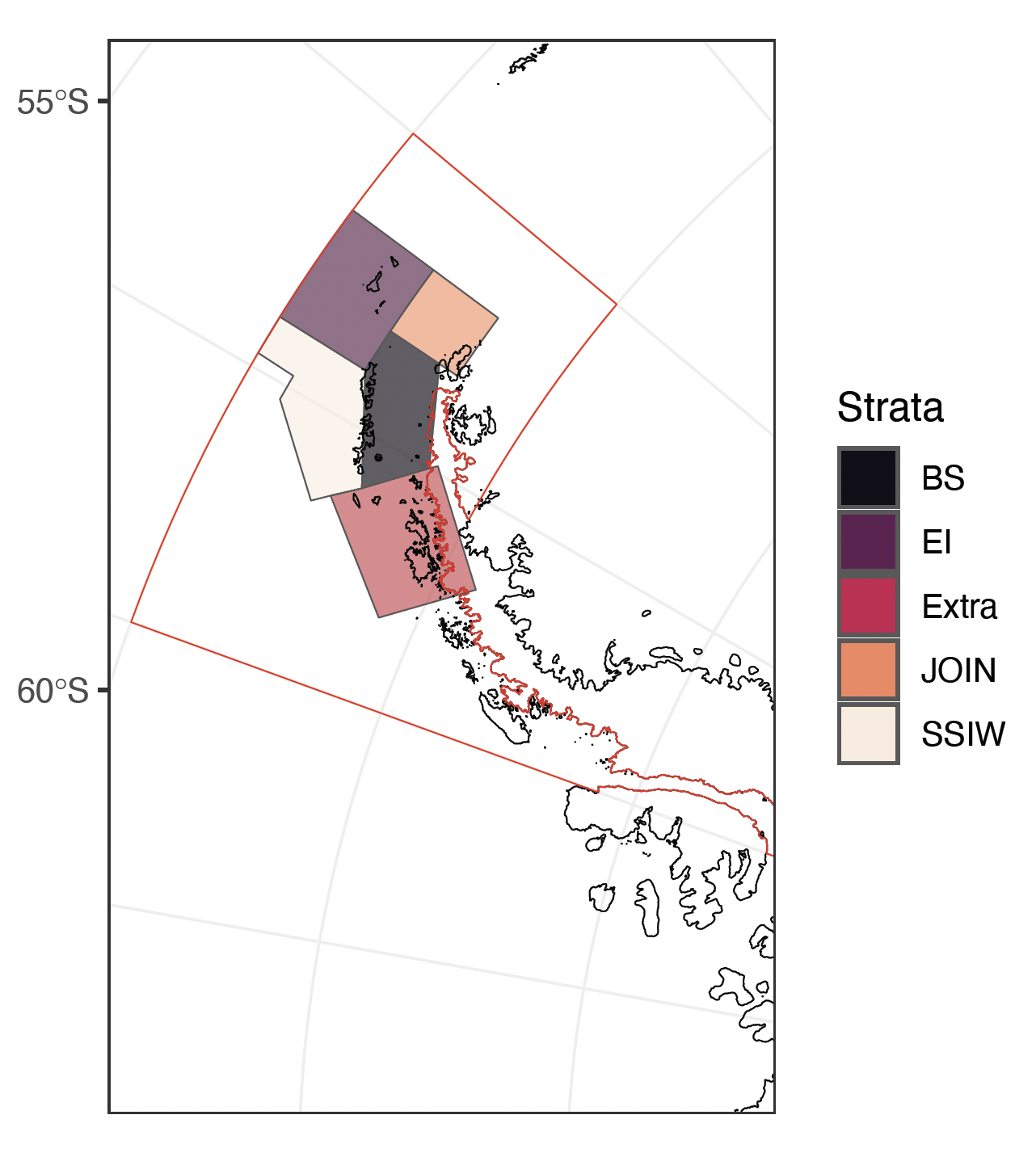


Figure 1. Subarea 48.1 and management strata considered in the spatio-temporal analysis of intrinsic productivity of Krill (BS=Brainsfield Straith, EI= Elephant Island, Extra= Extra, JOIN= Joinville Island, SSWI= South West)

## 2.2. Data

For this analysis, data from the monitoring of the krill fishery were used, which have been systematically collected on board fishing vessels by the SISO (Scheme of International Scientific Observation) program carried out by CCAMLR. Krill sizes compositions were obtained from the entire area 48.1, which was joined in each management stratum defined at 2.1 section (Figure 2).

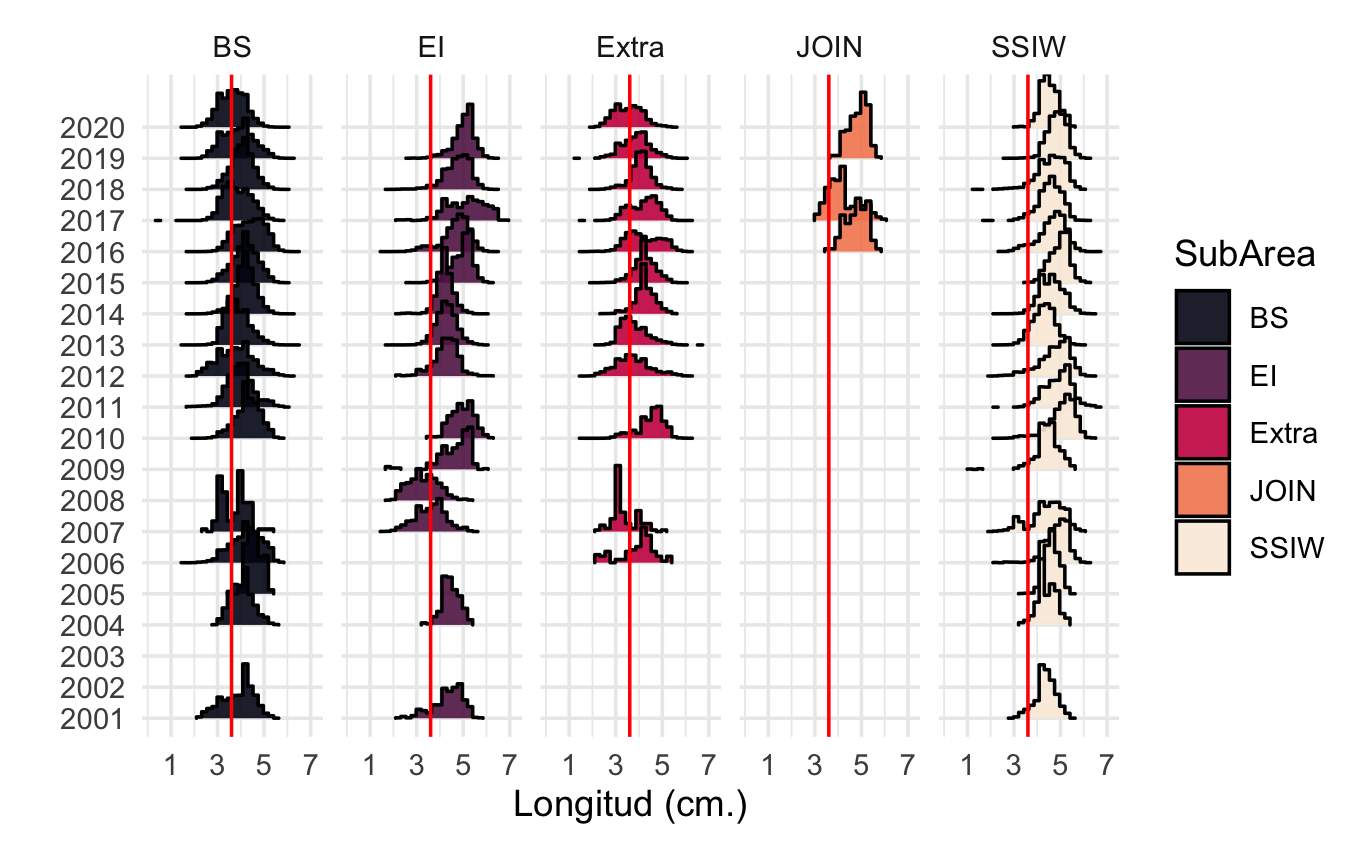


Figure 2. Sizes compositions from SISO program monitoring krill fishery

## 2.3 Assessment of intrinsic productivity

of a stock is defined as the proportion of potential unexploited spawning at any given level of fishing pressure (Goodyear, 1993; Walters and Martell, 2004)

The intrinsic productivity of krill was evaluated through a method that measures the reproductive potential of commercially exploited marine species known as LB-SPR (Length Based Spawining Potential Ratio) and described by A. R. Hordyk et al. ([2016](#ref-Hordyk2016)). The LB-SPR method has been developed for data-limited fisheries, where few data are available other than a representative sample of the size structure of the vulnerable portion of the population (i.e., the catch) and an understanding of the life history of the species. The LBSPR method assumes the reproductive characteristics of the species based on the life history parameters, being able to establish strategies for long-lived species with low reproductive output as well as highly reproductive species with a high growth constant such as krill ([Prince & Hordyk, 2018](#ref-Prince2018)).

LBSPR uses length-composition data and assumptions about biological parameters to make a rapid assessment of stock status relative to unfished levels assuming equilibrium conditions. While LB-SPR can use multiple years of length data, status determination is based on one year of data at a time (i.e., estimates of status over multiple years are based on that year’s length composition alone). Mean-length mortality estimators, first developed by Beverton & Holt ([1957](#ref-Beverton1957)), assume that fishing mortality directly influences mean length of the catch and therefore in the reproductive potential of the species. Al l this concept about life history and implications in spawning potential ratio was revisited by Jensen ([1996](#ref-Jensen1996)).

here are two versions of the LB-SPR model included in this methodology.

## 2.4. Life story and fishery parameters Krill

The model needs specifications related to both biological and fishery parameters according to species evaluated. In a descriptive way, the main parameter sets are described as follows;

**Biology**

* von Bertalanffy asymptotic length Linf
* M/K ratio (natural mortality)divided by von Bertalanffy K coefficient) MK
* Length at 50% maturity (L50)
* Length at 95% maturity (L95)

**Fishery**

* Length at 50% selectivity (SL50)
* Length at 95% selectivity (SL95)
* Biological Reference Point (BRP). F/M ratio (FM) or Spawning Potential Ratio (SPR). If you specify both, the F/M value will be ignored.

Size Classes

-Width of the length classes (BinWidth)

These parameters was borrowed from technical reports and/or indexed publications about krill life history and fishery ([Maschette et al., 2020](#ref-Maschette2020); [Thanassekos et al., 2014](#ref-Thanassekos2014)), which are described (Table 1).

Krill life history and fishery parameters

Value

Descrption

60

VB asymptotic length

34

Maturity 50%

55

Maturity 95%

0.889

M/K Ratio

40

SPR

56

Selectivity 50%

0.75

Seletivity 95%

1

a (Length-Weight Relation)

3.0637

b (Length-Weight Relation)

70

Bin Min

0

Bin Max

mm

Units

## 2.5. Model Estimation LB-SPR

Recent work has shown that, under equilibrium conditions (that is, constant F and no recruitment variability) and assuming the von Bertalanffy growth equation, constant natural mortality for all ages, and logistic or jack-knife selectivity, standardization of the composition of lengths of two populations with the same ratio of natural mortality to growth rate (M/k) and the same ratio of mortality by fishing to natural mortality (F/M) will be identical ([A. R. Hordyk et al., 2016](#ref-Hordyk2016)). Extension of this model to incorporate length-at-age variability and logistic selectivity confirms that, at equilibrium, the composition of the predicted duration of catch of an exploited population is primarily determined by the ratios of M/k and F/M. The analytical models developed in A. Hordyk et al. ([2014](#ref-Hordyk2014c)) suggest that with knowledge of the asymptotic von Bertalanffy length and the coefficient of variation in , the ratio of total mortality to the von Bertalanffy growth coefficient (Z /k) for a given population can be estimated from a representative sample of the size structure of the catch. If M/k is also known (from meta-analyses, life history theory, expert opinion, or population biological studies), then the results of A. R. Hordyk et al. ([2016](#ref-Hordyk2016)) suggest that it is possible to estimate F/M from the composition of the catch. Often the F/M ratio has been used as a biological reference point when is 1 ([Zhou et al., 2012](#ref-Zhou2012)).

The LB-SPR model requires the following parameters: an estimate of the M/k ratio, , , and knowledge of maturity by length (maturity ogive), both know in krill. This model uses data on composition by catch sizes to estimate intrinsic productivity or SPR. This concept was calculated following Goodyear ([1993](#ref-Goodyear1993)), where he calculated the ratio between the average lifetime egg production per recruit (EPR) in equilibrium for fish and non-fish resources. An algorithm route for the calculation of the SPR is the following;

where;

where = M + \*F, and is egg production at age assumed to be proportional to weight;

on the other hand, the calculation of the reproductive potential is the same as that of those captured without F;

Assuming that egg production is proportional to the size of mature fish, relative fecundity-at-size is given by;

where b is value of the exponent to reflect differente size fecunditity relationship and g is the fraction of recruits to group.

Assuming reasonable estimates of the M/K ratio, (or ), size-at-maturity, the parameters F/M, , and can be estimated from a representative sample of the length structure of the catch by minimizing the following multinomial negative loglikelihood function (NLL):

where and are the observed number and proportion in length class i, respectively, and is the model estimate of the probability in length class i ([A. R. Hordyk et al., 2016](#ref-Hordyk2016)).

Like any assessment method, the LBSPR model relies on a number of simplifying assumptions. In particular, the LBSPR models are equilibrium based, and assume that the length composition data is representative of the exploited population at steady state ([A. Hordyk et al., 2014](#ref-Hordyk2014c); [A. R. Hordyk et al., 2016](#ref-Hordyk2016)). This methodology was implemented through the package ([A. Hordyk et al., 2014](#ref-Hordyk2014c); A. Hordyk; [2021](#ref-LBSPR2021)) and this code and data could be visited in [LBPRKrill](https://github.com/MauroMardones/LBSPR_Krill).

## 2.6. Biological References Point (PBR) in Krill.

A constant challenge for krill has been to provide indicators of stock status that can be compared to predetermined biological reference points. The intrinsic productivity or SPR is commonly used to set the limit and target reference ([Goodyear, 1993](#ref-Goodyear1993); [Mace, 2001](#ref-Mace2001)). By definition, the SPR is equal to 100% in an unexploited stock, and zero in a non-spawning stock (eg all mature fish have been removed, or all females have been caught). The F40%, that is, the fishing mortality that allows an escape of 40% of the biomass to MSY, is the fishing mortality rate that translates into SPR = 40%, is considered a reference point to many species ([Clark, 2002](#ref-Clark2002)). Suitable SPR biological points can be derived from hypotheses about the steepness of the stock-recruit relationship ([Brooks, 2013](#ref-Brooks2013); [A. R. Hordyk et al., 2016](#ref-Hordyk2016)). However Prince et al. ([2014](#ref-Prince2014)) do some considerations in relation to the life strategy of the organisms and the SPR necessary to ensure the sustainability of the fishery. In this work, three types (I, II and III) are identified, which refers to the r and K life strategy. The krill is Type 1 (r-strategy), M/k=~1 (m=0.4, k =0.43) therefore, it requires a higher save of SPR.

On the other hand, and considering the current krill fisheries management schemes established by CCAMLR ([2010](#ref-CCAMLR2010)), Constable et al. ([2000](#ref-Constable2000)) proposes a decision rule scheme based on biomass that ensure the sustainability of this resource in the Ocean Southern. Through a simulation process, a 20-year projection of the krill population is generated, and a probability distribution is established around two decision rules. The first is based on the lowest level of exploitation allowed, around 20% of biomass, which could become a limit reference point. The second is the target level of the fishery, which indicates the statistical distribution of the biomass at the end of the 20-year projection under a constant catch that allows the average escape of 75% at pre-exploited levels (CCAMLR-2000 Survey).In this regards, we propose two reference points for intrinsic krill productivity, 20% SPR as the limit reference point and 75% as the target.

## 2.7. Running the Simulation Model

The LBSPR package can be used to generate the expected size composition, the SPR, and relative yield for a given set of biological and exploitation pattern parameters. The output of the LBSPRsim function is an object of class LB\_obj. This is another LBSPR object, and contains all of the information from the LB\_pars object and the output of the LBSPRsim function.

It is important to note that the F/M ratio reported in the LBSPR model refers to the apical F over the adult natural mortality rate. That is, the value for fishing mortality refers to the highest level of F experienced by any single size class ([A. Hordyk et al., 2014](#ref-Hordyk2014c)). If the selectivity pattern excludes all but the largest individuals from being exploited, it is possible to have a very high F/M ratio in a sustainable fishery (high SPR) and visceverse. Note that only the life history parameters need to be specified for the estimation model. The exploitation parameters will be estimated ([A. Hordyk et al., 2014](#ref-Hordyk2014c)).

## 2.8. Fitting Empirical Krill lengths compositions

Two objects are required to fit the LBSPR model to length data: life-history parameters (LB\_pars) described previously (2.4. section) and size compositions (LB\_lengths), which contains the length frequency data. We provide a set of global size data and also by strata, with which we will be able to identify the spatial differences of the potential.

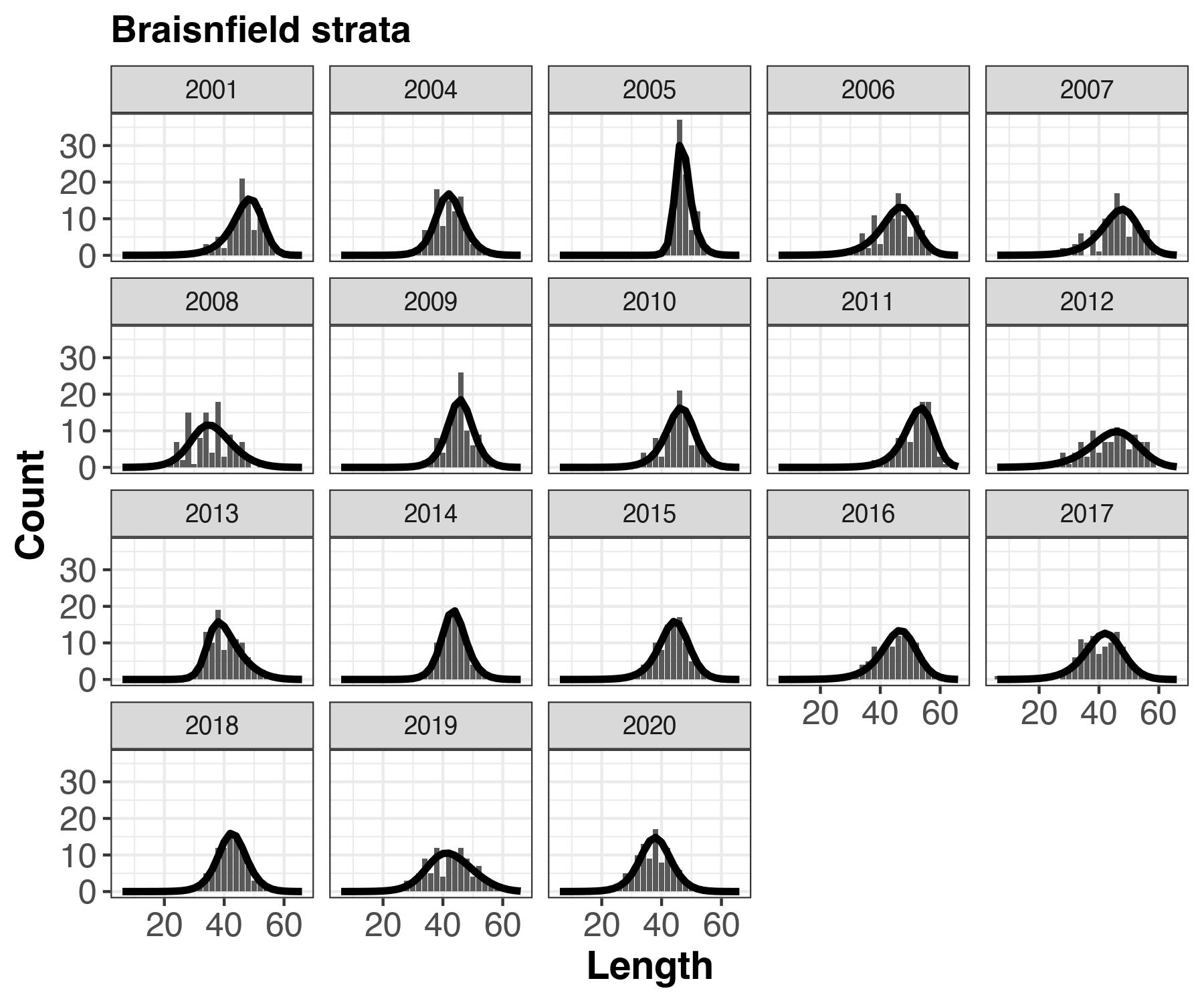
However, it is probably easier to create the LB\_lengths object by directly reading in a .csv. A length frequency data of krill set with multiple years (2001-2020) by strata in 48.1 Subarea.

## 2.9. Fit the Model by strata

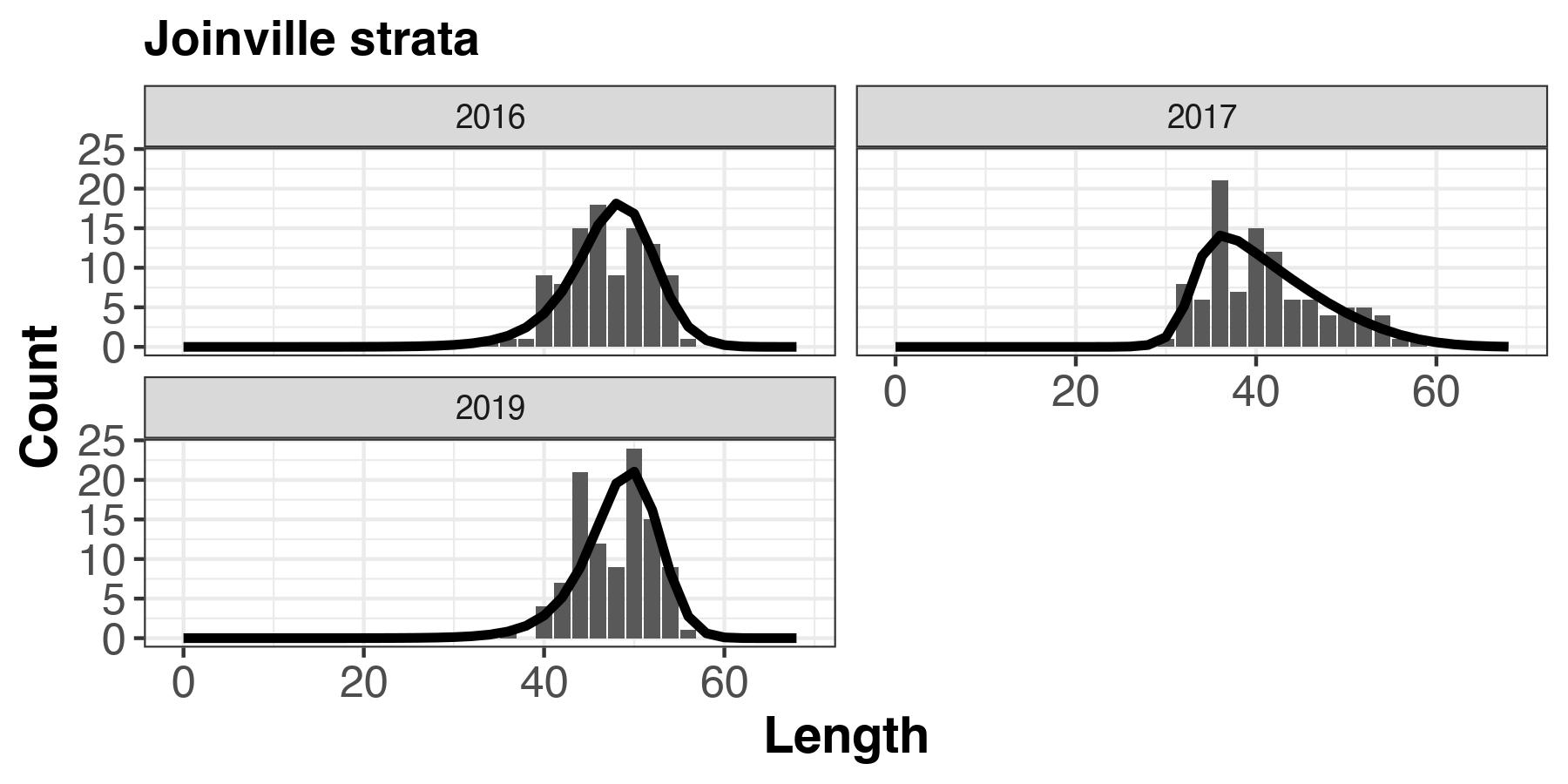
The LBSPR model is fitted by strata using the LBSPRfit function.

# 3. RESULTS

## 3.1. Model Perfomance

One way to evaluate the performance of the model for the estimation of the SPR is the fit to the data. An example of this can be seen through the settings in Braisnfield strata (Figure 3). 

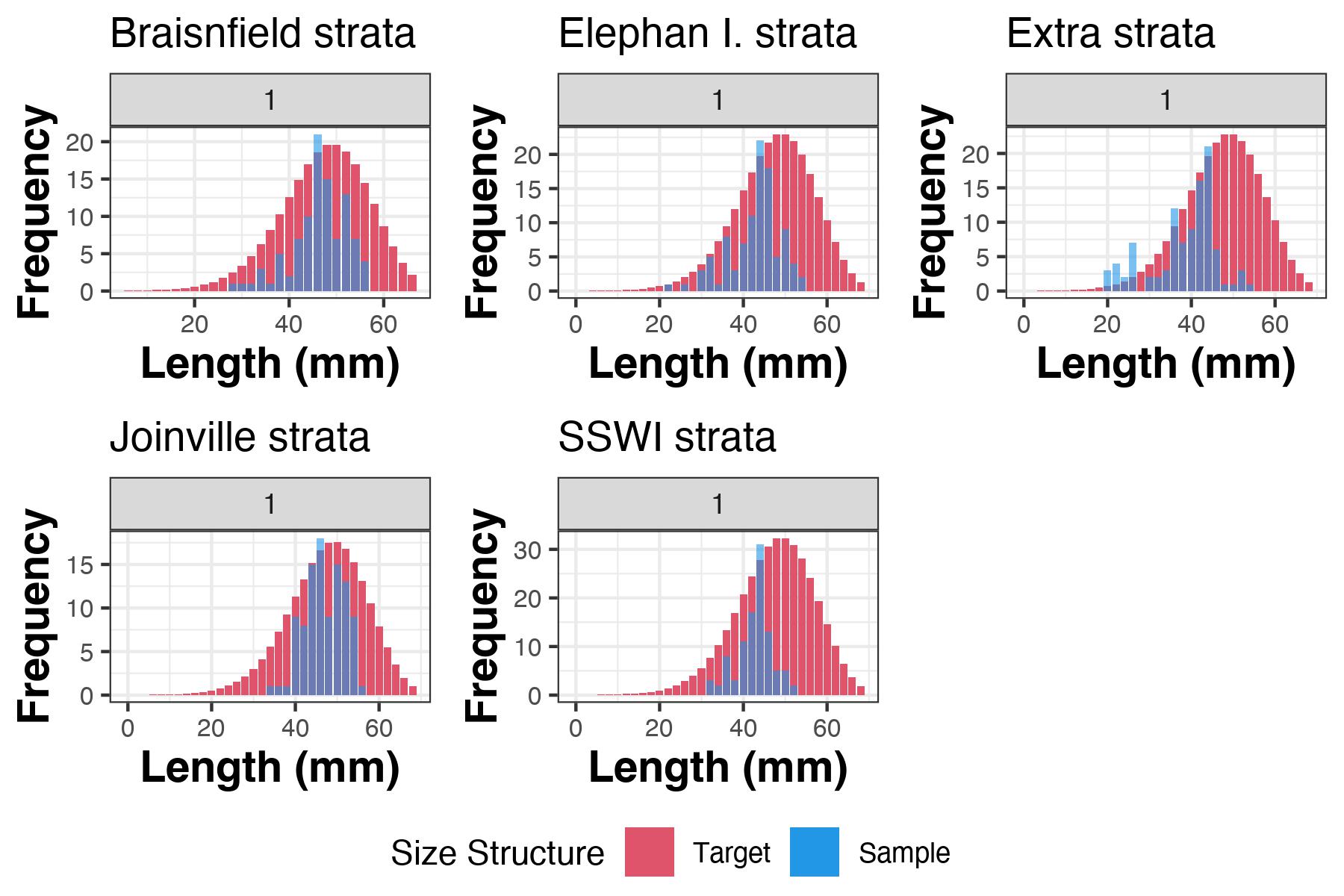
In all strata, the model adequately reproduces the observed sizes, except for the Joinville strata, possibly due to the few years of data (Figure 4).



Fit of the model to the data of lengths in Joinville strata

## 3.2. Comparing observed length data to target size structure

The first output is to visualize the difference between the observed accumulated size structure for each stratum and compare it with the expected size composition at a target SPR (75% SPR) through the life history parameters using the plotTarg function (Figure 5).



Difference between the observed accumulated size structure for each stratum related SPR objective

In Figure 5, we note that the furthest strata from the simulated composition are Elephant Island, Extra, and SSWI strata. This consideration is because we have different size structure in each strata.

With this differences, we proceed to search intrinsic productivity (Spawning Potential Ratio) by strata and by years. The LBSPR package uses a Kalman filter and the Rauch-Tung-Striebel smoother function (see FilterSmooth) to smooth out the multi-year estimates of SPR, F/M, and selectivity parameters.

For this, we extract SPR and variance from each slot in the fits models by strata (Table 2).

Estimates SPR by Strata

SPR

Variance

Year

SPR BS

SPR EI

SPR EX

SPR JO

SPR SSWI

Var BS

Var EI

Var EX

Var JO

Var SSWI

2001

0.339

0.223

NA

NA

0.194

0.025

0.017

NA

NA

0.003

2004

0.209

0.221

NA

NA

0.210

0.003

0.001

NA

NA

0.002

2005

0.325

NA

NA

NA

0.254

0.001

NA

NA

NA

0.000

2006

0.314

NA

0.152

NA

0.353

0.026

NA

0.008

NA

0.033

2007

0.372

0.090

0.069

NA

0.274

0.024

0.002

0.000

NA

0.017

2008

0.125

0.072

NA

NA

NA

0.002

0.001

NA

NA

NA

2009

0.296

0.319

NA

NA

0.234

0.003

0.011

NA

NA

0.001

2010

0.310

0.424

0.246

NA

0.457

0.006

0.027

0.019

NA

0.013

2011

0.579

NA

NA

NA

0.417

0.010

NA

NA

NA

0.014

2012

0.395

0.176

0.149

NA

0.362

0.061

0.006

0.001

NA

0.017

2013

0.193

0.182

0.128

NA

0.182

0.001

0.001

0.000

NA

0.003

2014

0.235

0.157

0.177

NA

0.294

0.001

0.000

0.001

NA

0.002

2015

0.247

0.385

0.182

NA

0.378

0.005

0.016

0.001

NA

0.023

2016

0.331

0.317

0.294

0.331

0.301

0.029

0.029

0.003

0.036

0.026

2017

0.211

1.000

0.190

0.254

0.262

0.008

0.000

0.015

0.002

0.007

2018

0.216

0.330

0.132

NA

0.291

0.002

0.034

0.001

NA

0.033

2019

0.331

0.421

0.125

0.345

0.367

0.010

0.018

0.002

0.023

0.002

2020

0.121

NA

0.085

NA

0.240

0.002

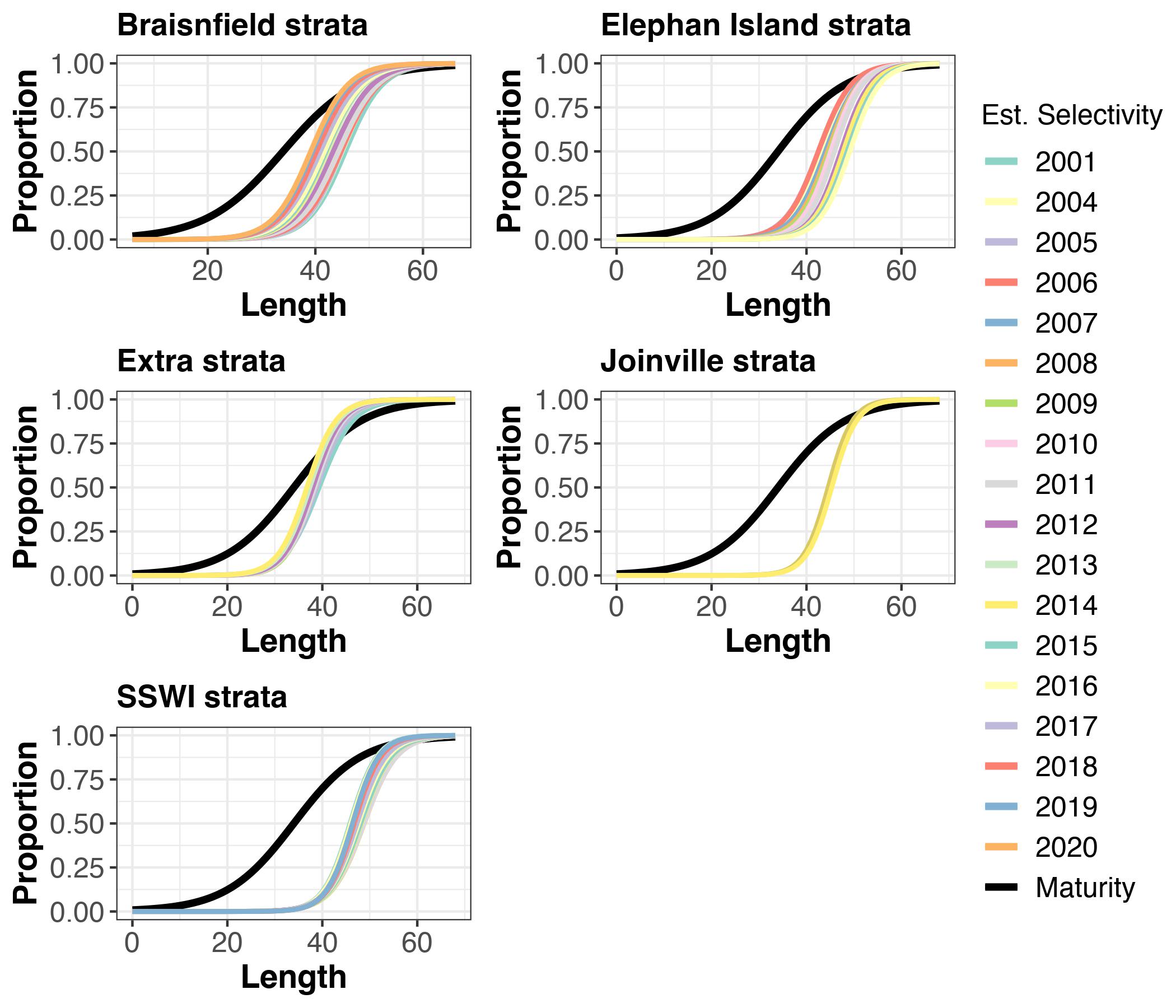
NA

0.001

NA

0.001

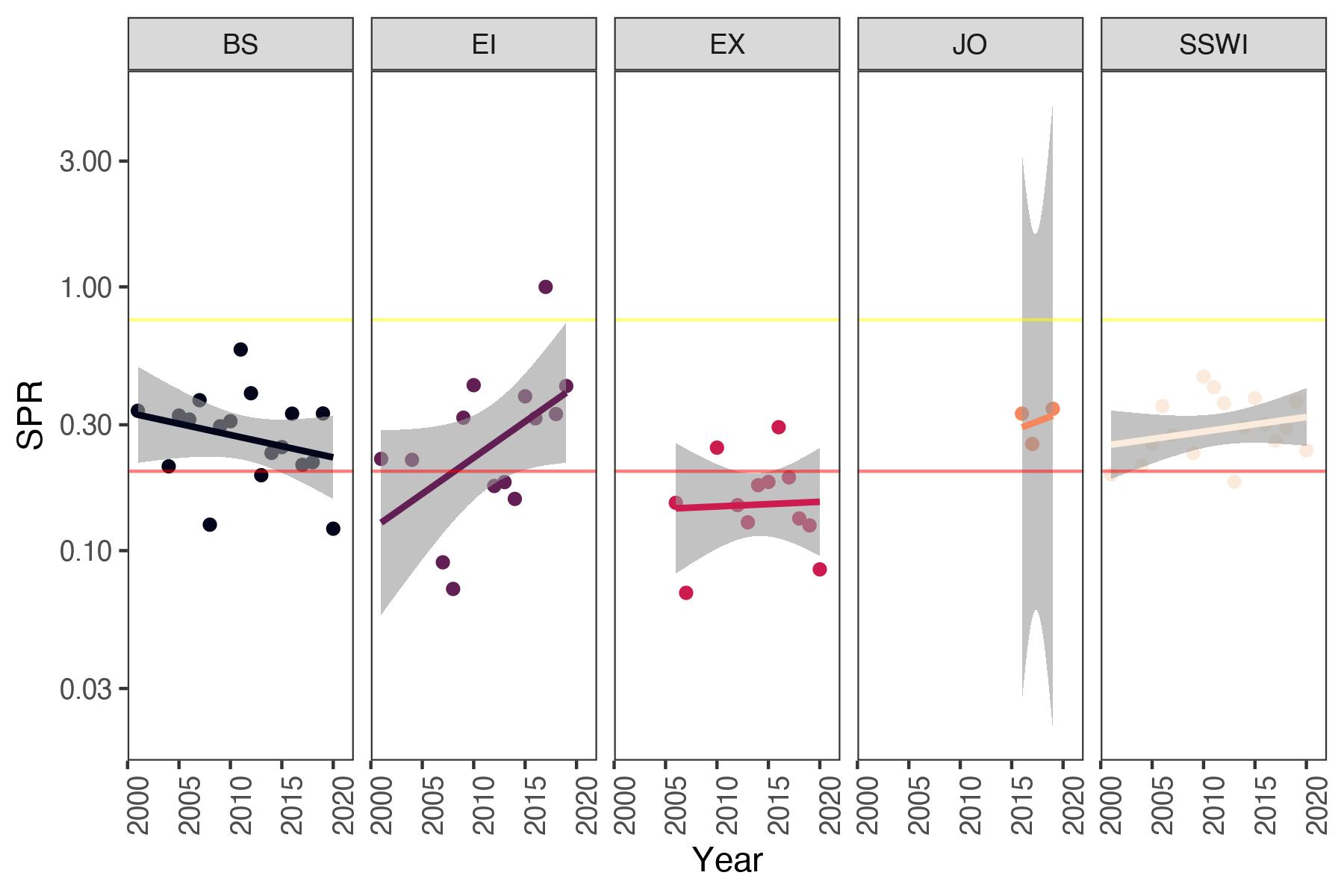
Similarly, the plotMat function can be used to show the specified maturity-at-length curve, and the estimated selectivity-at-length curve. This type of information does not give reference to the impact of the fishery on the population and its reproductive status. We can identify that one of the strata that has fewer mature individuals (more juveniles) is the Braisnfield stratum (Figure 6).



Maturity curves by strata

## 3.5. Comparing producivity between Strata

Finally, we identified the reproductive potential between years and strata for the krill population. It is possible to identify marked differences between stratas, where Brainsfield and Extra have low reproductive potential below the proposed management target of 75% for the last year at 0.121 and 0.085 respectively, and also below the limit reference point. This situation is due that these stratas concentrates a large proportion of immature individuals (juveniles) that are being exploited by the fishery, not allowing their reproductive cycles to end. In contrast, the Elephant Island stratum has higher SPR levels in recent years (0.421 in 2019) which is considered closer to a management objective. This situation is also due to the spatial structuring of krill, since in this stratum the proportion of adult individuals is greater than in all other strata. In figure 7, we can visualize the SPR trend between years and strata and also identify the references (yellow line =SPR Objective 75% and Red line= Limit SPR =20%).



Krill Intrinsic Productivity (SPR) by strata and by year

# 4. DISCUSION

Identifying the spatial and temporal changes of krill in the PA has been one of the biggest challenges in recent years. Krill is a key species in the Antarctic environment and understanding its population dynamics is a basic element to visualize the impacts on the functioning of the food web, conservation of the resource and management of the fishery. Our interest was to measure the reproductive potential of the species at fine scales of space and time in subarea 48.1, given that this area is where the fishery and resource have been concentrated for the last 20 years. Our results identify spatiotemporal variability of krill in different fishing management strata and, in turn, it was possible to propose Biological Reference Points based on the characteristics of the species, which in turn constitutes a recommendation for the current exploitation strategy carried out by CCMLAR. In this sense, they identify the historical fishing periods based on the reproductive potential and, in turn, an explicit spatial management is proposed based on these results.

## 4.1. Changes in Krill population structure

Changes in the dynamics and population structure of krill in the Antarctic Peninsula are manifested in various ways, such as distribution, biomass, recruitment, phenology, among others. The main drivers of these changes are associated with the changing behavior of the different environmental variables in the krill habitat ([Flores, Franeker, et al., 2012](#ref-Flores2012a); [Flores, Atkinson, et al., 2012](#ref-Flores2012); [Piñones & Fedorov, 2016](#ref-Pinones2016); [Saba et al., 2014](#ref-Saba2014); [Veytia et al., 2021](#ref-Veytia2021); [Walsh et al., 2020](#ref-Walsh2020)). Faced with this changing scenario, the intrinsic population productivity, that is, the reproductive potential of the species, has also undergone changes in the last decades ([Angus Atkinson et al., 2022](#ref-Atkinson2022); [McBride et al., 2021](#ref-McBride2021); [Perry, 2020](#ref-Perry2020)), both on the temporal scale as well as the spatial one. Similarly, the population structure of krill in the PA has been impacted by this type of environmental forcing ([Reiss et al., 2020](#ref-Reiss2020); [Siegel et al., 2013](#ref-Siegel2013))

## 4.2. Fishery data as population indicators

Krill in the PA have been harvested commercially since about 1970 and constitute the largest fishery in the Southern Ocean. The data on the fishing activity around krill have been systematically collected on board the fishing vessels through the SISO program, with which it has also been possible to identify changes in the population dynamics that have occurred during the last decade and throughout the area. of greater exploitation. Changes in the availability, distribution, and concentration, performance of the resource have been reflected in the data ([Atkinson et al., 2019](#ref-Atkinson2019a); [Krüger, 2019](#ref-Kruger2019); [Santa Cruz et al., 2018](#ref-SantaCruz2018), [2022](#ref-SantaCruz2022)). To identify changes in the intrinsic productivity of the krill population, we used one of the most representative pieces of information on the population dynamics of exploited marine resources that exist in this type of fisheries monitoring program, in this case, frequency data of catch size. [Hordyk et al., 2014; Froese et al., 2018; Prince et al., 2015; Rudd and Thorson, 2018; Ault et al., 2019; Chong et al., 2019; Pilling et al., 2008; Hordyk et al., 2015; Mildenberger et al., 2017]. ; Froese et al., 2018). This type of data is abundant and makes it possible to cover a large temporal and spatial scale, in this case, from 1980 to 2020 and throughout subarea 48.1 (Figure 1).

## 4.3. Temporal differences in intrinsic krill productivity

In temporal terms, the strata have differences in the reproductive potential and therefore in the intrinsic productivity of the population. During the last 20 years, the Elephant Island stratum has had an increase in reproductive potential, reaching levels of 56% by the year 2020. This is related to the changes in primary production levels that have occurred in this area. (appointment)

To demonstrate this, we analyzed more than 20 years of direct population indicators from the fishery data to identify intrinsic productivity changes on spatiotemporal scales of krill in the PA. These changes were quantitatively measured through reproductive potential using a novel method commonly used in world fisheries that considers the use of life history parameters, such as maturity, growth and growth rate, size structures, and simulations based on invariant parameters.

Changes in the spatial structuring of the krill population have been demonstrated in various ways. A. Atkinson et al. ([2009](#ref-Atkinson2009)); A. Atkinson et al. ([2008](#ref-Atkinson2008)) indicates that the population shows evident symptoms of contraction towards the southwest of the PA. This contraction of the distribution of the population has consequences for other phenomena such as productive yields that are manifested in fishing indicators as shown by Santa Cruz et al. ([2022](#ref-SantaCruz2022)); Santa Cruz et al. ([2018](#ref-SantaCruz2018)).

## 4.4. Spatial differences in intrinsic krill productivity

In this method we determined the differences between the simulated krill size structures based on their life history parameters ([Maschette et al., 2020](#ref-Maschette2020)) and those resulting from the fishery, which allows us to know the difference between the virginal reproductive potential and that currently caught. Strata such as and Extra are the most vulnerable in terms of their reproductive potential and this is due to the spatial structure of krill within subarea 48.1. Juvenile individuals, and therefore less reproductive potential, are located in these strata, which should be considered in a spatially explicit management scheme.

## 4.5. Anoher studies about Intrinsic productivity in krill

Mace & Sissenwine (1993) Review and meta-analysis of SPR reference points for teleosts: 20% SPR as limit reference points, & 35-40% SPR for MSY that have been internationally recognized in the US, USA, Australia, NZ etc. ([Goodyear, 1993](#ref-Goodyear1993); [Mace, 2001](#ref-Mace2001)).

and increasing the mean length of krill, suggesting that recruitment events are declining Perry ([2020](#ref-Perry2020))

# 5. CONCLUSION

* This study show the first analisys about intrinsic productivity of Antarctic krill (*Euphausia superba*) in Antarctic Peninsula, SubArea 48.1 through a quantitative method called LBSPR.
* It was possible to identify differences through time and space within one of the areas with the highest fishing activity on this resource.
* We propose reference points associated with the SPR to give management recommendations in the CCAMLR context.
* Considering these differences in an eventual spatially explicit management scheme could be beneficial to ensure sustainability of krill in subarea 48.1 and in the Antarctic peninsula..

# 5. SUPLEMENTARY INFORMATION

The methodology and data of this exercise can be found in the following link [Krill SPR](https://github.com/MauroMardones/LBSPR_Krill)

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