

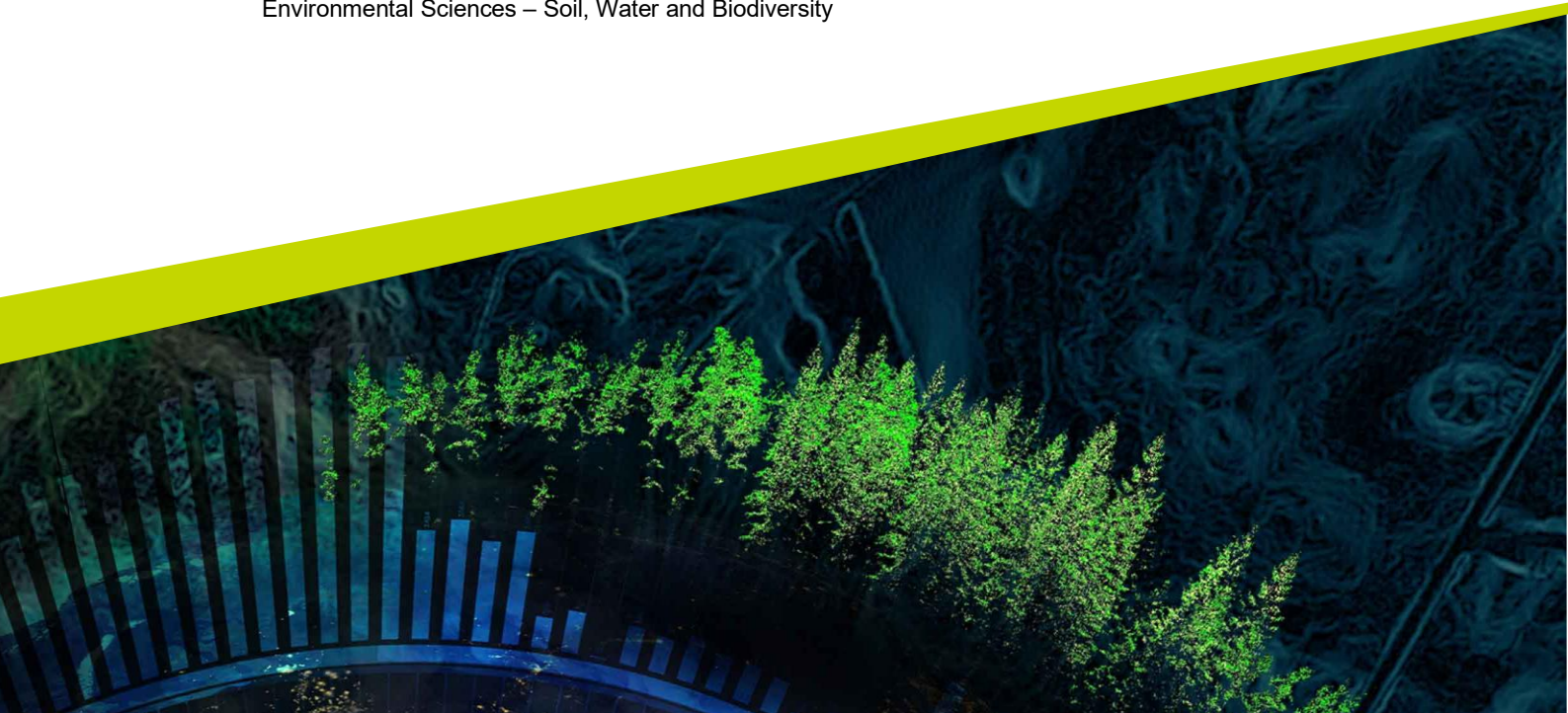


Exploring reconciliation pathways of commercial fisheries management and seabird conservation

An analysis on maximum sustainable yields of seabird prey stocks

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Swedish University of Agricultural Sciences, SLU
Department of Aquatic Resources
Environmental Sciences – Soil, Water and Biodiversity



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Abstract

Forage fish occupy a critical intermediate trophic position in marine ecosystems and they represent a key resource for seabird breeding success. Cury et al. (2011) illustrated consistently declining seabird breeding productivity below abundances of one third of maximum historical fish stock biomass ($B_{1/3}$), suggesting a quantitative conservation threshold. Commercial fisheries management, however, is predominantly guided by maximum sustainable yield (MSY) targets, and the compatibility of these targets with the $B_{1/3}$ threshold remains poorly examined at a fish stock scale. This study assessed the sustainability of spawning stock biomass management targets (SSB_{msy} RPs) relative to Cury's threshold ($B_{1/3}$ RP) for 70 globally distributed forage fish stocks from the RAM Legacy Stock Assessment Database. A Seabird Sustainability Index (SSI) was introduced as the ratio of SSB_{msy} RP to $B_{1/3}$ RP. Additionally, stock-wide biomass densities were derived using the GRSF Areas Database. The RP relationship, the effect of time series length, density translation adequacy, and the influence of qualitative stock variables were examined. The median SSI of 1.131 indicates that SSB_{msy} targets are on average sufficient to sustain reproductive success, yet 39% of stocks displayed an $SSI < 1$. However, only 46% of stocks recently exceeded their SSB_{msy} target, and 41% had recent SSB estimates below the $B_{1/3}$ RP, indicating prey abundances associated with reduced seabird breeding success. A potential influence of time series length on the SSI was observed, consistent with the shifting baseline syndrome, though explanatory power remained weak. Density medians ranged from 0.331 to 0.493 MT/km² and revealed a strong negative relationship with stock area size. Qualitative variables showed limited explanatory power, with observed patterns more reflective of management structures than ecological drivers. These findings highlight that current management targets are only partially aligned with seabird conservation needs and that consistent implementation of management targets would represent a meaningful improvement for both fisheries sustainability and seabird conservation. The $B_{1/3}$ RP is proposed as an additional conservation threshold within a broader ecosystem-based management framework, while limitations of single-species management and data constraints are discussed.

Keywords: Forage fish, seabird conservation, biomass at MSY, Seabird Sustainability Index, sustainable fisheries management, stock assessment

Table of contents

List of tables	5
List of figures	6
List of equations	8
Abbreviations	9
1. Introduction	10
2. Methodology	14
2.1 Data Extraction and Reorganization	14
2.2 Density Maps	17
2.3 Basic Calculations and Statistics	18
3. Results	21
3.1 Descriptive Statistics	21
3.2 Main Analysis.....	22
4. Discussion	27
4.1 Sustainability of Management Targets	27
4.2 Shifting Baseline Syndrome and the Effect of Time Series Length	28
4.3 Density Translation Using the GRSF Areas Database	30
4.4 Impact of Differences in Qualitative Data Variables.....	31
4.5 Management Implications.....	32
References	36
Popular science summary	46
Appendix 1	47
Appendix 2	61

List of tables

Table 1. Short Explanation of data variables.....	16
Table 2. Summary statistics of quantitative variables.	23
Table 3. Parameters values of all fitted LMs of the main analysis.....	23
Table A 1. Taxonomic overview.....	47
Table A 2. Statistical overview of LMs on RP relationship, including recent and median SSB	50
Table A 3. Quartiles of TS start and end.....	51
Table A 4. Statistical overview of SSI ANOVAs	53
Table A 5. Statistical overview of ANOVAs on density variabels for 'region'	54
Table A 6. Statistical overview of ANOVAs on density variabels for 'taxa'	56
Table A 7. Statistical overview of ANOVAs on density variabels for 'species specificity'	58
Table A 8. Statistical overview of ANOVAs on density variabels for 'typology'	59

List of figures

Figure 1. Example of density area compilation in the mediterranean sea using GRSF area polygons and the high-resolution shoreline shapefile.	17
Figure 2. Illustration of the Seabird Sustainability Index (SSI) for two example stocks. The upper left area shows the log (SSBmsy RP) plotted against the log (B1/3 RP); the dashed 1:1 line indicates SSI = 1, with stocks above the line having SSI < 1 and stocks below having SSI > 1. The lower plots show the SSB-TS (MT) for SARDMEDGSA17-18 (left) and HERR4RFA (right), with horizontal dashed lines indicating the SSBmsy RP (orange) and B1/3 RP (green).....	19
Figure 3. Global Map of analysed regions according to the RAM Legacy Database and associated forage fish species. Picture sources in reference list.	21
Figure 4. Histogram of SSI distribution across stocks with a median of 1.131 (mean = 1.558).	22
Figure 5. LM of log (SSBmsy RP) and log (B 1/3 RP). Dashed line displays 1:1 relationship.....	22
Figure 6. Overview of stock TS length and range. Each horizontal bar is representing one stock TS with the year of max. SSB displayed as the year of B1/3 RP. The vertical dashed line marks the median year of B1/3 RP (1995), and the colour grouping displays the region of the stocks.	24
Figure 7. LMs for log (B1/3 RP) and TS length and log (SSI) and TS length.....	24
Figure 8. Histograms of stock density distribution across variables.	25
Figure 9. LMs of log (density variables) and log (area size)	26
Figure 10. ANOVA on differences in log (SSI) associated with taxa	26
Figure 11. Overview of theoretical stock sustainability, recent stock status and differences in stocks that appear to be sustainable for seabird conservation needs.....	27
Figure A 1. Distribution of analysis data in qualitative variables.....	48
Figure A 2. Overview of analysed SSB-TS and associated RPs.....	49
Figure A 3. Histogram and QQ-Plot of residual distribution of RP relationship.....	50
Figure A 4. LMs of RPs with recent and median SSB	50
Figure A 5. Boxplot TS start and end distribution	51
Figure A 6. Histogram on TS length distribution.....	51
Figure A 7. Histogram on RP Year distribution.....	51

Figure A 8. Boxplot RP year distribution	51
Figure A 9. LMs of log (SSB _{msy} RP) and untransformed SSI with TS length	51
Figure A 10. Histogram and QQ-Plot of residual distribution of TS length.....	52
Figure A 11. Histogram and QQ-Plot of residual distribution of density ~ area relationship	52
Figure A 12. ANOVA on assessment method and Category for SSI.....	53
Figure A 13. ANOVA on Order and Family for SSI.....	53
Figure A 14. ANOVA on RP derivation method for SSI	53
Figure A 15. ANOVA on Region for SSI.....	54
Figure A 16. ANOVA on log (density SSB _{msy}) for region.....	54
Figure A 17. ANOVA on log (density B _{1/3} RP) for region	55
Figure A 18. ANOVA on log (recent density) for region	55
Figure A 19. ANOVA on log (median SSB density) for region	55
Figure A 20. ANOVA on log (density SSB _{msy} RP) for taxa.....	56
Figure A 21. ANOVA on log (recent density) for taxa	57
Figure A 22. ANOVA on log (density B _{1/3} RP) for taxa.....	57
Figure A 23. ANOVAs on density variables for species specificity.....	58
Figure A 24. ANOVAs on density variable for typology	59
Figure A 25. ANOVA on Area size for typology.....	60

List of equations

- Equation 1. Seabird Sustainability Index (SSI) computed as the ratio of stock specific SSB_{msy} RP and Cury's $B_{1/3}$ threshold (1/3 of maximum historical Biomass). ... 18
- Equation 2. Density computation of SSB (MT/km²) by dividing stock specific SSB variables with the associated stock area. 19

Abbreviations

Abbreviation	Description
$B_{1/3}$	Fish biomass at one third of the historical maximum sensu Cury et al. (2011)
B_{lim}	Fish biomass limit under which there is a risk of fish recruitment impairment
$(SS)B_{msy}$	Spawning stock biomass corresponding to maximum sustainable yield
B_{mgt}	Fish biomass corresponding to a management target
B_{pa}	Fish biomass corresponding to a precautionary approach, typically lower than B_{msy}
$B_{trigger}$	Biomass level corresponding to management implications, typically lower than B_{msy}
dvmb	Derived reference point value according to Appendix B (RAM Legacy Stock Assessment Database 2024b)
EST	Estimate
GIS	Geographic Information System
GRSF	Global Record of Stocks and Fisheries
IQR	Interquartile Range
LM	Linear Regression Model
MSY	Maximum Sustainable Yield
MT	Metric Ton
Pr	Proxy
RMSE	Root Mean Square Error
RP	Reference Point
SSB	Spawning Stock Biomass
SSI	Seabird Sustainability Index
TB	Total Biomass
TS	Time series

1. Introduction

Fish resource competition of commercial forage fish fisheries and marine predators (seabirds, large piscivorous fish and marine mammals) have been of long concern and effort has been made over the last decades to quantify the extends and possible trade-offs e.g. (Karpouzi et al. 2007; Engelhard et al. 2014; Hilborn et al. 2017; Grémillet et al. 2018; Hansson et al. 2018; Jessopp et al. 2025). Even though fishing mortality has decreased over the last decades it often remains above sustainable levels (Pauly & Zeller 2016; Winker et al. 2026). The main threats for seabirds at sea arise from ongoing competition, bycatch and discards (Croxall et al. 2012; Dias et al. 2019; Votier et al. 2023) and the declining productivity in seabird populations indicates further deterioration in epipelagic food webs, displaying varying responses across different ecosystems (Killeen et al. 2025; Sydeman et al. n.d.).

Forage fish are small, primarily planktivorous fish mainly inhabiting the epipelagic zone (0-200 m) of marine ecosystems around the globe (Sutton 2013). They are of significant importance in epipelagic food-webs as they display an intermediate trophic level (2.6 – 3.4) depending on the type and complexity of ecosystem they occupy (Pauly & Christensen 1995; Pikitch et al. 2014). In many marine ecosystems their trophic level is occupied by only a few or a single species, described as a “wasp-waist” structure, with potentially large effects on higher and lower trophic levels (Bakun 2006). Furthermore, forage fish display a high level of natural variability and environmental productivity regimes impact stock recruitment, while a rather weak relationship between spawning stock biomass (SSB) and recruitment is suggested (Hilborn et al. 2017). This natural variability, also referred to as a “boom-bust” dynamic, is highly relevant for ecosystem management as it influences predator-prey dynamics (Bakun 2006). While some forage fish species also prey on smaller forage fish and juvenile predatory fish in mature live stages (Bakun 2006), they may compete with juvenile live stages of piscivorous fish for zooplankton resources (Engelhard et al. 2014). By feeding on zooplankton they accumulate biomass that is transferred to higher trophic levels including top predators like seabirds, large piscivorous fish and marine mammals (Pauly & Christensen 1995).

Seabird populations are dependent on forage fish availability and are heavily affected by resource depletion (e.g. Lewis et al. 2001; Engelhard et al. 2014; Piatt et al. 2020; Arimitsu et al. 2021; Schoen et al. 2024). Breeding success was shown to be connected to a forage fish abundance threshold averaging in general around one third of historical maximum fish stock biomass or density estimates (Cury et al. 2011). Prey abundances below the threshold consistently led to reduced and more variable productivity, derived from 7 ecosystems and 14 bird species. Cury et al. (2011) suggested the one third threshold as a precautionary

guideline to sustain seabird populations and consequently healthy predator-prey dynamics. Furthermore, the spatial distribution of prey fish is crucial for seabirds, in particular during the breeding season, since foraging activities around the colonies are limited by bio-energetic mechanisms dependent on species specific physiology and linked forage ecology (Regular et al. 2014; Fayet et al. 2021; Hentati-Sundberg et al. 2021). Prey resource depletion around seabird colonies during the breeding season, a so-called Ashmole's halo, is common and well documented in scientific literature (Birt et al. 1987; Elliott et al. 2009; Hentati-Sundberg et al. 2021). It intensifies resource competition while simultaneously reducing forage efficiency, resulting in additional pressure on seabirds during the breeding season, which can finally lead to chick abandonment. This highlights the importance of fine-scale fisheries management around seabird colonies (Hentati-Sundberg et al. 2021), particularly if prey biomass removal is significantly spatiotemporally correlated with fishing effort (Jessopp et al. 2025).

International law legally obligates states to ensure that harvested fish stocks are maintained at or restored to levels capable of producing maximum sustainable yield (MSY) (United Nations 1982). Commercial fisheries exploit forage fish for fish oil and fish meal production, which is used in intensive farming systems e.g. aquaculture, and to a smaller extent for human consumption (Alder et al. 2008). Pikitch et al. (2014) illustrated that forage fish do not only have a direct commercial value for fisheries but a large indirect effect by sustaining commercial fisheries on predatory species. Besides their relevance for ecosystems, this might be a major reason for their broad scientific assessment coverage, in particular in the global north (Ricard et al. 2012). It has been shown that compound effects of fisheries can have detrimental effects on forage fish stocks, increasing the risk of population collapse (Engelhard et al. 2014; Essington et al. 2015; Pinsky & Byler 2015), and therefore emphasizing the need for good management practices. The main management approach that is applied and has evolved over the last decades is focused on single species strategies, targeting MSY (Hilborn 2012; Fogarty 2014). MSY is a so-called biological reference point (RP), which is periodically reevaluated in benchmark sessions to display a fishery management target adapted to current knowledge (ICES & WKPELA 2017; Silvar-Viladomiu et al. 2022). It has been shown that scientifically assessed and managed stocks are on average healthier and exploited more sustainably than stocks where no assessment and associated management is realized (Hilborn et al. 2020). However, the shifting baseline syndrome (Pauly 1995; Soga & Gaston 2018) suggests that knowledge scarcity of unexploited stock states may cause degraded ecosystems to be treated as natural baselines, biasing assessments of sustainable exploitation thresholds. Furthermore, the lacking implementation and surrogate uses of management RPs such as B_{trigger} or B_{pa} by the International Council for the Exploration of the Sea (ICES) aggravates the rebuilding of fish stocks, since these RPs are on average

(median) only 61 % of B_{msy} (Winker et al. 2026) and therefore stock rebuilding and sustainable exploitation estimates may be too optimistic (Britten et al. 2021; Winker et al. 2026). Furthermore, overoptimistic recruitment and stock rebuilding bias in model performances for SSB estimates, continuously led to excessive MSY exploitation levels, compromising scientific advice, stock rebuilding and ecosystem health for larger catches (Froese et al. 2025). Nevertheless, it remains possible to rebuild fish stocks to B_{msy} levels, if strict management goals are implemented and executed (Winker et al. 2026).

As single-species management currently dominates fisheries management strategies (Fogarty 2014; Winker et al. 2026), the broad implementation of ecosystem-based fisheries management (EBFM) (Pikitch et al. 2004) and dynamic ocean management (Maxwell et al. 2015; Dunn et al. 2016) could benefit ecosystem recovery, health and resilience while simultaneously stabilizing fisheries efforts and yield on a sustainable level. This may be particularly important with accelerating climate change increasing pressure on forage fish populations (Engelhard et al. 2014; Pinsky & Byler 2015). A growing number of publications of environmental models (in Europe) increase our understanding of potential management impacts on structure and dynamics of ecosystems and may support the transition to a more holistic management approach (Keramidas et al. 2023). Froese et al. (2025) highlight the need to align harvest control rules (HRCs) with existing laws and regulations and drew a path on how to implement MSY and B_{msy} within a EBFM framework.

The objective of this project is to examine the scientific knowledge gap regarding the sustainability of forage fish fishery targets (B_{msy}) related to the formulated seabird conservation needs according to Cury et al. (2011). Additionally, stock wide target densities for both B_{msy} and Cury's threshold will be derived for a global fish stock dataset using the GRSF (Global Record of Stocks and Fisheries) Areas Database to translate SSB estimates into a unit directly relevant for seabird conservation. Therefore, the following research questions will be asked:

- What is the relationship between B_{msy} and Cury's one-third rule?
- To what biomass density (MT/km²) does B_{msy} and Cury's threshold translate for seabird prey stocks?

Based on the introduced topics and research questions the following hypotheses will be tested:

1. Current B_{msy} targets are sufficient to meet seabird needs according to Cury's one third rule.
2. The impact of time series length on the seabird sustainability index (SSI: see Methodology) is significant in the sense of describing the shifting baseline syndrome.

3. The GRSF area database can be safely used to translate biomass estimates into fish stock densities.
4. There is no significant difference in the quantitative variables (SSI, density) related to associated qualitative variables (e.g. taxa, assessment method, region. see Methodology: Simple calculations and statistics).

2. Methodology

The analysis of this project is mainly based on contents of the RAM Legacy Stock assessment database (RAM Legacy Stock Assessment Database 2024b; a) and the GRSF Areas Database (FIRMS GRSF Technical Working Group 2025). Its implementation included several steps of data extraction and reorganization, area compilation in ArcGIS Pro and statistical analysis (R). These steps will be elaborately presented hereafter.

In this analysis forage fish are defined as species whose fishery is described as forage fisheries in the RAM Legacy Database (RAM Legacy Stock Assessment Database 2024b). Other highly relevant seabird prey resources like Krill, Cephalopods and Myctophids (Karpouzi et al. 2007; Cherel et al. 2010; Olivar et al. 2019) are not considered in this analysis. Furthermore, the management target B_{msy} is hereafter explicitly referred to as SSB_{msy} .

2.1 Data Extraction and Reorganization

Before diving into the process, it is important to differentiate between two RAM Legacy Stock Assessment Database versions, being ‘asmt’ (assessment data only) (RAM Legacy Stock Assessment Database 2024b) and ‘mdl’ (model-fit) (RAM Legacy Stock Assessment Database 2024a) and how their contents were used in the analysis. While the ‘asmt’ version is the basis of this project and contains the assessment data on time series (TS) and assessment-based reference points (RP), the ‘mdl’ version includes generated data to fill in knowledge gaps and was only used for stocks with missing RPs. These have been estimated post-hoc with surplus production models (RAM Legacy Stock Assessment Database 2024a) and were extracted to increase the sample size of evaluable stocks. In the following, the ‘asmt’ version will be referred to as the RAM Legacy Database and the ‘mdl’ version as the ‘model-fit’ database. The data was extracted from the Excel version of the RAM Legacy Database.

The first step of data extraction included the filtering of the ‘Taxonomy’ - sheet of the RAM Legacy Database for the fishery type ‘Forage Fish’. It included two ‘Tax Groups’ (forage fish and carangids-mackerels) containing multiple taxa/species and an associated taxonomic serial number (tsn). The tsn was then used to filter the ‘Stock’ - sheet for the associated Stock IDs which were extracted with their supplementary data, including 163 of 1514 Stocks of the RAM Legacy Database. After filtering out ‘deprecated’ stocks, 145 Stocks with a ‘current’ assessment state were available for further investigation.

The Stock ID was used to search for Biomass-TS of associated stocks in the ‘timeseries.1’-sheet. The available TS were extracted and their TS-unit (‘Spawning Stock Biomass in metric tons’ (SSB-MT) or ‘Total Biomass in metric

tons' (TB-MT)) and the assessment ID was noted. For 85 Stocks a TS with SSB-MT equal or longer than 11 years was available, satisfying the detection limit for maximum historical biomass (Cury et al. 2011). Since a decent sample size of SSB-TS was available, TB-TS were excluded from further analysis.

Subsequently the 'Stock Summary Files' (taxGroup) of the RAM Legacy Database were searched for RPs of SSB_{msy} for the extracted stocks. Multiple other stock RPs for management (SSB_{mgt} -MT, SSB_{lim} -MT, TB_{msy} -MT, TB_{lim} -MT) were noted to get an overview of overall RP availability and create options for further analysis, since the sample size for SSB_{msy} -RPs was not predictable. However, the final analysis only included SSB-TS and associated SSB_{msy} -RPs.

For the best representation of SSB_{msy} -RPs, only direct assessment (SSB_{msy} -MT) and proxy values (SSB_{msy} -pr-MT) were extracted from the RAM Legacy Database. They were available for 28 Stocks (six proxy values), and it was noted from which assessment year the RPs originated from. The search for RPs was repeated in the 'model-fit' database and RPs in 'EST'-form (performed surplus production model fit to generate the supplemented RP) and 'dvmb' form (ICES Stocks with SSB_{lim} -MT \rightarrow SSB_{msy} -dvmb-MT = SSB_{lim} -MT * 2) (RAM Legacy Stock Assessment Database 2024b). Estimates were available for 24 Stocks, and 18 'dvmb'-RPs could be extracted, complementing the stock sample size with both SSB-TS and SSB_{msy} -RP availability to a total of 70 fish stocks.

Additional stock assessment variables (assessment method (model), RP derivation method, assessment category, assessor) were added by filtering the stock-TS associated 'assessment ID' in the 'assessment'-sheet of the RAM Legacy Database to find the 'assessment method'. Assessment based RPs that were derived from a different assessment (other year) than the TS, were assigned the model their assessment was based on as the 'RP derivation method'. Otherwise, they were assigned the same model as their TS or one of the complementing RP derivation methods (Pr, EST, dvmb). The variable of 'assessment category' included different model types (Biomass dynamics model, Integrated Analysis, Statistical catch at age model, Statistical catch at length model, Virtual Population Analysis, Unknown) to which the 'assessment method' was assigned to, according to the 'assessment methods'-sheet of the RAM Legacy Database. In case the model of the 'RP derivation method' for an assessment-based RP differed from the 'assessment method' of the TS the 'assessment category' displayed the model type of the 'RP derivation method', since RP was the variable of particular interest in this analysis.

Multiple ICES stocks displayed an 'Unknown' assessment method. These stocks were reviewed (ICES 2026d) and classified according to information in the ICES advice (ICES 2018; 2021b; c; d; 2023a; b; c; e; d) or benchmark / working group reports (ICES & WKARCT 2015; ICES & WKPELA 2016; 2017; ICES &

WGWISE 2019; ICES & HAWG 2020; 2023; 2024; ICES & WGHANSA 2020; 2021; ICES & WGBFAS 2023) .

The ‘assessment ID’ was finally used to filter the ‘assessor’-sheet of the RAM Legacy Database and extract the associated ‘assessor ID’ including the assessor institution (‘assessor full’) and general management institution (‘management’) of the analysed stocks.

The summary of data variables extracted from the RAM Legacy Database and the ‘model-fit’ database, which were included in the analysis, are displayed in Table 1.

Table 1. Short Explanation of data variables

Variable	Explanation
Stock ID	Stock specific ID
Species name	Commonly used species name
Scientific name	Taxa or scientific species name
Order and Family	Higher order of taxonomic group
Assessment ID	Assessment specific ID
Region	Fisheries associated countries or regions
Assessor ID	Assessment institution or working group
Assessor full	Full name of assessor
Management	Superior management institution
Assessment method	Specific model used in assessment
Assessment Category	Model category used in assessment
RP derivation method	Model or calculation to derive reference point estimate
SSB – TS	Time series of spawning stock biomass
TS length	Length of time series in years
SSB _{msy} -RP	Reference point for spawning stock biomass with MSY
Year of SSB _{msy} -RP	Year of assessment associated with SSB _{msy} -RP
GRSF area ID	Area specific ID
Typology	Type of area use in fisheries management
Species specific	Yes or no
GRSF area type	Specific type of area

2.2 Density Maps

To achieve a transparent translation of fish stock biomass estimates into a relevant density unit for seabird conservation (MT/km²), ArcGIS Pro was used to visualize and calculate the size of the associated stock areas from the GRSF Area Database (FIRMS GRSF Technical Working Group 2025), according to their ‘GRSF Area ID’ embedded in the RAM Legacy Database.

The shapefile ‘main_grsf_areas’ (FIRMS GRSF Technical Working Group 2025) was uploaded into the geodatabase. The spatial reference was checked and WGS 1984 (WKID: 4326) chosen as the geographic coordinate system for this project. Following, the function ‘export features’ was used to extract the relevant areas, filtered by the ‘GRSF area ID’, into a created feature class. Since many areas expanded onto the continental area of the associated countries it was necessary to erase these parts to be able to calculate the coastal / marine expansion of the stock areas. Therefore, the high-resolution shoreline shapefile from the GSHHG Database (Global Self-consistent, Hierarchical, High-resolution Geography Database) (Wessel & Smith 2026) was added to the projects table of content. High-resolution was chosen over full resolution due to the global application in this project (Wessel & Smith 1996). Then the ‘Pairwise Erase’ function was used to erase overlapping continental area from the GRSF areas and the shoreline shapefile.

Since some stocks are assessed over multiple GRSF areas, single Stock ID feature classes were generated and their associated GRSF area(s) exported from the generated feature class. If a stock consisted of multiple areas, they were merged using the ‘Dissolve’ function to avoid overlap and create a single shapefile and area for the specific stock. ‘Pairwise Dissolve’ and ‘Dissolve’ were both tested on multiple areas, created similar results and the latter was used further on. Figure 1 illustrates the density map compilation for stocks (ANCHMEDGSA, SARDMEDGSA) in the Mediterranean Sea with the high-

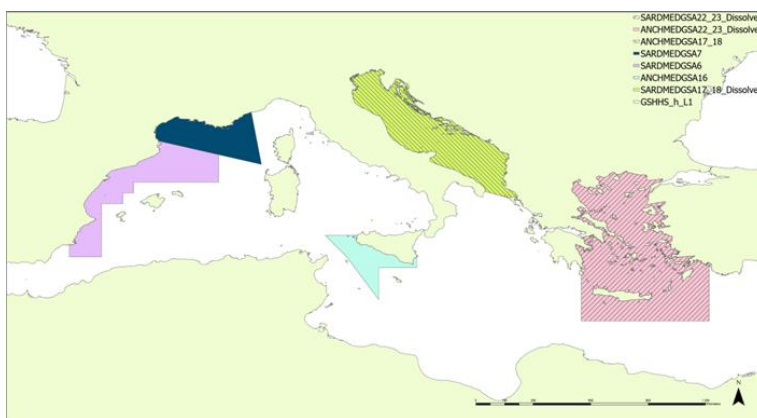


Figure 1. Example of density area compilation in the mediterranean sea using GRSF area polygons and the high-resolution shoreline shapefile.

resolution shoreline (GSHHS_h_L1). To simplify the stock area calculation the single stock feature classes were copied into a summarizing feature class, containing all stock areas, using the ‘Merge’ function.

Fields for ‘Area km²’, ‘Mean latitude’ and ‘Mean longitude’ were then created and calculated using the ‘calculate geometry’ function for ‘Area (geodesic)’ in km² for stock areas and ‘centroid x and y’ in decimal degrees for their mean latitude and longitude. Additionally, it was noted if the area was ‘species specific’, as well as associated ‘typology’ (assessment area, biological area, management area, statistical area) and if available a specific ‘GRSF area type’ (Table 1).

Three GRSF areas from Japan (jpn_faj:MAS_PJPN; jpn_faj:JJM_PJPN; jpn_faj:CHP_PJPN) turned out to be fully on land and the associated stocks were excluded from the density analysis. Some other stocks (JANCHOPJPN; RHERRTSST; HERRWCVANI) displayed rather small areas (<2000 km²) and were filtered according to their density values (see: Basic calculations and statistics) for the statistical analysis. These errors were assumed to be projection errors occurring in the compilation of the GRSF area database.

2.3 Basic Calculations and Statistics

The sustainability of forage fish fisheries management targets in relation to seabird conservation needs was assessed by comparing the biomass of target stock sizes SSB_{msy} RP with the $B_{1/3}$ threshold according to Cury et al. (2011). The $B_{1/3}$ threshold was derived by multiplying the maximum historical SSB of each individual stock TS by 1/3 and is hereafter referred to as the $B_{1/3}$ RP. To quantify the relationship between the two RPs, the Seabird Sustainability Index (SSI) was introduced, expressing their ratio (Equation 1).

Equation 1. Seabird Sustainability Index (SSI) computed as the ratio of stock specific SSB_{msy} RP and Cury’s $B_{1/3}$ threshold (1/3 of maximum historical Biomass).

$$SSI = \frac{SSB_{msy} RP}{max. historical SSB \times \frac{1}{3}}$$

An $SSI = 1$ displays a SSB_{msy} management target that is congruent with the minimum SSB for sustainable seabird breeding success. An $SSI > 1$ indicates a target SSB with sufficient prey availability for good breeding conditions, while $SSI < 1$ indicates a management target with a poor prey abundance for seabirds, resulting in challenging conditions with increased variance and general lower breeding success (Cury et al. 2011). Two example stocks are displayed in Figure 2, one with an $SSI < 1$ (HERR4RFA) and one with an $SSI > 1$ (SARDMEDGSA 17-18). Their SSI is visually displayed in a scatterplot of $\log(SSB_{msy} RP)$ against $\log(B_{1/3} RP)$ around the 1:1 line indicating $SSI = 1$. The underlying relationship of $SSB_{msy} RP$ and $B_{1/3} RP$ in the TS plots of each stock is illustrated as the vertical distance of the horizontal reference lines (Figure 2). As a reference to the two RP

variables, the ‘median SSB’ and the most ‘recent SSB’ of each stock TS was noted.

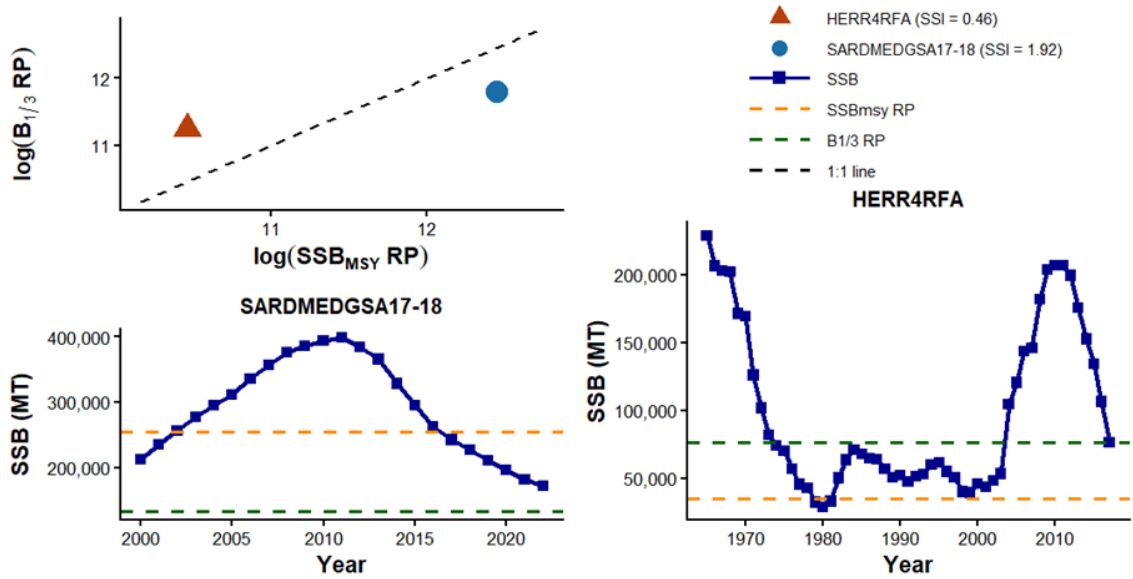


Figure 2. Illustration of the Seabird Sustainability Index (SSI) for two example stocks. The upper left area shows the $\log(\text{SSB}_{\text{msy}} \text{ RP})$ plotted against the $\log(B_{1/3} \text{ RP})$; the dashed 1:1 line indicates $\text{SSI} = 1$, with stocks above the line having $\text{SSI} < 1$ and stocks below having $\text{SSI} > 1$. The lower plots show the SSB-TS (MT) for SARDMEDGSA17-18 (left) and HERR4RFA (right), with horizontal dashed lines indicating the $\text{SSB}_{\text{msy}} \text{ RP}$ (orange) and $B_{1/3} \text{ RP}$ (green).

Next, the translation of SSB estimates into a density unit directly relevant for seabird conservation was realized. Stock densities were calculated by dividing the different SSB variables ($\text{SSB}_{\text{msy}} \text{ RP}$, $B_{1/3} \text{ RP}$, median SSB, recent SSB) with the derived stock areas (Equation 2).

Equation 2. Density computation of SSB (MT/km^2) by dividing stock specific SSB variables with the associated stock area.

$$\text{Density} = \frac{\text{SSB parameter}}{\text{stock area}} (\text{MT}/\text{km}^2)$$

All extracted and calculated values were transferred to a ‘Calculation’ Excel-file, that contains the summarized data. The TS and most variables of the single stocks were presented in stock sheets and a summary-sheet, displayed an overview including all variables despite the TS.

The statistical analysis was performed in R (version 4.4.3). Prior to the analysis, non-finite density variables were replaced by NA. Furthermore, all density variables were set to NA if ‘median SSB density’ was $\geq 10 \text{ MT}/\text{km}^2$ to remove biologically implausible outliers, which are most likely related to the before mentioned projection errors in the GRSF database. Since only single

species SSB was considered in this analysis, a cap at 10 MT/km² of median SSB of a multidecadal TS was assumed to be reasonable and conservative as an ecological density exclusion baseline. It is well above average and max. densities for Anchovy TB at the coast of Japan (1,55-4,86 t/km²; Murase et al. 2012) and clearly below multi-species TB in a tropical seascape in the Chagos Archipelago (32,45-279 t/km²; Letessier et al. 2022), excluding local and temporal peak densities.

Summary statistics (N, mean, median, standard deviation, quartiles, inter quartile range (IQR), lower and upper whisker at 1,5 x IQR, minimum, maximum, N outliers) were computed for all key quantitative variables, including TS length, RP years, SSI, area size and the four density variables. Data distributions were visualised using histograms and boxplots.

Subsequently, linear regression models (LMs) were fitted with natural log-transformed variables, despite the variable of 'TS length', and the model diagnostics followed the same approach for all models. Three groups of LMs were fitted: First to assess the RP relationship, with SSB_{msy} RP as the explanatory variable and B_{1/3} RP as the response variable. Furthermore, 'median SSB' and 'recent SSB' were separately fitted as explanatory variables for both RPs. Second, to quantify the effect of 'TS length' on the RPs individually and on their ratio 'SSI'. And third, to explore the effect of 'area size' on the four density variables.

Model performance was evaluated with the parameters R, R², adjusted R², RMSE, the slope with its standard error (SE) and 95% confidence interval, F-statistic and significance threshold at p < 0.05. Residual normality was assessed visually through residual histograms, quantile-quantile (QQ) plots and an additional Shapiro-Wilk normality test with significance threshold p < 0.05 (Results on residual normality: see Appendix 1).

To identify differences in the quantitative variables (SSI, density) across qualitative groups one-way ANOVAs were performed. If the ANOVA indicated significant (p < 0.05) variation between groups a post-hoc pairwise comparison was performed with 'Tukey's Honest Significant Difference' (HSD) test at p < 0.05. The SSI was tested for seven qualitative variables (taxa, family, order, assessment method, RP deviation method, assessment category, region), while each of the density variables was tested for variations in 'region', 'taxa', 'typology' and 'species specificity'. Finally, an ANOVA was performed to test for differences of 'area size' in 'typology'.

3. Results

3.1 Descriptive Statistics

The analysed dataset comprised 70 Stocks from around the globe covering 12 ‘regions’ with a majority of stocks distributed across Europe, followed by Japan, South America and Canada, the United States and a few stocks from Southern Africa and Australia (Figure 3). The stocks comprised 24 taxa from seven families and three taxonomic orders. Clupeiformes (n = 48) and Perciformes (n = 20) made up 68 Stocks, while only two stocks of Osmeriformes were included in the analysis. Clupeidae, Engraulidae, Scombridae and Carangidae were the most represented families and *Clupea harengus* (Herring) was the most represented taxa covering 20 % (n = 14) of assessed stocks (Table A1).

An overview of the stock ‘regions’ according to the RAM Legacy Database and the associated taxa analysed is given in figure 3. In Appendix 1 there is a detailed overview of the qualitative variable distribution across stocks (Figure A1) and an illustration of all TS including their RPs (Figure A2).

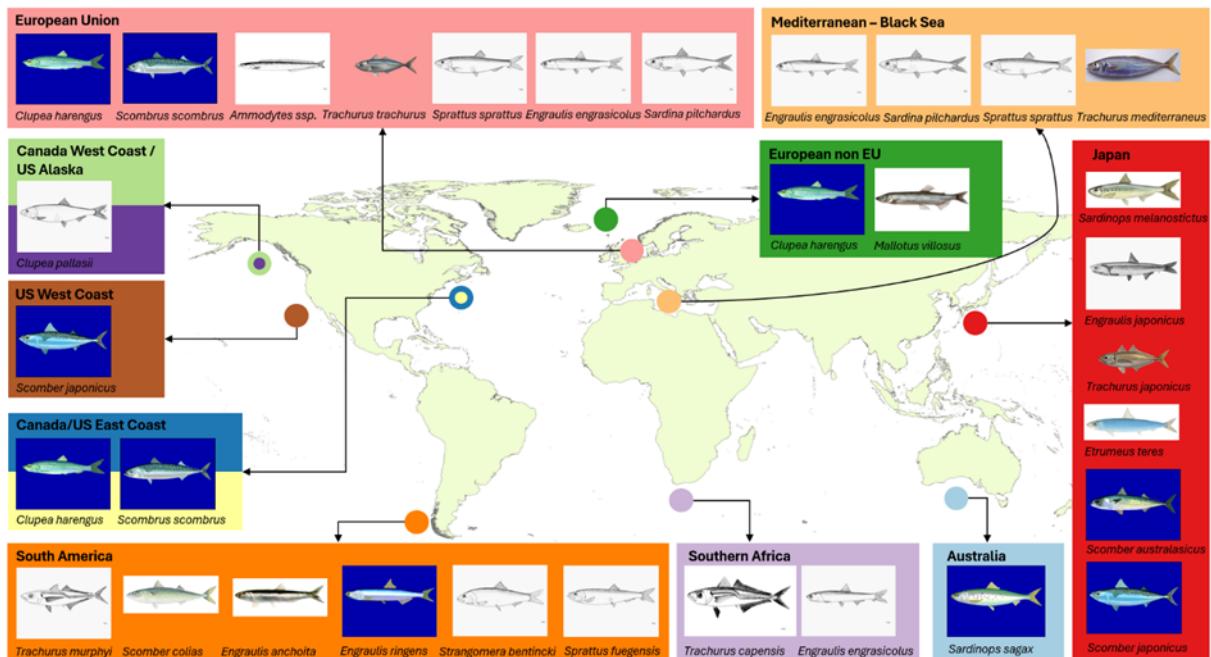


Figure 3. Global map of analysed regions according to the RAM Legacy Database and associated forage fish species. Copyright references see Appendix 2.

3.2 Main Analysis

In the main analysis the SSI was computed for all stocks and the relationship of SSB_{msy} RP and the $B_{1/3}$ RP was examined. The median SSI was 1.131 (mean = 1.558), indicating a right skewed distribution driven by outliers in the range of 3.3 – 8.6 (Figure 4, Table 2). Most stocks showed an SSI around or slightly below 1, reflected by the IQR of 0.898 (Q1 = 0.873, Q3 = 1.771) with a denser value spread below the median than above. Overall, 61 % (n = 43) of stocks displayed an $SSI \geq 1$ (Figure 11).

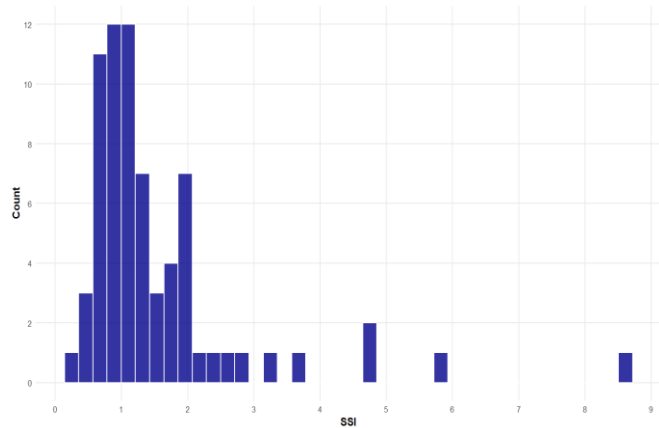


Figure 4. Histogram of SSI distribution across stocks.

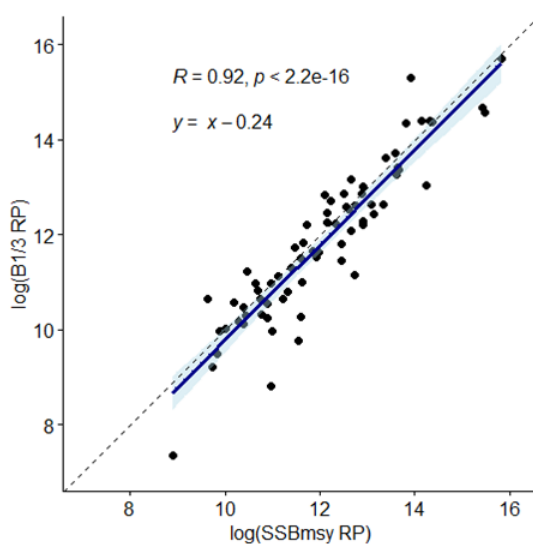


Figure 5. LM of $\log(SSB_{msy} RP)$ and $\log(B_{1/3} RP)$. Dashed line displays 1:1 relationship.

The log transformed LM of SSB_{msy} RP and $B_{1/3}$ RP displayed a strong positive and significant correlation ($R = 0.92$, $p < 0.0001$) (Figure 5, Table 3). The linear model explained 85 % of variation in the response variable ($R^2 = 0.850$, $RMSE = 0.625$). The slope equalled almost 1 with a small SE (0.051) and was best described as: $y = x - 0.24$. This is consistent with the SSI distribution indicating that the $B_{1/3}$ RP is in general slightly lower than the SSB_{msy} RP across stocks.

Next, the analysis on the impact of TS length on the SSI was performed. An overview of the length and time range of all TS is displayed in Figure 6, including the year of each $B_{1/3}$ RP (year of max. SSB), the median $B_{1/3}$ RP year (dashed line) and the median range and length (grey box). The stocks are ordered by their first assessment year and display a ‘region’ - colour to which they are associated to.

Table 2. Summary statistics of quantitative variables.

	TS Length	Year SSB _{msy} RP	Year B _{1/3} RP	SSI	SSB _{msy} RP (MT/km ²)	B _{1/3} RP (MT/km ²)	Recent SSB (MT/km ²)	Median SSB (MT/km ²)	Area km ²
N	70	70	70	70	64	64	64	64	64
Median	38	2019	1995	1,131	0,486	0,331	0,38	0,493	368085
Mean	40,43	2018,47	1994,34	1,558	1,267	1,178	1,279	1,181	1663266
1 st Qu.	30	2018	1986	0,873	0,148	0,129	0,116	0,122	109824
3 rd Qu.	48,75	2021	2006	1,771	1,522	1,502	1,239	1,585	1860336
IQR	18,75	3	20	0,898	1,374	1,373	1,124	1,463	1750511
SD	15,19	3,88	18,01	1,339	1,838	1,889	2,519	1,71	4077504
Lower Whisker	17	2014	1958	0,246	0,005	0,005	0,007	0,007	3396
Upper Whisker	77	2024	2022	2,812	3,51	3,426	2,342	2,504	3645677
Min	17	2003	1947	0,246	0,005	0,005	0,007	0,007	3396
Max	77	2024	2022	8,610	9,448	11,114	14,714	8,136	30736802
N (Outliers)	-	6	3	6	6	5	6	5	n.a.

Table 3. Parameters values of all fitted LMs of the main analysis

Model	N	Intercept	Slope	Slope SE	CI low	CI up	R ²	Adj R ²	F stats	p value	RMSE	Shapiro-Wilk test
log(B _{1/3} RP) ~ log(SSB _{msy} RP)	70	-0,241	1,002	0,051	0,900	1,104	0,850	0,848	384,940	1,043e-29	0,625	0,093
log(SSB _{msy} RP) ~ TS Length	70	11,344	0,018	0,012	-0,006	0,041	0,033	0,019	2,298	1,342e-01	1,461	0,462
log(B _{1/3} RP) ~ TS Length	70	10,731	0,028	0,013	0,003	0,053	0,066	0,052	4,811	3,170e-02	1,560	0,936
log(SSI) ~ TS Length	70	0,613	-0,010	0,005	-0,020	0,001	0,055	0,041	3,937	5,126e-02	0,608	0,335
log(SSB _{msy} density) ~ log(area)	64	6,670	-0,582	0,086	-0,753	-0,410	0,425	0,416	45,853	5,337e-09	1,264	0,531
log(B _{1/3} density) ~ log(area)	64	6,360	-0,574	0,093	-0,761	-0,388	0,380	0,370	37,951	5,951e-08	1,371	0,519
log(Median SSB density) ~ log(area)	64	5,980	-0,533	0,088	-0,708	-0,357	0,372	0,362	36,727	8,802e-08	1,293	0,159
log(Recent density) ~ log(area)	64	5,561	-0,509	0,092	-0,694	-0,325	0,330	0,319	30,5	7,011e-07	1,357	0,201

The median TS length was 38 years (mean = 40.43) with half of the stock assessments spanning between 30 to 48.75 years (IQR; Figure A6, Table 2). The shortest TS covered 17 years and the longest 77 years. The distribution is slightly right skewed indicating that long TS > 50 years are relatively rare despite a small secondary peak of assessments around 65 years (Figure A6). The median TS start is in 1982, while the median TS end is in the year 2020 (Figure A5). The median B_{1/3} RP year (1995) falls closer to the median TS start, approximately at one third of the range of median TS start to end. Half of the stocks displayed their max. SSB between 1986 and 2006 (sd = 18.01) (Figure A8, Table 2). The oldest B_{1/3} RPs date back up to 1947 and are statistical outliers (n = 3; 1947-1955), while the most recently assessed max. SSB occurred in 2022 (Figure 6, Figure A8).

The majority of SSB_{msy} RPs are from the last decade with a median year of 2019 (sd = 3.88), indicating up-to date benchmark sessions or derivations from recent stock assessments. The most recent SSB_{msy} RPs is from 2024, while the

earliest one originates from 2003 and is one of the statistical outliers (n = 6) from before 2012 (Table 2).

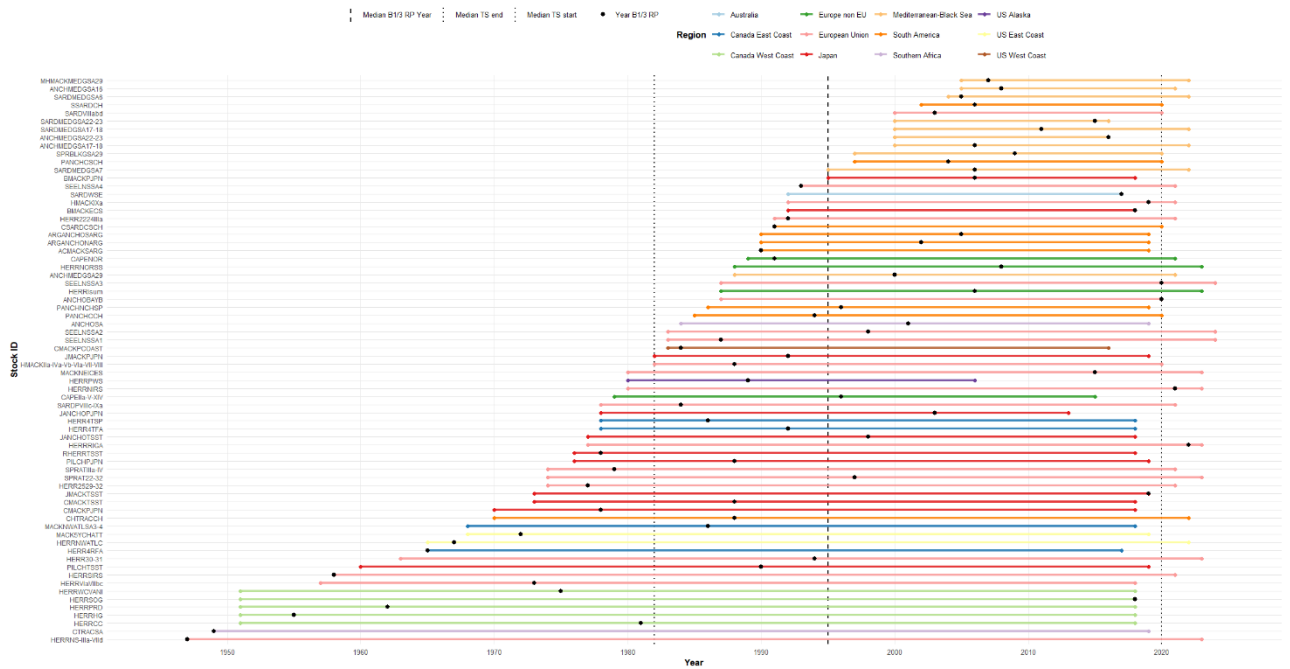


Figure 6. Overview of stock TS length and range. Each horizontal bar is representing one stock TS with the year of max. SSB displayed as the year of $B_{1/3}$ RP. The vertical dashed line marks the median year of $B_{1/3}$ RP (1995) and the dotted lines the median TS start (1982) and end (2020). The colour grouping displays the region of the stocks.

In the performed LM the variable of $\log(B_{1/3} RP)$ displayed a significant positive response to TS length ($R = 0.26$; $p = 0.032$), indicating that longer TS are more likely to contain larger $B_{1/3} RP$ (Figure 7, Table 3). However, TS length only explained 6.6 % of variance ($R^2 = 0.066$) of $\log(B_{1/3} RP)$. The relationship of $\log(SSI)$ and TS length was marginally non-significant ($R = -0.23$; $p = 0.051$), displaying a trend of decreasing SSI with increasing TS length. This reflected the varying response of the two RPs to TS length, as $\log(SSB_{msy} RP)$ displayed a slightly positive non-significant relationship ($R = 0.18$; $p = 0.13$) (Figure A9, Table 3). Consequently, $\log(B_{1/3} RP)$ increases more strongly with increasing TS length than $\log(SSB_{msy} RP)$, resulting in a decreasing SSI with increasing TS length.

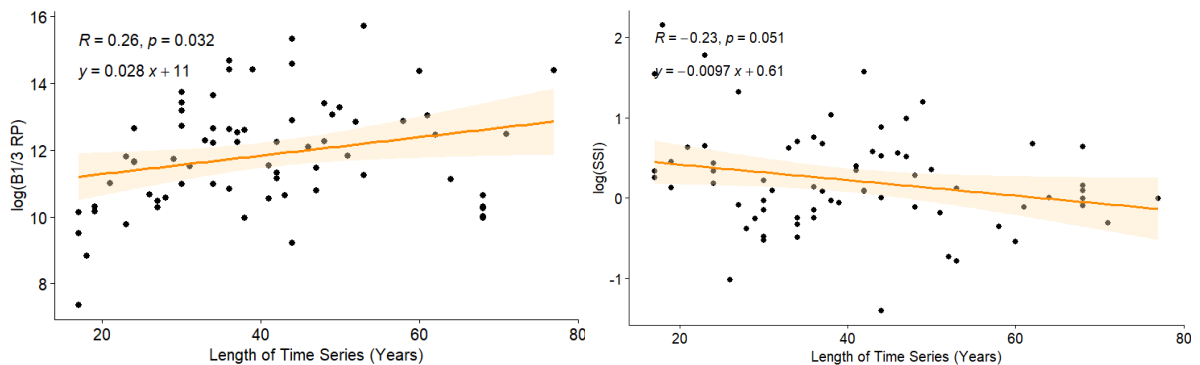


Figure 7. LMs for $\log(B_{1/3} RP)$ and TS length and $\log(SSI)$ and TS length

To analyse the adequacy of the density transformation, the density results were compared across the 4 density variables and the relationship to area size was examined. Due to the common cap at ‘median density’ >10 (MT/km²) for the density variables the sample size of the following analysis was reduced (n = 64) and was also applied for the exploration of area size to ensure the same stock coverage for all density related variables.

Stock distribution areas had a median size of 368.085 km² (mean = 1.663.266 km²) (Table 2). Explored stocks covered areas between 3.396 – 30.736.802 km² with an IQR of 1.750.511 km² (Q1 = 109.824 km², Q3 = 1.860.336 km²). Excluded area sizes ranged between 7.88 – 1.796 km², complemented by the three areas on land (see Methodology: Density Maps).

All four density variables shared a similar strongly right-skewed distribution with tight IQRs between 1.124 and 1.463 MT/km² and long upper tails driven by

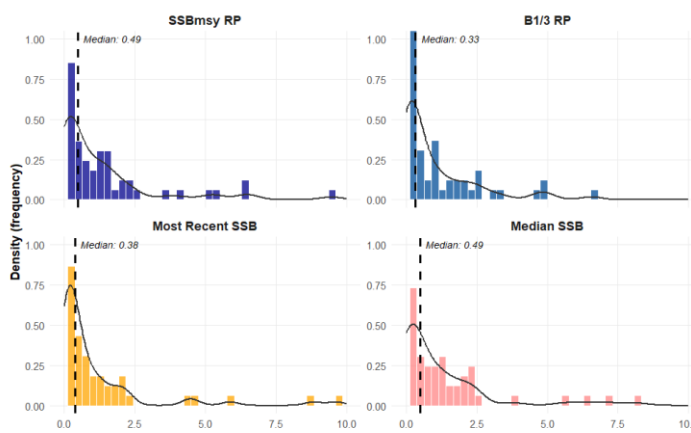


Figure 8. Histograms of stock density distribution across variables.

outliers reaching up to 14.714 MT/km² (Table 2, Figure 8). The median SSB_{msy} RP density (0.486 MT/km²; mean = 1.267) was larger than the median B_{1/3} RP density (0.331 Mt/km²; mean = 1.178), consistent with the SSI distribution where the SSB_{msy} RP generally exceeds the B_{1/3} RP. The median

SSB density across each full TS reflected a slightly larger density (0.493 MT/km²; mean = 1.181) than the median SSB_{msy} RP density, while the median recent SSB density (0.38 MT/km²; mean = 1.279) was lower and was closer to the B_{1/3} RP density.

All four log-log LMs of stock area against biomass density revealed a consistent, significant negative relationship across the density metrics (R = -0.57 to -0.65, all p < 0.0001), with slopes ranging from -0.509 to -0.582 (Figure 9, Table 3), indicating decreasing SSB densities with increasing area size. The LMs explained between 33 % and 43 % of variance in the density variables with log (Area km²). Of these, the SSB_{msy} density model explained the most variance (R² = 0.425) and displayed the lowest RMSE (1.264), while the recent SSB density model had the lowest explained variance (R² = 0.330).

The effect of qualitative variables on SSI and density was examined by performing multiple ANOVAS. The qualitative variables tested for SSI included

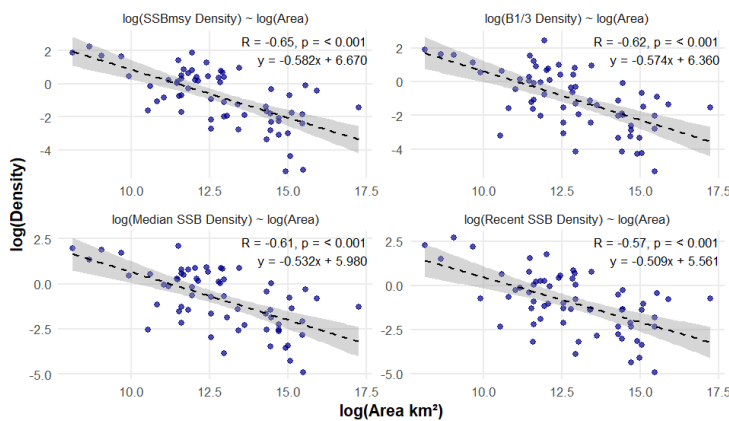


Figure 9. LMs of log (density variables) and log (area size)

< 0.05) and the HSD identified *Trachurus mediterraneus* (Mediterranean horse mackerel) displaying a significant difference to *Sardinops melanostictus* (Japanese sardine) and *Sardinops sagax* (Sardine) (Figure 10). Other taxa displayed no significance. All other variables (Order, Family, Assessment method, RP derivation method, Assessment category and region) displayed no significance as explanatory variables within the groups.

The ANOVA on the difference of ‘region’ displayed significance ($p < 0.05$) in each density variable. The HSD identified varying ‘region’ significance outcomes (Figures A16-19; Table A5).

For ‘Density SSB_{msy} ’, densities from ‘Canda west Coast’ and ‘European Union’ were significantly larger than the ones from ‘South America’ and ‘Australia’, while the other regions did not differ significantly within or towards these groups. For the ‘ $B_{1/3}$ RP’ density ANOVA only ‘South America’ was significantly lower in relation to ‘Canda west Coast’ and ‘European Union’. The HSD could not identify significantly varying groups for ‘recent density’. The ANOVAS on typology and species specificity did not display significant differences across the density variables, while taxa displayed multiple significant variations which were not further evaluated but are displayed in the Appendix (Figures A20-22, Table A6).

Finally, ‘species specificity’ and ‘typology’ did not display significant differences in density across stocks (Figure A23-24, Table A7-8) and ‘typology’ was also insignificant in ‘area size’ (Figure A25).

‘taxonomy’, ‘assessment method’, ‘RP derivation method’, ‘assessment category’ and ‘region’. For the density variables ANOVAS were performed for ‘region’, ‘taxa’, ‘typology’ and ‘species specificity’.

The SSI ANOVA on taxa displayed a significant difference (p

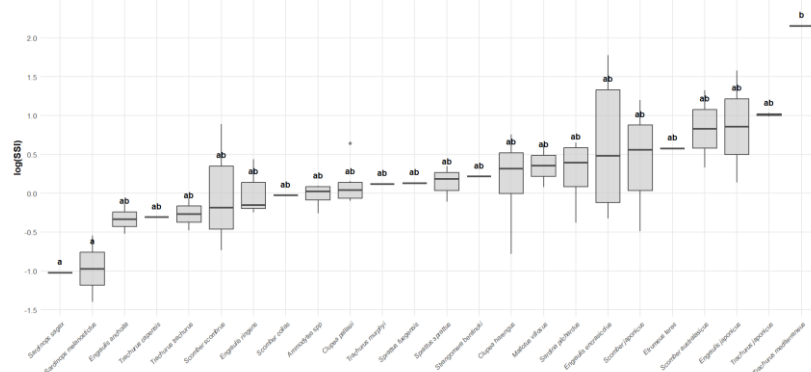


Figure 10. ANOVA on differences in log (SSI) associated with taxa

4. Discussion

4.1 Sustainability of Management Targets

The main finding of this analysis is that current commercial fisheries management targets (SSB_{msy} RPs) are not consistently aligned with seabird conservation needs. Although the majority of analysed stocks (61 %, $n = 43$) had an $SSI \geq 1$ (median = 1.131) (Figure 11), indicating compatibility with the minimum prey threshold associated with seabird breeding success (Cury et al. 2011), more than one third of stocks (39 %, $n = 27$) displayed management targets insufficient to meet this threshold. The strong linear relationship of the RPs indicates a similar scaling across stocks and suggests a high explanatory function of management targets to $B_{1/3}$ RPs. However, the average tendency of $B_{1/3}$ RPs to fall below the associated SSB_{msy} RP cannot be interpreted as evidence for sustainable seabird breeding conditions. More importantly, theoretical compatibility of management targets does not necessarily reflect current ecological conditions. Speaking in numbers: only 37 % ($n = 16$) of stocks with an $SSI \geq 1$ recently displayed a $SSB \geq SSB_{msy}$ (6x Europe, 4x South America, 3x Mediterranean, 2x Japan, 1x Canada West Coast) and overall, only 46 % ($n = 32$) of stocks had a SSB above their management target (Figure 11).

From a seabird conservation perspective, 59 % ($n = 41$) of stocks were recently above their $B_{1/3}$ RP consisting of 3 different sub-groups which are important to differentiate: (1) 16 stocks with an $SSI \geq 1$ and recent stock levels above management targets, (2) 13 stocks with an $SSI \geq 1$, recent stock levels below management targets yet above the $B_{1/3}$ RP, (3) 12 stocks with an $SSI < 1$ but recent stocks levels above the $B_{1/3}$ RP (see e.g. ARGANCHOSARG in Figure

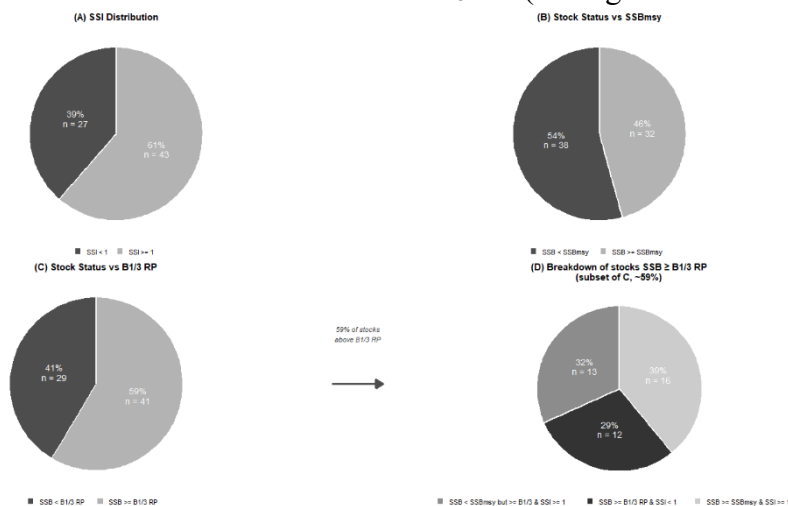


Figure 11. Overview of theoretical stock sustainability, recent stock status and differences in stocks that appear to be sustainable for seabird conservation needs.

A2). The latter group is the one most vulnerable to increases in fishing mortality, as the current stock size exceeds the management target and fisheries exploiting the stock to levels at SSB_{msy} would cause a decrease in SSB below the $B_{1/3}$ RP.

It must be mentioned that all statistical outliers have an $SSI \geq 1$ and make up 14 % ($n = 6$) of stocks with a positive SSI. Half of them originate from Japan (JANCHOTSST, BMACK ECS, CMACKPJP) and the other half from the Mediterranean-Black Sea (ANCHMEDGSA16, ANCHMEDGSA17-18, MHMACKMEDGSA29). It is striking that none of the outliers ever displayed a SSB above their SSB_{msy} RP in the TS, indicating depleted or highly (over-) exploited stocks, which significantly affect the $B_{1/3}$ RP estimate. In these cases, the SSI is most probably overoptimistic and recent SSB above the $B_{1/3}$ threshold cannot be safely assumed to provide prey abundances sustaining breeding success. Consequently, recent SSB consistent with seabird conservation needs can only be assumed for approximately 50 % of the analysed stocks, rather than 59 %.

In the broader picture, the recent states of SSB reflect the challenges and shortcomings faced in fish stock recovery and rebuilding (Britten et al. 2021; Froese et al. 2025; Winker et al. 2026). Approximately 41 % of stocks displayed recent SSB estimates below the $B_{1/3}$ RP indicating prey shortages leading to reduced breeding success, which might aggravate the further decline of seabird populations. As a first conclusion, the SSB_{msy} management targets of stocks are partially sufficient to sustain prey levels for sustainable seabird breeding success, but fisheries management systems often fail to reach their goals and maintain SSB levels compatible with sustainable exploitation and ecosystem functioning.

4.2 Shifting Baseline Syndrome and the Effect of Time Series Length

The effect of TS length on RPs and SSI must be interpreted with caution. The LM displayed a significant positive relationship of $B_{1/3}$ RP with TS length, while the positive relationship of SSB_{msy} RP was weaker and not significant. The SSI showed a marginally non-significant decline with increasing length of the TS, consistent with the larger increase of $B_{1/3}$ RP compared to SSB_{msy} RP with TS length. This pattern mirrors the logic of the shifting baseline syndrome of including historically less exploited stock sizes within longer TS (Pauly 1995), which would directly affect and raise the seabird conservation threshold, while SSB_{msy} RPs are based on a multitude of variables alleviating the effect of a singular peak SSB (Silvar-Viladomiu et al. 2022). Nevertheless, the models only explained around 6.6 % of the variance in $B_{1/3}$ RP and 5.4 % of the variance in SSI, indicating weak explanatory power of the relationship.

A second indicator of the shifting baselines is the median year of $B_{1/3}$ RP (1995) falling considerably closer to the median TS start (1982), than to the median TS end (2020). This suggests that historical maximum SSB was more commonly reached in the earlier years of assessed TS, consistent with continuous stock exploitation reducing peak biomass over time (Pauly & Zeller 2016). This effect would be amplified if the consistent recruitment model overestimation

(Froese et al. 2025) is assumed globally, as 6 stocks (9 %) display their historical max. in the last year of the TS (2x Europe, 2x Japan, 1x Mediterranean, 1x Canada, 1x Australia) and another 5 stocks within the last 5 years of the assessment (4x Europe, 1x Mediterranean).

A direct test of this susceptibility was performed for a small European sample ($n = 5$; SEELNSSA3, HERRRIGA, HERRNIRS, ANCHOBAYB, HMACKIXa, mean TS length = 32.2 years). The most recent TS model estimates of ICES advice (ICES 2025h; e; a; k; 2026a) were compared with the ones in the RAM Legacy Database. They displayed a mean drop of 24 % (median = 16 %) in the $B_{1/3}$ RP compared to the earlier TS estimates. Two assessments displayed their new historical maximum again in the final year, two displayed the same or the following year and one maximum dropped 37 years from 2021 to 1984. Although this is based on a small sample size that is not statistically robust, it demonstrates the susceptibility of the $B_{1/3}$ RP to model errors and updates, with direct impacts on the SSI (e.g. ANCHOBAYB: SSI increasing from 0.724 to 0.859; HMACKIXa: SSI increasing from 0.619 to 1.327). Additionally, a test on 22 updated ICES stocks (ICES 2021a; 2025h; e; a; k; j; n; p; o; f; r; c; q; m; d; g; b; l; i; 2026a; b; c) including $B_{1/3}$ RP years from the whole TS range did not suggest a decrease in the $B_{1/3}$ RP (mean = + 0.57 %, median = - 1%), and $B_{1/3}$ RP year (mean = - 0.59, median = 0). This suggests that the susceptibility of $B_{1/3}$ RPs is driven by the described phenomenon of recruitment overestimation in the most recent assessment years, rather than reflecting a general pattern in updated stock biomass estimates.

A further potential source of bias on the effect of TS length on $B_{1/3}$ RPs and the SSI could originate from the statistical SSI outliers. Their mean TS length (29.3, $n = 6$) falls slightly below the IQR and they display a low $B_{1/3}$ RP. Therefore, they rather support the pattern of shifting baselines as they display the expectation that historical maximum SSBs are lower or less likely to be captured in shorter and more recent assessment periods.

One alternative explanation for the shifting baselines pattern arises from the fact that larger, economically more important stocks were prioritized in assessment efforts (Ricard et al. 2012; Hilborn et al. 2020) and therefore tend to cover longer time periods. Consequently, this could drive the observed positive relationship between TS length and $B_{1/3}$ RP, as larger biomasses tend to be associated with longer TS.

Overall, the results on the effect of TS length should be cautiously interpreted as suggestive evidence for shifting baselines and historical stock depletion, which in turn may impact the seabird conservation threshold as it is more sensitive to the assessment length. However, a significant impact on SSI cannot be derived.

4.3 Density Translation Using the GRSF Areas Database

Density medians across variables reflected the larger average SSB_{msy} RP (0.486 MT/km²) relative to the $B_{1/3}$ threshold (0.331 MT/km²), as well as the shortfall of recent SSB density (0.380 MT /km²) relative to management targets, consistent with the SSI distribution and recent stock status findings. Mean densities (1.181-1.279 MT/km²) were notably closer to the upper end of the third quartile, suggesting a strong influence of the upper outliers. Nevertheless, the overall density translation is considered a reasonable representation of the RP relationship and SSB estimates.

The LMs revealed a strong negative relationship of the density variables with stock area, with ‘area’ explaining 38 % of density variance in $B_{1/3}$ RP and 42.5 % of density variance of SSB_{msy} RP. This shows that stocks managed or assessed over a larger area had on average lower densities. At the same time the ANOVAS did not reveal a significant effect of area ‘typology’ on biomass densities, even though ‘biological areas’ (n = 3), which are supposed to represent the stock distribution accurately, displayed marginally larger median densities than assessment or statistical areas (Figure A24). Correspondingly, they showed lower median area sizes, while median ‘assessment’ and ‘statistical areas’ were insignificantly larger (Figure A25). This indicates that the demarcation of stock area boundaries influences density more strongly than actual stock SSB levels. Reasons for that could be that widespread fish species occur at low abundance across large areas, or they occupy parts of these areas in higher abundances. The real stock distribution could also be unknown, and another reasoning (e.g. institutional areas of responsibility) used to draw the borders of assessment and statistical areas. Cadrin et al. (2023) illustrated how stock boundary revision can improve stock assessment by encompassing biological populations more closely and highlighted simulation testing as a tool to improve assessment for spatially complex populations.

The density translation of SSB variables by using polygons of the GRSF areas database displayed two kinds of limitations. The first major issue was the projection error of polygons that most likely appeared while integrating certain polygons into the database. This led to stock areas displaying biologically implausible densities or even being fully on land and consequently being erased / excluded in the process of the shoreline implementation. The density threshold set for the statistical analysis can be fairly described as a limited but sufficient approximation, as only densities of anchovy and a tropical reef ecosystem were used for the estimation (Murase et al. 2012; Letessier et al. 2022). Secondly, it must be mentioned that the GRSF areas database can support approximations of stock-wide density translation, but it cannot be treated as a robust proxy for

biologically meaningful prey density around colonies or within foraging ranges of seabirds. Furthermore, species overlap and the resulting density aggregation across prey species within the dietary range of seabirds were not considered, as the analysis mirrored the single-species approach of fisheries management to derive individual forage fish stock densities.

In conclusion, the GRSF areas database can support stock-wide density translation of SSB estimates and is considered a reliable tool for this exploratory purpose. However, absolute density values should be interpreted with caution, given the aforementioned limitations. In particular, it cannot yet serve as a robust proxy for biologically meaningful prey densities within the foraging range of seabird breeding colonies, as this relationship remains to be explored.

4.4 Impact of Differences in Qualitative Data Variables

The majority of qualitative variables examined did not reveal significant differences in SSI or biomass densities.

Among the SSI ANOVAs significant results were limited to ‘taxa’, displaying significant differences in species with small sample sizes (*Trachurus mediterraneus* (n = 1), relative to *Sardinops sagax* (n = 1) and *Sardinops melanostictus* (n = 2)) and therefore not considered as statistically robust. The result likely reflects the status of *Trachurus mediterraneus* as the largest outlier in the SSI, probably reflecting persistently (over-) exploited stock biomasses throughout the TS. All other variables did not show significant differences in SSI. Notably, even the RP derivation method which considerably differs across assessment-based models, surplus production models and simple RP target value calculations ($dvmb = B_{lim} * 2$), did not derive significantly different SSI estimates. This suggests methodological robustness of the SSI across assessment approaches, ‘taxa’ and ‘regions’.

The ANOVAs on stock density variables revealed significant differences in ‘region’. While this may indicate variation in ecosystem productivity, ‘region’ closely corresponds to assessment and ‘management’ institution, limiting the direct ecological interpretation. It would have been more informative to perform the ANOVA on the ‘management’ variable and additionally incorporate the data on mean longitude and latitude of each stock area as a continuous regional indicator or define ecosystem-based region groups following e.g. (Keramidas et al. 2023; Killeen et al. 2025). No significant differences were found for ‘species specificity’ and ‘typology’ of GRSF areas. It is worth mentioning that the results for ‘typology’ are consistent with the insignificant differences in area size discussed in the previous section, displaying lower densities for larger stock area types. The results of differences in ‘taxa’ are presented in the Appendix (Figures A20-22, Table A6) but were not further investigated.

Overall, the qualitative variables displayed limited explanatory power for variations in the SSI or density variables. The observed patterns reflected management shortcomings or institutional decisions rather than ecological or methodological drivers.

It must be noted that the analysis carries a regional bias due to overrepresentation of stocks from Europe and North America. Nevertheless, stocks from Japan and South America are also well represented, reflecting the continuous updating of the RAM Legacy Database, as these ‘regions’ were underrepresented in former versions (Ricard et al. 2012). African and Australian fisheries remain only marginally represented here.

At a taxonomic level Clupeiformes are disproportionately represented relative to their natural occurrence, mirroring the overrepresentation of this order within the RAM Legacy Database (Ricard et al. 2012). In this study this pattern was further driven by the families Clupeidae and Engraulidae specifically.

4.5 Management Implications

Given the results and considerations outlined above it is now crucial to derive their implications for forage fisheries management. It was shown that management targets are only partially sufficient to sustain seabird conservation needs and management shortcomings are reflected in recent SSB and density estimates. In conservation terms, the key issue is not the median stock but the substantial minority for which management targets remain below the prey levels implied by seabird breeding requirements and those whose theoretical target compatibility is not reflected in current stock conditions. Therefore, it will be crucial to improve and effectively implement management measures to reach SSB_{msy} management targets (Froese et al. 2025; Winker et al. 2026). This would improve sustainability and breeding conditions across a considerable number of stocks examined (63 % ($n = 27$) of stocks with $SSI \geq 1$), while also setting international standards facilitating global comparability. For those stocks with an $SSI < 1$ the sustainability of SSB_{msy} targets should be reevaluated and a higher prioritization of seabird conservation efforts could be considered when setting and managing towards updated biomass targets. Further improvements in model performance and reductions in recruitment overestimations (Froese et al. 2025) could lead to better-adjusted fishing mortality rates facilitating stock rebuilding, while simultaneously reducing the effects of these errors on the $B_{1/3}$ RP estimate.

In regions with fewer scientific stock assessments and data limitations (e.g. only catch data available) the focus should lie on the assessment of stock status with methods applicable under data-limited conditions (Rosenberg et al. 2018). Accordingly, the implementation of management measures is critical, as management based on scientific assessments and advice results on average in a more sustainable stock status (Hilborn et al. 2020).

The $B_{1/3}$ RP could be considered as an additional conservation and management threshold to the SSB_{msy} RP. This would add one layer of an ecosystem perspective to current single-species management practice, to evaluate its sustainability relative to seabird breeding success, bearing in mind that the translation to prey abundance in colony vicinity remains to be examined. However, it cannot be assumed with certainty that adjusting and reaching SSB_{msy} targets compatible with the $B_{1/3}$ RP will consistently lead to guaranteed seabird breeding success and population recovery. Undoubtedly, it would be a critically important step in this direction, potentially mitigating pressures such as prey shortages on seabird populations, but ecosystem-level species interactions would remain insufficiently accounted for, introducing uncertainty regarding risks and potential detrimental feedback loops.

One way to address these uncertainties is implementing holistic management frameworks encompassing multi-species and ecosystem approaches (Pikitch et al. 2004; Fogarty 2014). Such frameworks would need to thoroughly account for species-specific forage ecology including dietary diversity (e.g. Montevercchi et al. 2009) and the degree of dependence on individual prey species. This would consequently require accounting for forage fish species interactions, overlap and its effect on prey density within foraging ranges (Peck et al. 2014). Pathways to implement such management frameworks have been illustrated extensively (Pikitch et al. 2004; Fogarty 2014). They may include ecosystem-wide MSY targets replacing single-species targets as illustrated by Froese et al. (2025), which could yield significantly larger commercial catches when fish stocks are managed at these MSY targets. Managing trade-offs between conservation and economic interests would likely be facilitated as they could be evaluated within a holistic framework rather than through isolated single species assessments (White et al. 2012). Furthermore, spatially dynamic, fine-scale management could improve the effectiveness of management measures (Maxwell et al. 2015; Dunn et al. 2016; Hentati-Sundberg et al. 2021). This could ultimately contribute to more sustainable commercial fisheries and more effective conservation outcomes. As this may not only improve the conservation status of seabirds and commercial fisheries catches but could lead to overall improvements in ecosystem functioning resulting in improved ecosystem services and resilience, it is difficult to argue against broader implementations of the EBFM approach (Fogarty 2014). Beyond at-sea measures such as no-take zones (Pichegru et al. 2012; Sherley et al. 2015) this would also include land-based measures that have also been shown to potentially rebuild seabird populations and benefit the ecosystem (Dunn et al. 2025).

In particular, with the increasing impact of climate change it will be crucial to consider the interconnectedness of forage fish species, seabirds and community-level impacts (Engelhard et al. 2014; Pinsky & Byler 2015; Sydeman et al. 2015;

Killeen et al. 2025). Heatwaves over the past decades have had detrimental effects on fish stocks and seabird populations and full population recovery may not occur (Piatt et al. 2020; Arimitsu et al. 2021; Suryan et al. 2021; Renner et al. 2024; Schoen et al. 2024). Additional feeding disruptions such as resource mismatches (Regular et al. 2014) may occur more frequently, affecting seabird breeding success, particularly in species with limited adaptive capacity (Killeen et al. 2025). Compound risks from exploitative fisheries for forage fish stocks need to be considered (Pinsky et al. 2011; Engelhard et al. 2014; Essington et al. 2015; Pinsky & Byler 2015).

As top-down governance remains crucial as the legal basis for sustainable fisheries management (Melnychuk et al. 2025) it will also be of critical importance to improve knowledge exchange between scientists and decision-makers (Cvitanovic et al. 2015) to align management systems with the current best scientific knowledge. As ocean conditions change rapidly, effective decision making must consider ecological forecasts on multiple timescales (Pinsky & Smith 2026). McClenachan & Colby (2026) have illustrated how our societies' relationship with the sea and its wildlife has changed across decades and centuries and there is an urgent call to end the destructive ways of resource extraction as ecosystems face critical tipping points (Fletcher et al. 2024). We now have knowledge about our patterns of exploitation and may choose a pathway that reconciles conservation targets and economic interests.

For future research it will be important to explore the translation of forage fish stock density to prey density within the vicinity of seabird colonies and their foraging ranges. A first attempt could be made by comparing stock-wide densities to prey abundances reported by Cury et al. (2011) and Hentati-Sundberg et al. (2021) in the foraging range of seabird breeding colonies (Analysis overlap of prey stocks with Cury et al. (2011): Sandeel in North Sea, Herring in Norwegian Sea, Sardine and Anchovy in Benguela Current (Southern Africa); with Hentati-Sundberg et al. (2021): Herring and Sprat in North Sea). It is also suggested to examine the historical reference stock size B_0 (unexploited stock state) as an alternative value in relation to historical TS maximum as a potentially more informative and ecologically stable conservation RP. Furthermore, it is important to further connect seabird distribution, diet diversity and flexibility in foraging tactics to manage spatial and species-specific prey species overlap. Increased understanding of environmental regimes and their impact on forage fish recruitment would help to better adjust fisheries management, building on the research efforts made in the last decades (Peck et al. 2021). Finally, it would have been valuable to complement the analysis by performing generalised linear models (GLMs) to identify the combined explanatory power of multiple variables in a single model and implement coordinate data.

In conclusion, this analysis illustrated how management targets of forage fish stocks are partially sufficient to sustain prey levels for sustainable seabird breeding success, but fisheries management systems often fail to reach these targets and maintain SSB levels compatible with sustainable exploitation and ecosystem functioning such as seabird breeding success. A potential influence of time series length on the SSI was observed, yet no significant evidence for the shifting baseline syndrome was found. The GRSF areas database is considered a reliable tool to translate stock biomass estimates into densities if the aforementioned limitations are considered. Differences across qualitative variables were scarce, reflecting management shortcomings and institutional decisions rather than direct ecological drivers.

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Popular science summary

Every summer, millions of seabirds return to coastlines around the world to breed and raise a new generation of chicks. To succeed, they need enough fish, close enough to the colony to reach it without spending too much energy. Herring, anchovies and sardines are some of many small fish species that support the reproduction of seabirds. They are also the same fish that commercial fisheries have harvested for decades.

The question that arises is, when we fish these species at supposedly sustainable management targets, is there still enough left for seabirds to feed their young? Science offers a useful reference point for that. A study by Cury and colleagues in 2011 showed that seabird breeding success is consistently lower when fish stocks fall below one third of their historical maximum. This threshold ($B_{1/3}$) was suggested to protect seabird populations. But fisheries management is built around a different goal, the maximum sustainable yield (MSY), which is the largest catch that can be taken, while keeping the stock at a high reproductive level and without depleting it over time.

This thesis compared MSY biomass targets directly with the $B_{1/3}$ seabird threshold for 70 forage fish stocks from around the world. A new metric, the Seabird Sustainability Index (SSI), was developed to express this relationship as a single number. An SSI above 1 means the fishery target is compatible with seabird needs, if the SSI is below 1, it is not.

The results are mixed. Approximately 60 % of stocks have MSY targets compatible with the seabird threshold, but 40% do not provide enough fish for seabirds. Additionally, management systems often fail to reach their own targets. Only 46% of stocks had biomasses at or above their MSY target in recent years. Reaching MSY targets globally would already represent a meaningful improvement for seabird conservation and fisheries sustainability but it would likely not be sufficient on its own. A truly sustainable fishery needs to account for the needs of the whole ecosystem: the fish, the birds, and everything in between.

Appendix 1

A1 Overview qualitative variables and TS

Table A 1. Taxonomic overview

	Order	Family	Scientific Name	Common Name	Nr. of stocks
1	Clupeiformes	Clupeidae	<i>Clupea harengus</i>	Herring	14
2	Clupeiformes	Clupeidae	<i>Clupea pallasii</i>	Pacific herring	6
3	Clupeiformes	Engraulidae	<i>Engraulis encrasicolus</i>	Anchovy	6
4	Clupeiformes	Clupeidae	<i>Sardina Pilchardus</i>	Sardine (European pilchard)	6
5	Perciformes	Ammodytidae	<i>Ammodytes ssp.</i>	Sand eel	4
6	Clupeiformes	Engraulidae	<i>Engraulis ringens</i>	Peruvian anchoveta	3
7	Perciformes	Scombridae	<i>Scomber japonicus</i>	(Pacific) Chub mackerel	3
8	Perciformes	Scombridae	<i>Scomber scombrus</i>	(Atlantic) Mackerel	3
9	Clupeiformes	Clupeidae	<i>Sprattus sprattus</i>	Sprat	3
10	Clupeiformes	Engraulidae	<i>Engraulis anchoita</i>	Argentine anchoita	2
11	Clupeiformes	Engraulidae	<i>Engraulis japonicus</i>	Japanese anchovy	2
12	Osmeriformes	Osmeridae	<i>Mallotus villosus</i>	Capelin	2
13	Clupeiformes	Clupeidae	<i>Sardinops melanostictus</i>	Japanese sardine	2
14	Perciformes	Scombridae	<i>Scomber australasicus</i>	Spotted mackerel	2
15	Perciformes	Carangidae	<i>Trachurus japonicus</i>	Japanese jack mackerel	2
16	Perciformes	Carangidae	<i>Trachurus trachurus</i>	Horse mackerel	2
17	Clupeiformes	Dussumieriidae	<i>Etrumeus teres</i>	Round herring	1
18	Clupeiformes	Clupeidae	<i>Sardinops sagax</i>	Sardine	1
19	Perciformes	Scombridae	<i>Scomber colias</i>	Argentine chub mackerel	1
20	Clupeiformes	Clupeidae	<i>Sprattus fuegensis</i>	Southern Sardine	1
21	Clupeiformes	Clupeidae	<i>Strangomera bentincki</i>	Chilean Sardine	1
22	Perciformes	Carangidae	<i>Trachurus capensis</i>	Cape horse mackerel	1
23	Perciformes	Carangidae	<i>Trachurus mediterraneus</i>	Mediterranean horse mackerel	1
24	Perciformes	Carangidae	<i>Trachurus murphyi</i>	Chilean jack mackerel	1

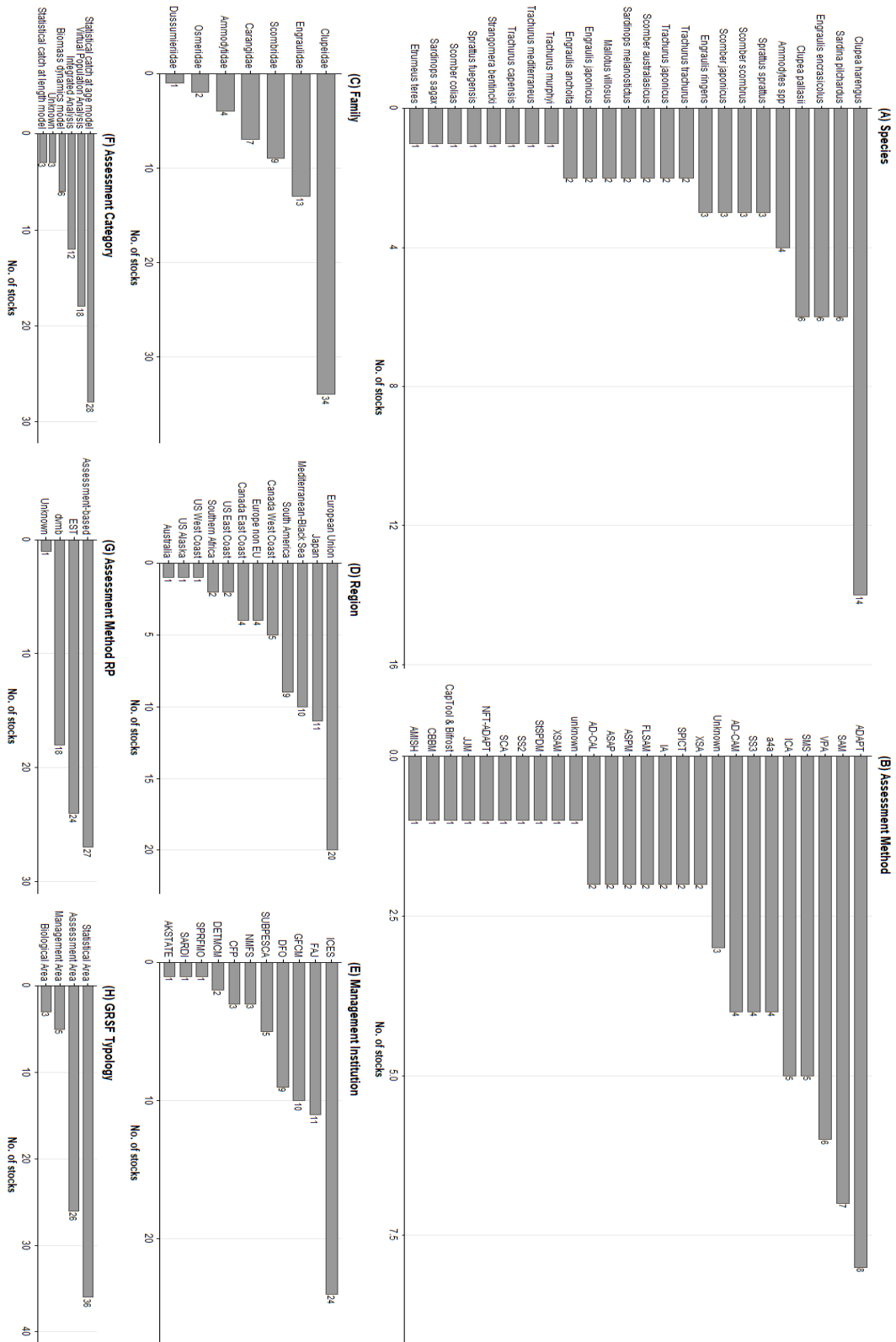


Figure A 1. Distribution of the analysis data in qualitative variables

SSB Time Series with SSBmsy & B 1/3 Reference Points

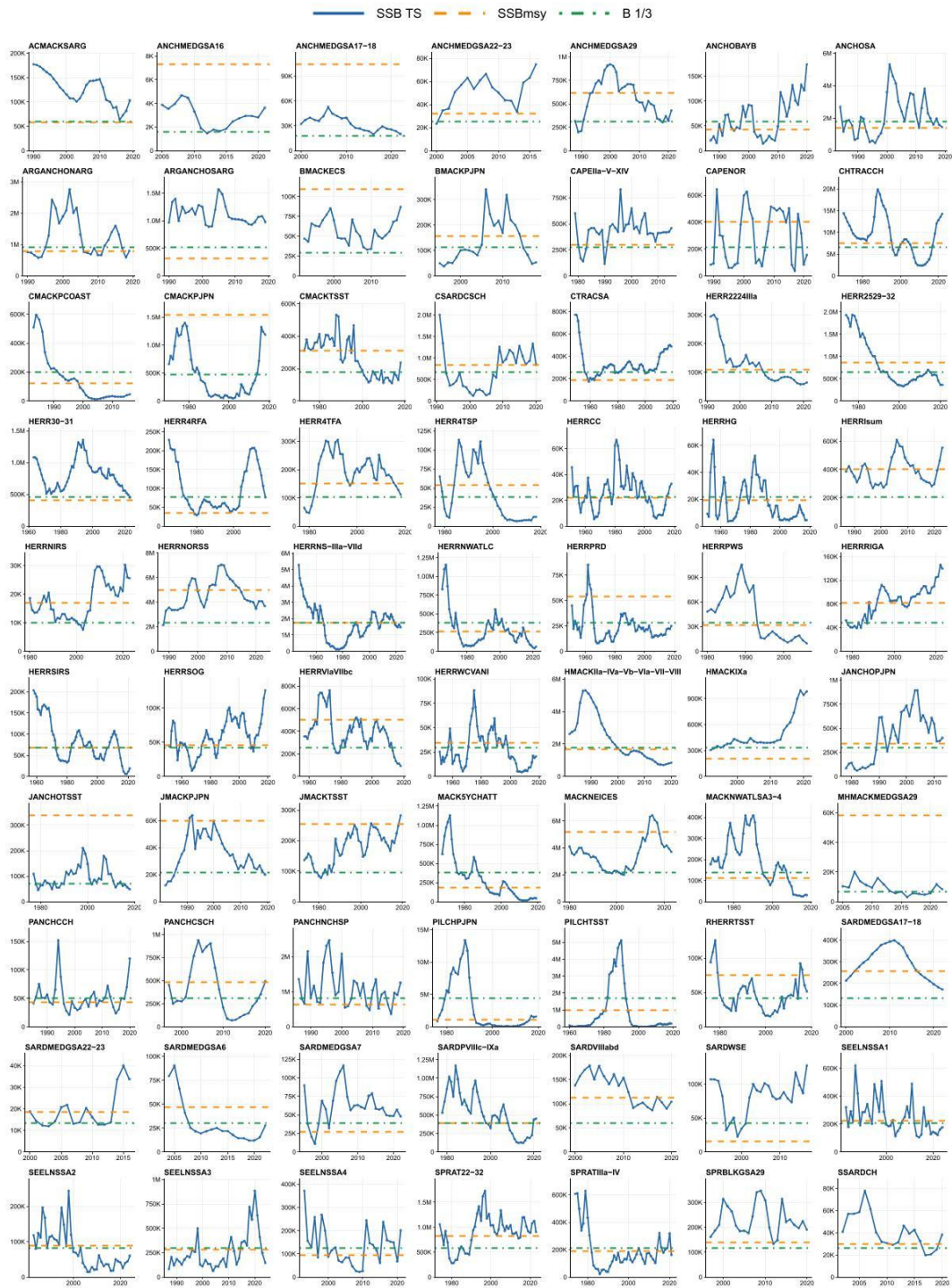


Figure A 2. Overview of analysed SSB-TS and associated RPs

A2 Main results

A2.1 SSI and RP relationships

The LMs with log transformed recent and median SSB as explanatory variables for SSBmsy RP or B1/3 RP did display weaker correlation or were rejected as they did not satisfy the normality assumption ($p < 0,05$).

Table A 2. Statistical overview of LMs on RP relationship, including recent and median SSB

Model	N	Intercept	Slope	Slope_SE	R2	Adj_R2	F_stats	P	RMSE	Shapiro-Wilk test
log (B1/3 RP) ~ log (SSBmsy RP)	70	-0,241	1,0017	0,0511	0,8499	0,8477	384,94	1,043e-29	0,6253	0,093
log (SSBmsy RP) ~ log (Recent SSB)	70	3,0115	0,7624	0,0575	0,7212	0,7171	175,92	1,554e-20	0,7843	0,1792
Log (B1/3 RP) ~ log (Recent SSB)	70	1,7538	0,8497	0,0581	0,7588	0,7553	213,98	1,096e-22	0,7925	P<0,05
Log (SSBmsy RP) ~ log (Median SSB)	70	1,5482	0,8793	0,0472	0,8361	0,8337	346,99	2,059e-28	0,6013	P<0,05
Log (B1/3 RP) ~ log (Median SSB)	70	0,1215	0,9801	0,0439	0,88	0,8782	498,57	5,079e-33	0,5591	P<0,05

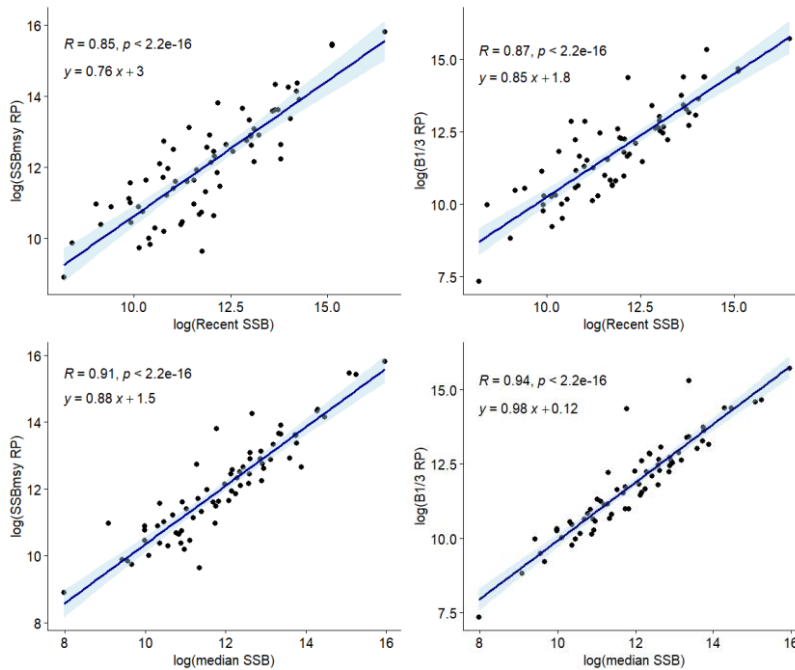


Figure A 4. LMs of RPs with recent and median SSB

The residual histogram displayed a slightly left-skewed normal distribution, also visible in the quantile's plot, additionally displaying larger deviation at the upper and lower end of RP estimates (Figure A 3). However, the normality assumption was satisfied (HSD: $p > 0,05$).

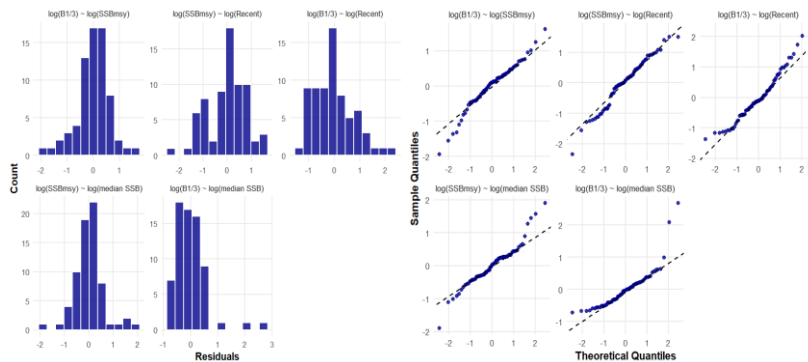


Figure A 3. Histogram and QQ-Plot of residual distribution of RP relationship

A2.2 TS length and area relationship

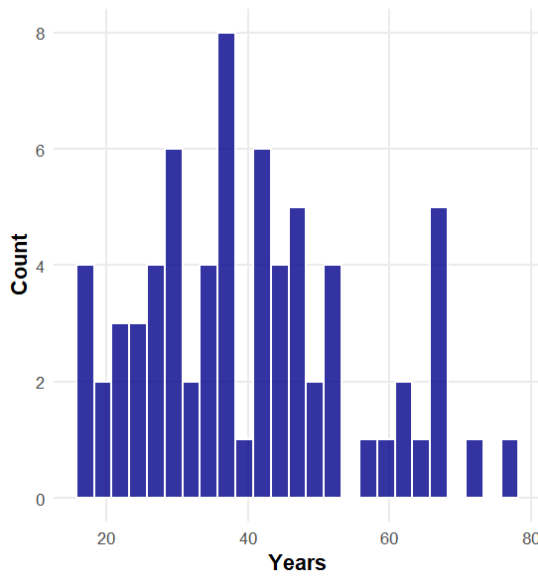


Figure A 6. Histogram on TS length distribution

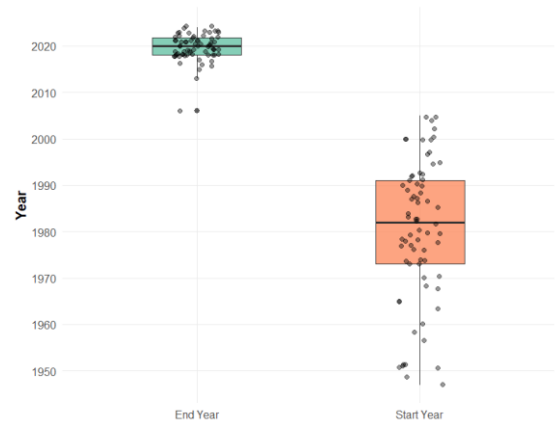


Figure A 5. Boxplot TS start and end distribution

Table A 3. Quartiles of TS start and end

	10 %	25 %	50 %	75 %	90 %
First Year of TS	1956.4	1973	1982	1991	2000
End Year of TS	2017	2018	2020	2021.75	2023

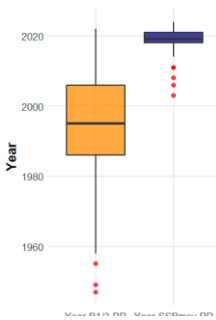


Figure A 8. Boxplot RP year distribution

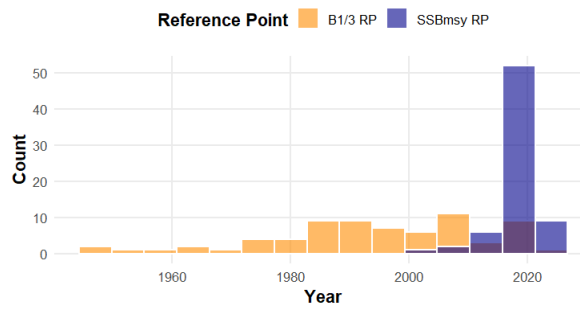


Figure A 7. Histogram on RP Year distribution

LMs TS length

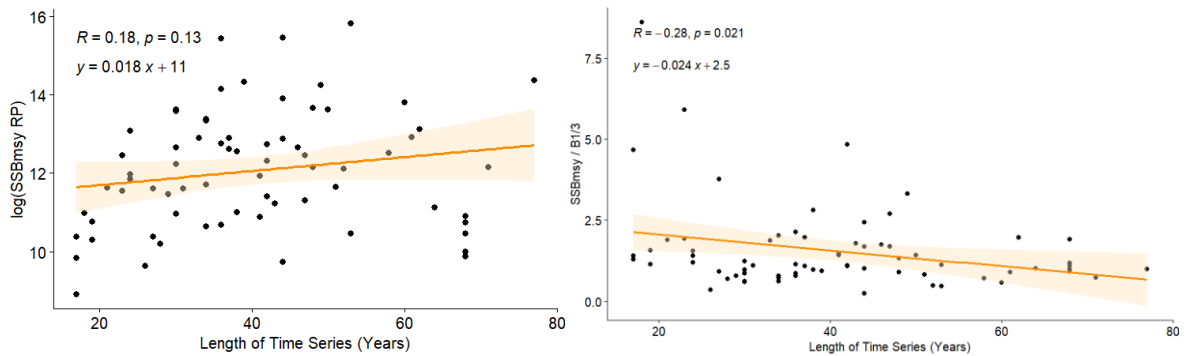


Figure A 9. LMs of log (SSBmsy RP) and untransformed SSI with TS length

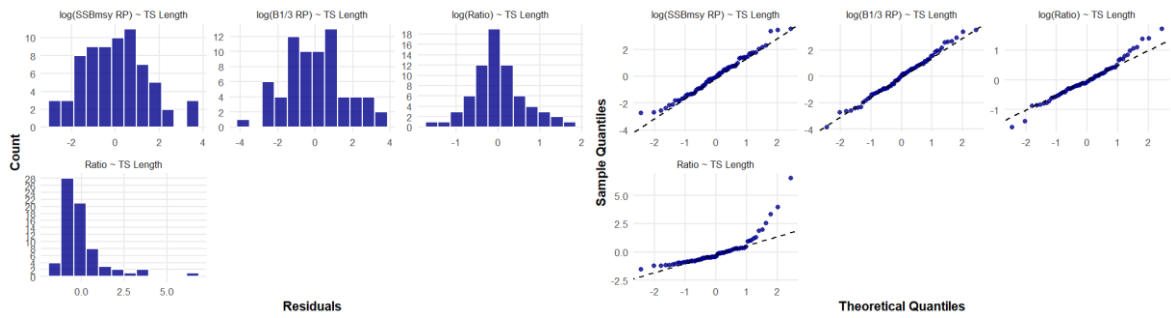


Figure A 10. Histogram and *QQ*-Plot of residual distribution of TS length

The residual histograms were approximately bell-shaped and centred near zero. The *QQ* plots display an overall normal distribution with slight deviations and the outer ends. The Shapiro-Wilk test confirmed the met normality assumption for the three models but not the model with untransformed SSI.

Residuals of LMs Density ~ area

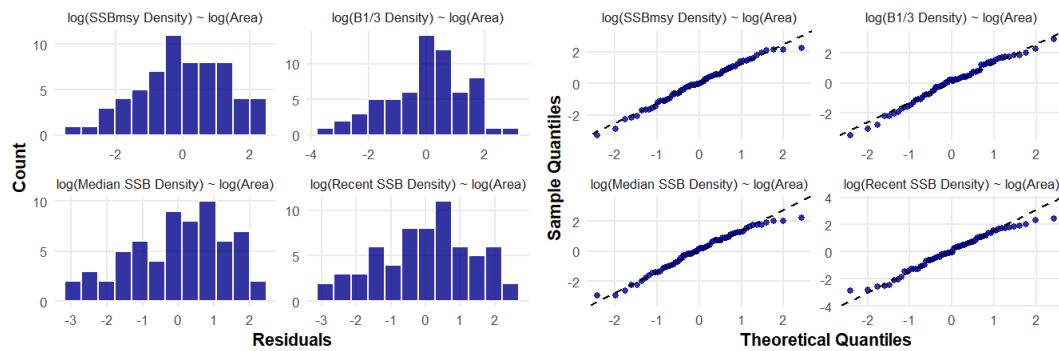


Figure A 11. Histogram and *QQ*-Plot of residual distribution of density ~ area relationship

The residual histograms showed roughly a normal distribution. The *QQ* plots indicated a sufficient normality approximation which was confirmed by the Shapiro-Wilk test ($p > 0,05$).

A2.3 ANOVAs on SSI and density variables

SSI

Table A 4. Statistical overview of SSI ANOVAs

Grouping	Df between	Df within	F value	P value	Significance
Species	23	46	2.1739	1.245e-02	*
Family	2	67	0.3429	7.109e-01	ns
Order	6	63	0.7565	6.067e-01	ns
Assessment	25	44	1.2445	2.575e-01	ns
Method					
RP derivation	4	65	1.1095	3.597e-01	ns
Assessment	5	64	2.1564	6.995e-02	.
category					
Region	11	58	2.6683	7.7013e-03	**

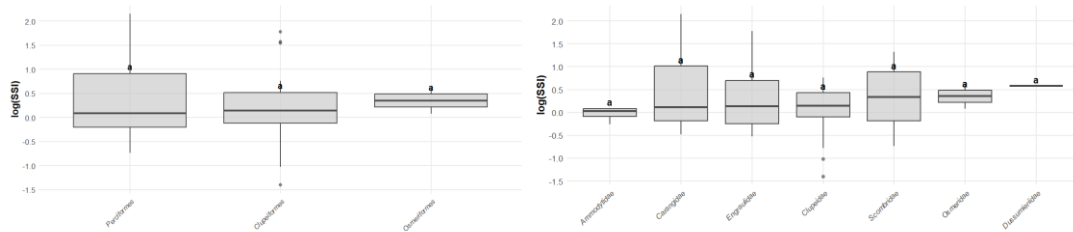


Figure A 13. ANOVA on Order and Family for SSI

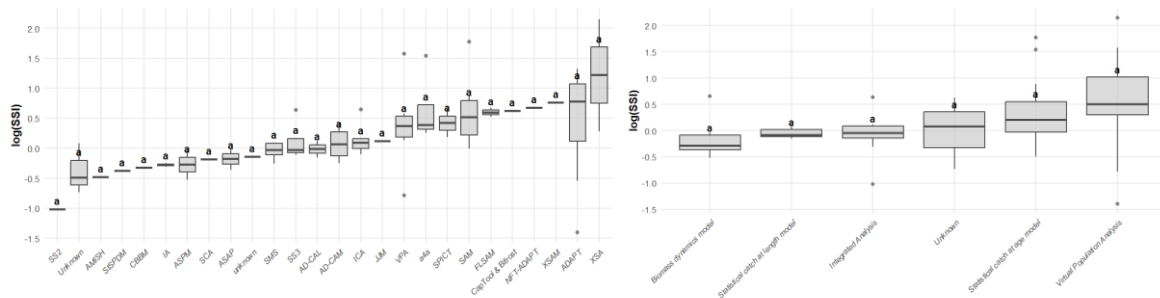


Figure A 12. ANOVA on assessment method and Category for SSI

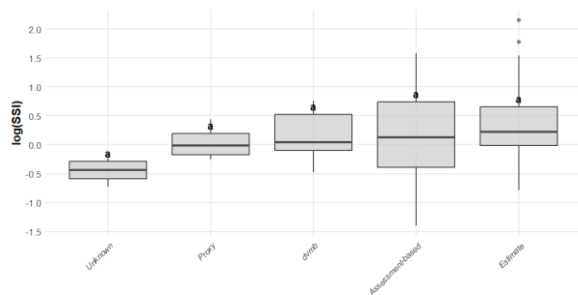


Figure A 14. ANOVA on RP derivation method for SSI

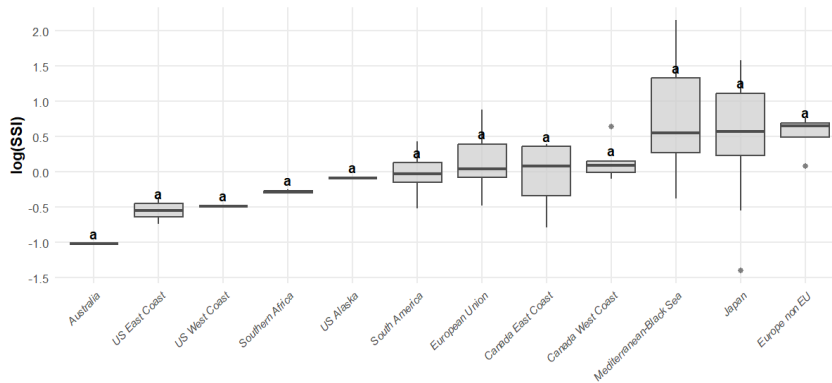


Figure A 15. ANOVA on Region for SSI

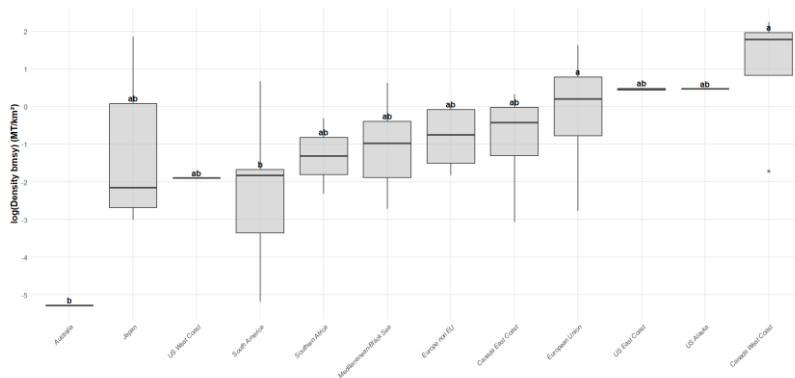
"A significant effect of region was found ($F = 2.67, p = 0.008$), though pairwise Tukey HSD post-hoc tests revealed no individually significant regional pairs after correction for multiple comparisons."

Density variables

Density ~ Region

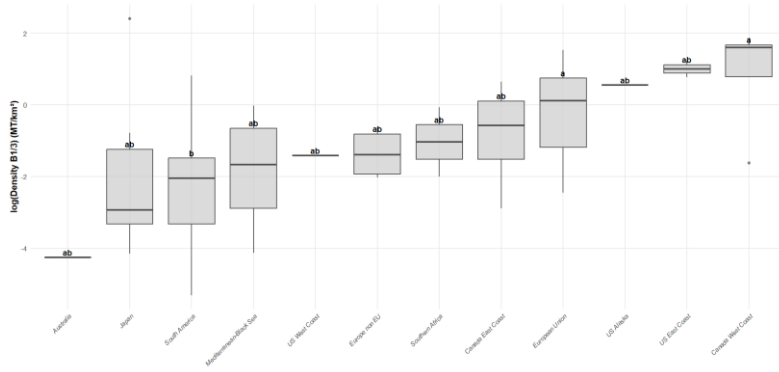
Table A 5. Statistical overview of ANOVAs on density variables for 'region'

Region with	Df between	Df within	F value	P value	Significance
log (Density SSB _{msy} RP)	11	52	3,4846	1,086e-03	**
Log (density B1/3 RP)	11	52	3,1556	2,483e-0,3	**
Log (Recent Density)	11	52	2,0196	4,505e-02	*
Log (Median density)	11	52	2,9642	4,037e-03	**



South America-European Union
 $p = 0.006547622$
 Canada West Coast-Australia
 $p = 0.009331603$
 South America-Canada West Coast
 $p = 0.009449691$
 European Union-Australia
 $p = 0.027009731$

Figure A 16. ANOVA on log (density SSB_{msy}) for region



South America-European Union
 p = 0.029998897
 South America-Canada West Coast
 p = 0.034087180

Figure A 17. ANOVA on log (density $B_{1/3}$ RP) for region

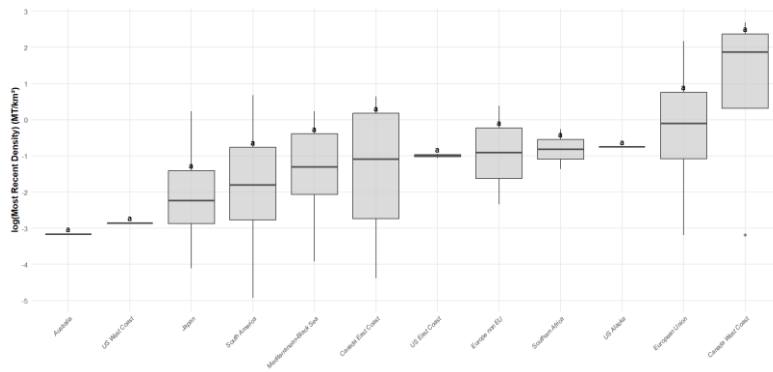
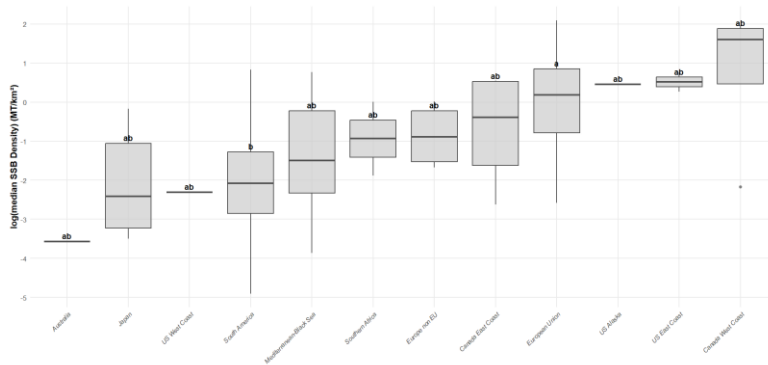


Figure A 18. ANOVA on log (recent density) for region



South America-European Union
 p = 0.025512331

Figure A 19. ANOVA on log (median SSB density) for region

Density ~ Taxa

Table A 6. Statistical overview of ANOVAs on density variables for 'taxa'

Taxa with	Df between	Df within	F value	P value	Significance
log (Density SSB _{msy} RP)	22	41	4.1972	3.670e-05	***
Log (density B1/3 RP)	22	41	4.4095	2.079e-05	***
Log (Recent Density)	22	41	2.1997	1.433e-02	*
Log (Median density)	22	41	3.4140	3.349e-04	***

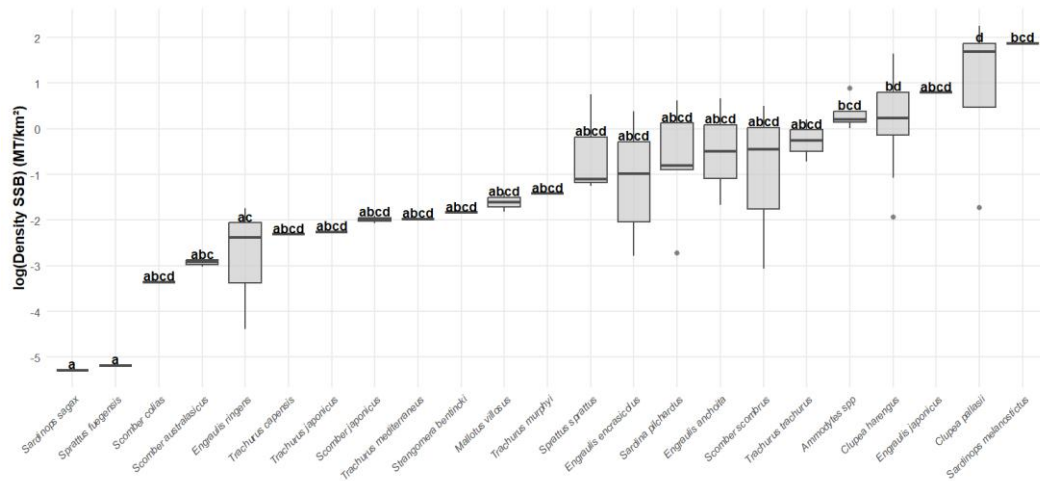


Figure A 20. ANOVA on log (density SSB_{msy} RP) for taxa

Clupea pallasii-Sardinops sagax...1	p = 0.002821521	SSB scientific_name
Clupea pallasii-Sprattus fuegensis...2	0.003581352	SSB scientific_name
Clupea harengus-Sardinops sagax	0.007335666	SSB scientific_name
Clupea harengus-Sprattus fuegensis...9	0.009352082	SSB scientific_name
Clupea pallasii-Engraulis ringens...11	0.010845845	SSB scientific_name
Sardinops melanostictus-Sardinops sagax...12	0.012723718	SSB scientific_name
Ammodytes spp-Sardinops sagax	0.013932516	SSB scientific_name
Sardinops melanostictus-Sprattus fuegensis...14	0.015125839	SSB scientific_name
Ammodytes spp-Sprattus fuegensis...17	0.017313436	SSB scientific_name
Clupea harengus-Engraulis ringens...25	0.027384052	SSB scientific_name
Clupea pallasii-Scomber australasicus...33	0.038882630	SSB scientific_name

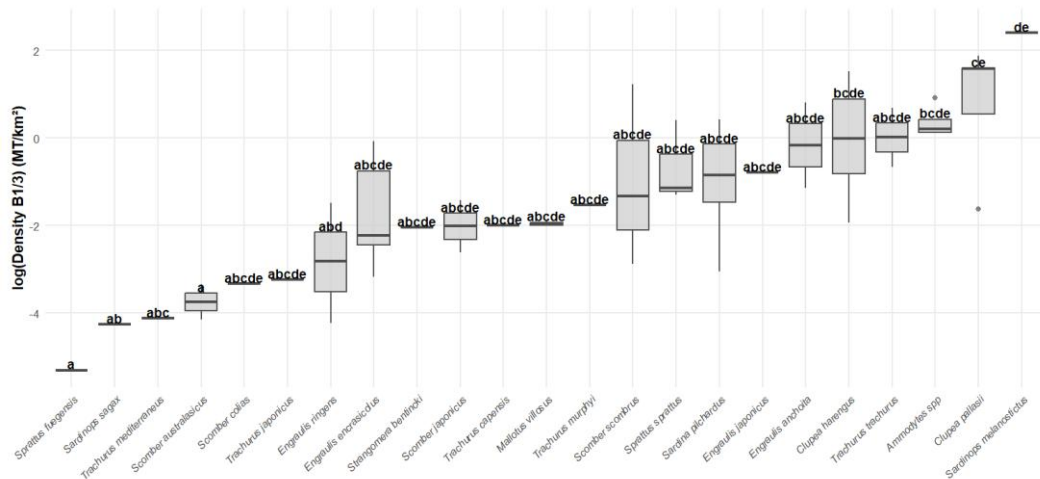


Figure A 22. ANOVA on log (density B1/3 RP) for taxa

Clupea pallasii-Sprattus fuegensis...3	p = 0.004983101	B1/3 scientific_name
Sardinops melanostictus-Sprattus fuegensis...5	0.006687475	B1/3 scientific_name
Clupea pallasii-Scomber australasicus...6	0.007035639	B1/3 scientific_name
Clupea harengus-Sprattus fuegensis...15	0.015892283	B1/3 scientific_name
Ammodytes spp-Sprattus fuegensis...16	0.017002122	B1/3 scientific_name
Sardinops melanostictus-Scomber australasicus	0.018640026	B1/3 scientific_name
Clupea pallasii-Engraulis ringens...20	0.020486886	B1/3 scientific_name
Clupea harengus-Scomber australasicus...21	0.024200059	B1/3 scientific_name
Ammodytes spp-Scomber australasicus	0.035717525	B1/3 scientific_name
Sardinops melanostictus-Sardinops sagax...32	0.037660722	B1/3 scientific_name
Sardinops melanostictus-Trachurus mediterraneus	0.046114083	B1/3 scientific_name
Clupea pallasii-Sardinops sagax...36	0.046420348	B1/3 scientific_name

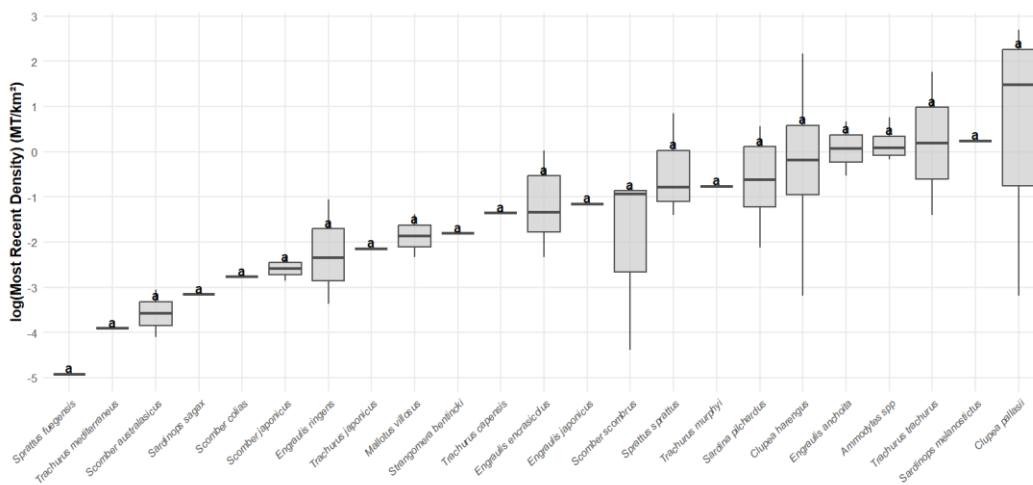


Figure A 21. ANOVA on log (recent density) for taxa

ANOVA on mediana density for Taxa:

Clupea pallasii-Sprattus fuegensis...19	p = 0.020011739	Median scientific_name
Clupea pallasii-Scomber australasicus...23	0.026595412	Median scientific_name
Clupea harengus-Sprattus fuegensis...27	0.030236461	Median scientific_name
Clupea harengus-Scomber australasicus...29	0.035353973	Median scientific_name
Clupea pallasii-Engraulis ringens...31	0.037406341	Median scientific_name
Clupea harengus-Engraulis ringens...34	0.043757281	Median scientific_name

Density ~ species specificity

Table A 7. Statistical overview of ANOVAs on density variabls for 'species specificity'

Region with	Df_between	Df_within	F_value	P_value	Significance
log (Density SSBmsy RP)	1	62	3.2423	7.663e-02	.
Log (density B1/3 RP)	1	62	3.2500	7.628e-02	.
Log (Recent Density)	1	62	0.2992	5.863e-01	ns
Log (Median density)	1	62	0.6030	4.404e-01	ns

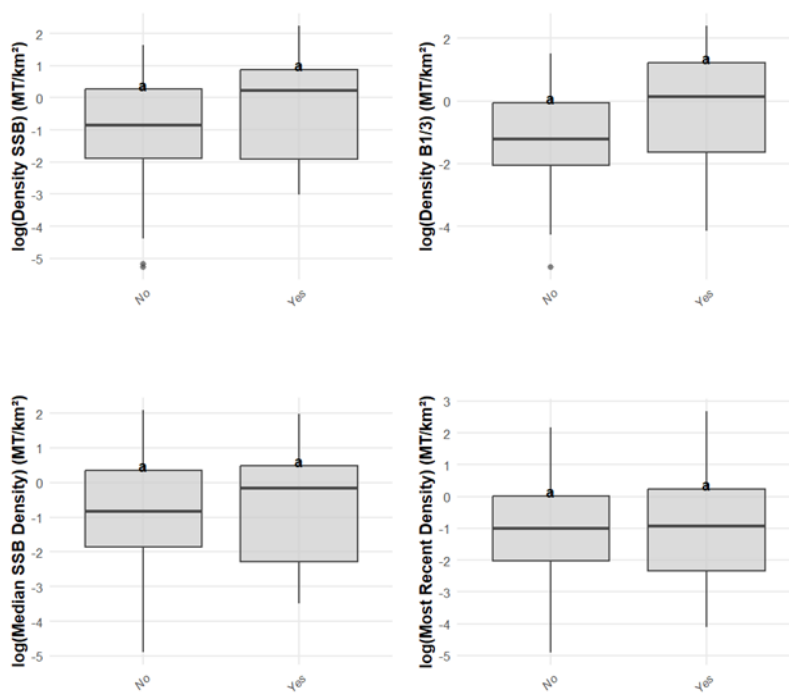


Figure A 23. ANOVAs on density variables for species specificity

Density ~ Area Typology

Table A 8. Statistical overview of ANOVAs on density variables for 'typology'

Region with	Df between	Df within	F value	P value	Significance
log (Density SSBmsy RP)	3	60	0.7618	5.199e-01	ns
Log (density B1/3 RP)	3	60	1.2396	3.033e-01	ns
Log (Recent Density)	3	60	0.3679	7.764e-01	ns
Log (Median density)	3	60	0.7067	5.518e-01	ns

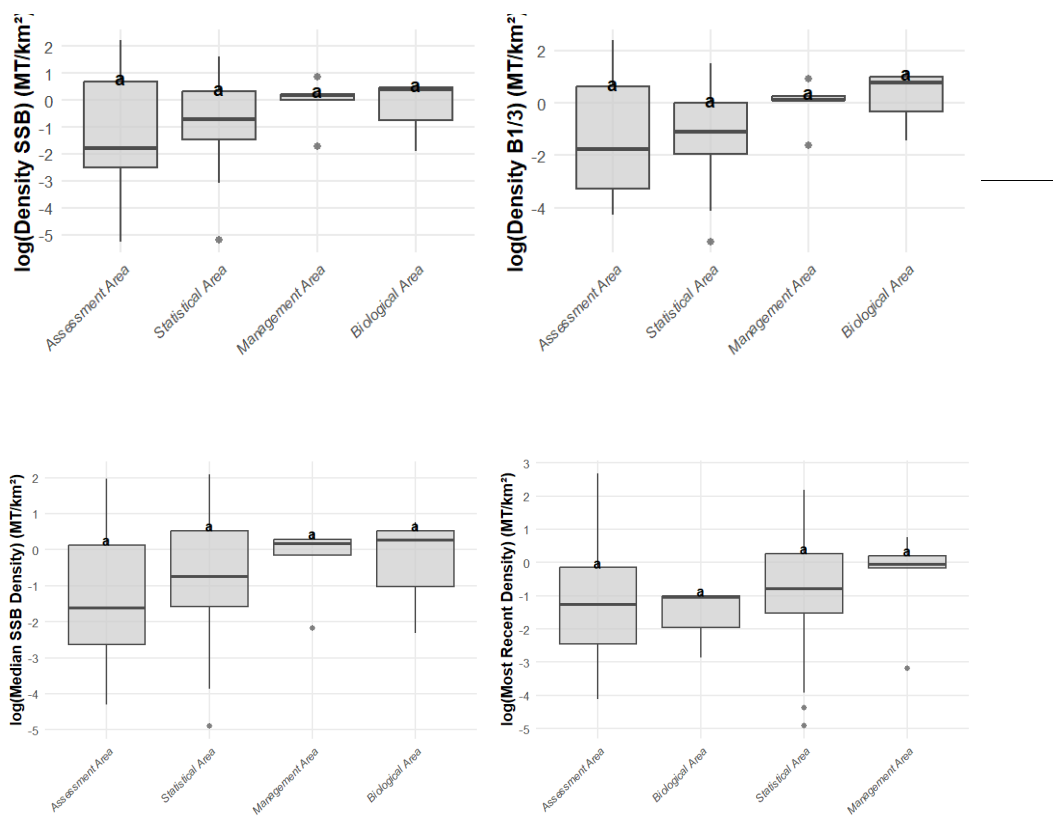


Figure A 24. ANOVAs on density variable for typology

Area size ~ Area Typology

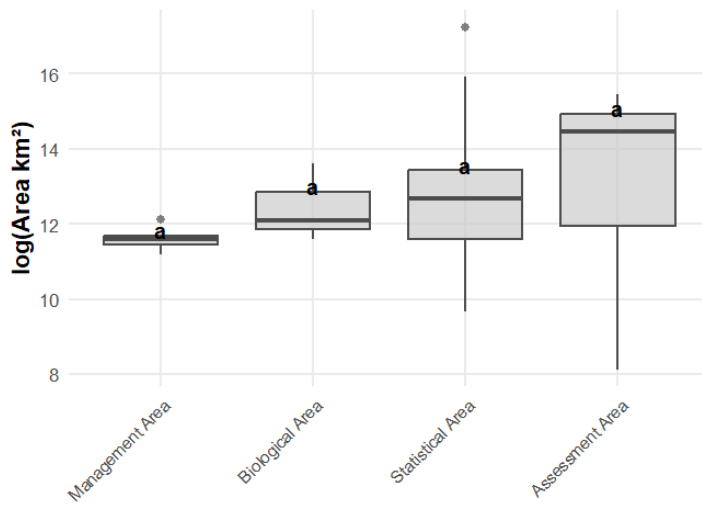


Figure A 25. ANOVA on Area size for typology

Appendix 2

Copyright Sources of global fish stock map

- Ammodytes ssp.* - Bauchot, M.-L., 1987 Poissons osseux.
- Clupea, pallasii, Sardina pilchardus, Sprattus sprattus, Sprattus fuegensis, Strangomera bentincki* - Whitehead, P.J.P., 1985 FAO Species Catalogue. Vol. 7. Clupeoid fishes of the world (suborder Clupeoidei). An annotated and illustrated catalogue of the herrings, sardines, pilchards, sprats, shads, anchovies and wolf-herrings.
- Engraulis encrasicolus* - Schneider, W., 1990 FAO species identification sheets for fishery purposes. Field guide to the commercial marine resources of the Gulf of Guinea. Prepared and published with the support of the FAO Regional Office for Africa.
- Clupea harengus, Engraulis ringens, Scomber japonicus, Scomber scombrus, Sardinops sagax, Scomber australasicus* - Cada, Robbie N. - Former FB staff
- Engraulis anchoita* - Cousseau, B. and R.G. Perrotta, 1998 Peces marinos de Argentina. Biología, distribución, pesca.
- Engraulis japonicus* - Whitehead, P.J.P. and T. Wongratana, 1986 Engraulidae.
- Mallotus villosus* - Fisk Basen; <https://fiskbasen.se/lodda/mallotus-villosus/>
- Sardinops melanostictus* - https://fishillust.com/Sardinops_sagax_melanosticta
- Etrumeus teres* - https://fishillust.com/Etrumeus_teres
- Scomber colias*- https://fishillust.com/Scomber_colias
- Trachurus japonicus* - https://wiki.fishingplanet.com/Japanese_Jack_Mackerel
- Trachurus trachurus* - https://wiki.fishingplanet.com/Atlantic_Horse_Mackerel
- Trachurus capensis* - Bianchi, G., 1986 Fichas FAO de identificação de espécies para propósitos comerciais. Guia de campo para as espécies comerciais marinhas e de águas salobras de Angola.
- Trachurus mediterraneus* - Mariano Garc;
<https://fishbase.se/photos/ThumbnailsSummary.php?ID=1278#>
- Trachurus murphyi*- Smith-Vaniz, W.F., 1995 Carangidae. Jureles, pámpanos, cojinúas, zapateros, cocineros, casabes, macarelas, chicharros, jorobados, medregales, pez pilota.

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