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A Spatio-Temporal Approach for Standardizing Acoustic Survey Indices of Chilean Jack Mackerel in Chile

Chile

A spatio-temporal approach for standardizing acoustic survey indices of Chilean jack mackerel in Chile

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Abstract

Fishery-independent acoustic surveys provide key indices of abundance for Chilean jack mackerel (Trachurus murphyi), but interannual differences in spatial survey coverage can influence conventional biomass estimates and complicate temporal comparisons. We developed a common spatio-temporal modelling framework to standardize biomass indices from the northern (2006–2026) and central-southern (1997–2023) Chilean acoustic surveys using delta-Gamma generalized linear mixed models implemented in the R package sdmTMB. Both surveys were analysed using a consistent modelling strategy based on stochastic partial differential equations (SPDE), anisotropic spatial random fields and first-order autoregressive spatio-temporal processes (AR1), while prediction was performed over fixed common spatial domains to reduce the influence of interannual differences in survey coverage.

The fitted models produced coherent annual biomass surfaces that captured the principal spatial patterns observed during the acoustic surveys. The resulting standardized indices revealed contrasting temporal dynamics between survey regions, with increasing biomass in northern Chile during recent years and comparatively higher biomass in the central-southern region during the late 1990s and early 2000s followed by a prolonged decline and partial recovery. Comparisons with the conventional acoustic biomass indices demonstrated that the standardized indices reproduced the principal long-term temporal trends while exhibiting differences in the magnitude of annual biomass estimates, particularly during

periods of changing survey coverage.

The proposed framework provides a consistent approach for deriving standardized acoustic biomass indices while explicitly accounting for spatial dependence, temporal structure and interannual variation in survey coverage. These standardized time series provide an alternative representation of relative biomass that can be evaluated alongside the acoustic indices currently used in SPRFMO stock assessment.

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1. Introduction

Fishery-independent acoustic surveys provide one of the principal sources of information on the abundance and spatial distribution of Chilean jack mackerel (*Trachurus murphyi*), and their derived biomass indices constitute an important input to the stock assessment conducted by the Scientific Committee of the South Pacific Regional Fisheries Management Organisation (SPRFMO). In Chile, two long-term acoustic survey series are available: a northern survey, conducted since 2006, and a central-southern survey, conducted since 1997. Together, these surveys provide valuable information on the temporal dynamics of the stock over a large proportion of its Chilean distribution.

Although acoustic surveys follow standardized protocols, differences in annual survey coverage are unavoidable owing to operational, logistical and oceanographic constraints. Consequently, the spatial extent sampled may vary among years, particularly at the margins of the survey domain. Conventional biomass estimates are obtained by integrating observed acoustic densities over the surveyed area, which means that changes in spatial coverage may influence annual biomass estimates independently of changes in stock abundance. This effect can complicate the interpretation of long-term trends and reduce the temporal consistency of abundance indices used in stock assessment.

Spatio-temporal statistical models provide an alternative framework for estimating abundance indices by explicitly accounting for spatial dependence, temporal structure and observation uncertainty. By predicting biomass over a common spatial domain each year, these models reduce the influence of annual differences in survey coverage and generate standardized indices that are directly comparable through time. Such approaches have become increasingly common in fisheries science and have proven particularly useful for long-term monitoring programmes in which sampling designs evolve over time.

The objective of this working paper is to develop and apply a common spatio-temporal modelling framework to standardize biomass indices from the northern and central-southern Chilean jack mackerel acoustic surveys. Although the two surveys differ in their historical coverage and spatial sampling characteristics, both analyses were implemented using a consistent modelling strategy adapted to the characteristics of each survey series. The resulting standardized indices are compared with the conventional acoustic biomass estimates currently used in stock assessment and are presented as a methodological framework for evaluating the potential use of spatio-temporal standardized acoustic indices in future SPRFMO stock assessments.

2. Methodology

2.1. Acoustic survey data

This study used data from two long-term acoustic surveys conducted by the Instituto de Fomento Pesquero (IFOP) to monitor Chilean jack mackerel (*Trachurus murphyi*). The northern survey covered the period 2006–2026, with no survey conducted in 2022, whereas the central-southern survey covered the period 1997–2023, with additional gaps in the time series. The spatial distribution of the acoustic observations included in the northern and central-southern analyses is shown in Figures 1 and 2, respectively.

For both surveys, acoustic observations were available at the elementary sampling unit level and expressed as biomass density (t nmi^2). Biomass density was derived from Nautical Area Scattering Coefficient observations using echo-integration conversion factors that accounted for the length composition of jack mackerel within aggregation zones, based on biological samples collected during identification hauls, together with survey-specific length–weight relationships. For historical observations lacking detailed biological information, conversion factors were reconstructed from available biomass and abundance estimates to maintain consistency across the survey series.

Both zero observations, representing elementary sampling units where jack mackerel was not acoustically detected, and positive biomass-density observations were retained. The acoustic databases were subjected to routine quality-control procedures before analysis. Geographic coordinates were projected to WGS84/UTM Zone 19S for the northern survey and WGS84/UTM Zone 18S for the central-southern survey and expressed in kilometres for spatial modelling.

The response variable was acoustic biomass density. Because both datasets contained a high proportion of zeros and strongly right-skewed positive observations, biomass density was analysed using a delta modelling framework that separately represented the probability of occurrence and biomass density conditional on occurrence.

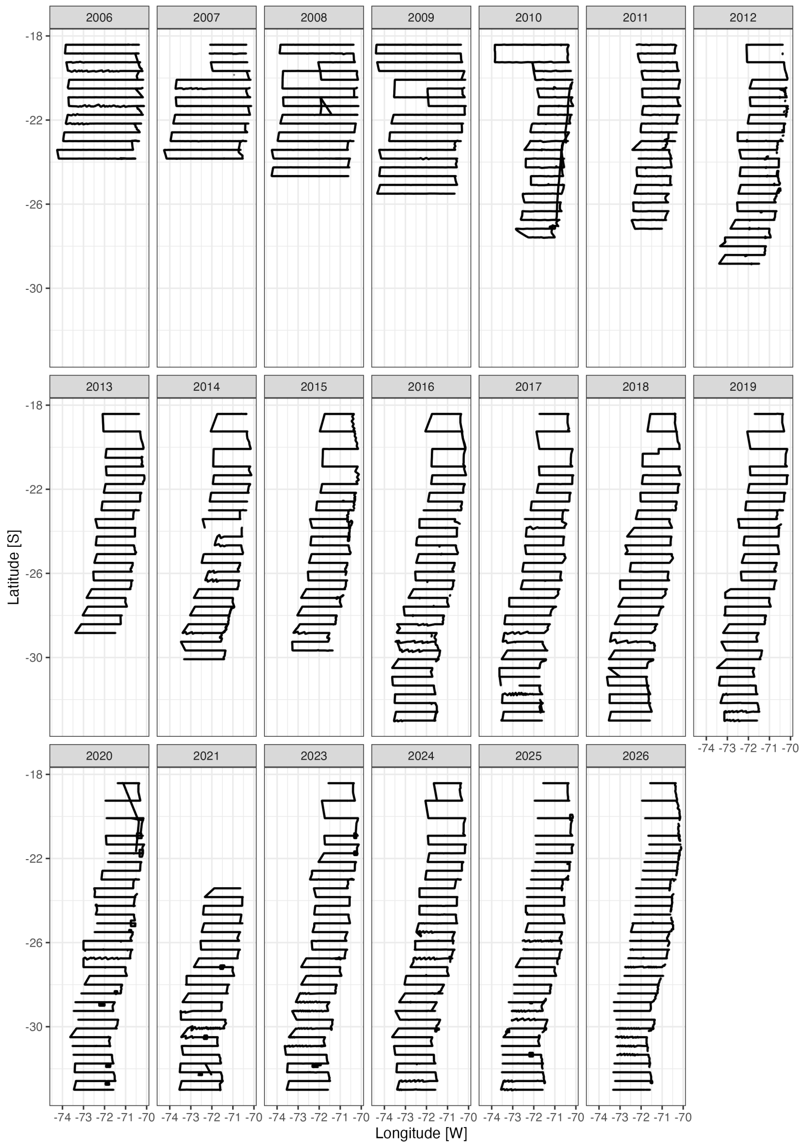

Figure 1: Annual spatial distribution of acoustic observations from the northern Chilean jack mackerel survey, 2006–2026. Each panel represents a survey year, and points indicate elementary acoustic sampling units included in the spatio-temporal analysis. No survey was conducted in 2022.

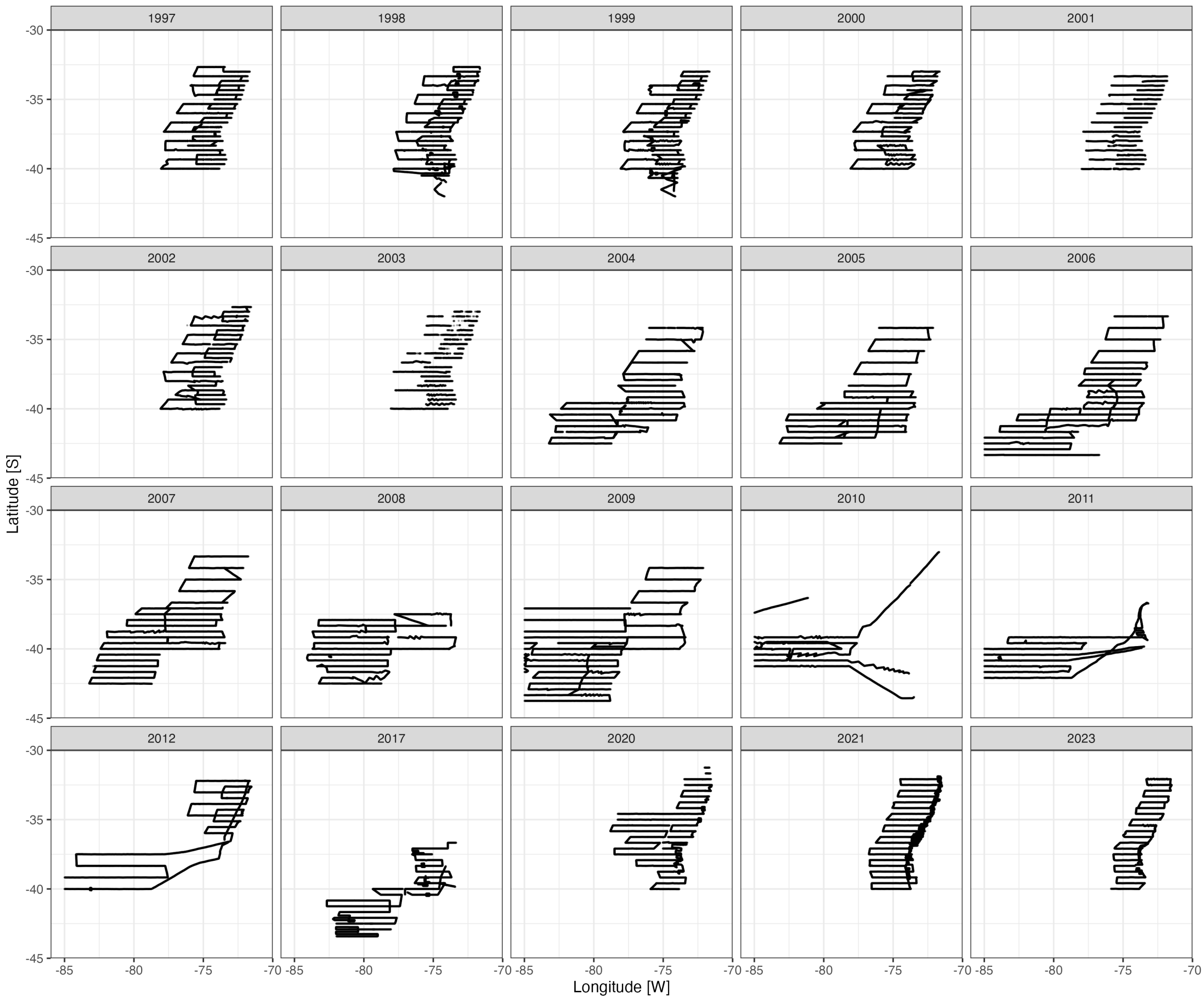

Figure 2: Annual spatial distribution of acoustic observations from the central-southern Chilean jack mackerel survey, 1997–2023. Each panel represents a survey year, and points indicate elementary acoustic sampling units included in the spatio-temporal analysis.

2.2. Spatio-temporal modelling framework

Acoustic biomass density was modelled using the sdmTMB package in R (Anderson et al., 2025), which implements generalized linear mixed models with spatial and spatio-temporal random fields represented through the stochastic partial differential equation (SPDE) approach. This framework enables the estimation of continuous biomass surfaces while explicitly accounting for spatial dependence and temporal correlation.

Because acoustic observations consisted of a large proportion of zero values together with continuous positive biomass densities, both survey series were analysed using a delta-Gamma model. The occurrence component was modelled using a binomial distribution with a logit link, whereas positive biomass densities were modelled using a Gamma distribution with a log link. Annual variation common to the entire survey domain was represented using a penalized smooth function of year, s(year) ($k = 6$), allowing for gradual long-term changes in biomass while avoiding unnecessary model complexity.

Spatial dependence was represented through Gaussian random fields defined over an SPDE mesh. Temporal dependence of the spatial fields was modelled using a first-order autoregressive (AR1) process, allowing biomass distributions in consecutive years to remain correlated. Anisotropy was included in both survey models to allow spatial correlation to differ among directions, reflecting the elongated geometry of the Chilean continental margin.

Although both surveys were analysed using the same modelling framework, the final random-effects structure differed slightly between survey series following model development and diagnostic evaluation. For the northern survey, a persistent spatial random field was retained for the occurrence component only, whereas the positive-density component was represented exclusively by the spatio-temporal random field. In contrast, the central-southern survey was represented solely by spatio-temporal random fields in both model components, without persistent spatial effects.

Several environmental variables, including sea surface temperature, chlorophyll-a, sea level anomaly and wind turbulence, were explored during model development. However, none consistently improved model performance, and therefore the final standardized biomass indices presented here were derived from structural spatio-temporal models that relied exclusively on temporal and spatial random effects.

2.3. Spatio-temporal modelling framework

Spatial random fields were represented using the stochastic partial differential equation (SPDE) approach over triangular meshes. Mesh configuration was adapted to the spatial extent and sampling density of each survey while maintaining a common modelling framework. Sampling locations were discretized solely for mesh construction (2-km resolution in the northern survey and 4-km resolution in the central-southern survey), whereas model fitting was performed using the original observation locations.

For the northern survey, the spatial domain was defined from a concave hull encompassing all sampling locations across years. A regular 2×2 km prediction grid was generated within this boundary. The final SPDE mesh was constructed using a cutoff distance of 16 km, with maximum inner and outer triangle edge lengths of 32 and 160 km, respectively.

For the central-southern survey, annual survey footprints were delineated from the sampling locations and expanded using a 20-km buffer. A common prediction domain was subsequently defined by retaining grid cells sampled in at least 50% of survey years. Predictions were made on a regular 4×4 km grid covering this common domain. The corresponding SPDE mesh was built using a cutoff distance of 32 km, with maximum inner and outer triangle edge lengths of 64 and 320 km, respectively.

The prediction domain was held constant through time for each survey, providing a consistent spatial framework for annual biomass estimation while accommodating differences in historical survey coverage and spatial extent between regions.

Figure 3 illustrates the final SPDE meshes used for the two surveys, including the observation locations and the corresponding prediction domains.

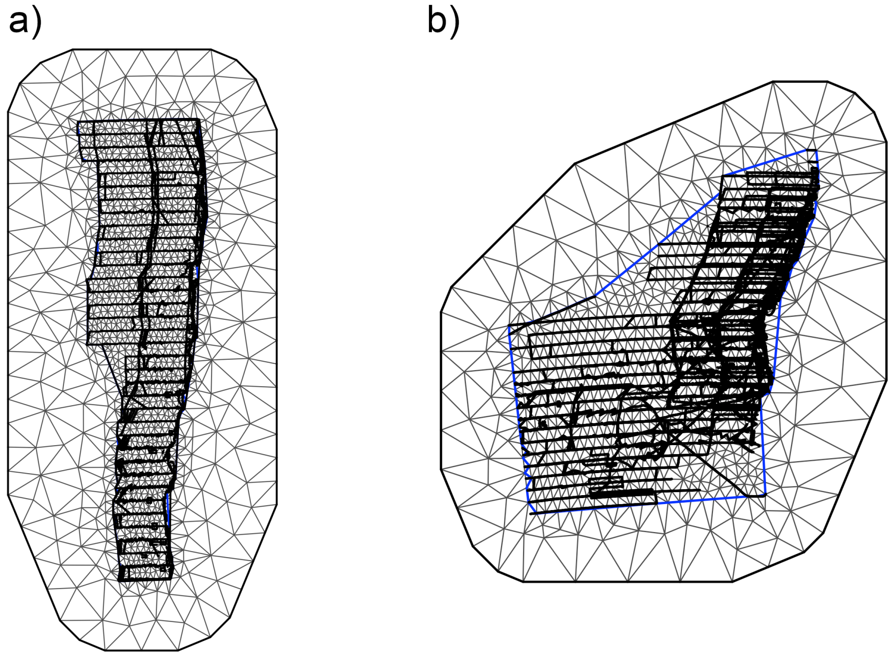

Figure 3: Final SPDE meshes used for the spatio-temporal models. (a) Northern Chile acoustic survey (2006–2026) showing the concave-hull domain, sampling locations, and mesh constructed with a 16-km cutoff. (b) Central-southern Chile acoustic survey (1997–2023) showing the common 50% prediction domain, sampling locations, and mesh constructed with a 32-km cutoff.

2.4. Standardized biomass indices

Annual standardized biomass indices were obtained by predicting biomass density over the fixed spatial domain defined for each survey series. Predictions were generated for every survey year using the same set of grid cells within each series: a 2 × 2 km grid for the northern survey and a 4 × 4 km grid for the central-southern survey.

Holding the prediction domain constant through time reduced the influence of inter-annual changes in survey coverage and provided a consistent spatial basis for estimating annual biomass. Expected biomass density in each grid cell was calculated by combining the occurrence probability and positive-density components of the delta-Gamma model. Annual biomass was then estimated by spatially integrating the predicted density surface using `sdmTMB::get_index()`. Because acoustic density was expressed in t nmi^{-2}, grid-cell areas were converted from km^2 to nmi^2 before integration, yielding annual biomass estimates in tonnes.

Approximate 95% confidence intervals were obtained from the uncertainty propagated by `get_index()`. Bias correction was not applied to the final indices. Relative biomass indices were calculated by dividing each annual estimate by the mean estimated biomass across years with observed surveys within the corresponding series.

For the northern survey, the complete annual sequence from 2006 to 2026 was predicted, including 2022 as a latent year without direct survey observations. This year was identified separately in the resulting index and was not treated as an observed acoustic estimate. For the central-southern survey, indices were reported only for years with direct survey observations.

The standardized biomass estimates were subsequently compared with the corresponding conventional IFOP acoustic biomass estimates in both absolute and relative terms.

2.5. Model evaluation

Model convergence was evaluated using the numerical diagnostics provided by `sdmTMB`, including convergence of the nonlinear optimizer, positive-definite Hessian matrices, gradients of the estimated parameters, and the `sanity()` diagnostic routine. Model performance was assessed by comparing observed and predicted biomass densities on the logarithmic scale using Pearson's correlation coefficient and root mean square error (RMSE). Spatial and spatio-temporal variance parameters were also examined to evaluate the stability and biological plausibility of the fitted random fields.

Finally, standardized biomass indices were compared with the corresponding conventional IFOP acoustic biomass estimates currently used in stock assessment.

3. Results

3.1. Spatio-temporal model performance

The spatio-temporal delta model reproduced the main structural features of the data, including the high proportion of zero observations and the spatial aggregation of positive densities. Model diagnostics suggested an overall reasonable fit, although residual variability remained relatively high, as expected for zero-inflated and spatially heterogeneous data.

Alternative spatio-temporal structures (off, iid, AR1 and RW) were evaluated. The AR1 formulation provided the best model fit according to AIC, whereas the model without a spatio-temporal component (off) showed slightly better predictive performance in cross-validation. This indicates a trade-off between model fit and predictive skill. The AR1 structure was retained to represent temporal persistence, although this choice introduces uncertainty in model selection.

The inclusion of anisotropy improved model fit ($\triangle$AIC = 25.7), indicating directional spatial dependence consistent with the coastal configuration of the study area. The estimated temporal autocorrelation parameter (ρ) was low to moderate, suggesting limited persistence in spatial distribution between consecutive years.

3.2. Spatial domains and SPDE meshes

Spatial random fields were represented using the stochastic partial differential equation (SPDE) approach over triangular meshes. Mesh configuration was adapted to the spatial extent and sampling density of each survey while maintaining a common modelling framework. Sampling locations were discretized solely for mesh construction (2-km resolution in the northern survey and 4-km resolution in the central-southern survey), whereas model fitting was performed using the original observation locations.

For the northern survey, the spatial domain was defined from a concave hull encompassing all sampling locations across years. A regular 2 $\times$ 2 km prediction grid was generated within this boundary. The final SPDE mesh was constructed using a cutoff distance of 16 km, with maximum inner and outer triangle edge lengths of 32 and 160 km, respectively.

For the central-southern survey, annual survey footprints were delineated from the sampling locations and expanded using a 20-km buffer. A common prediction domain was subsequently defined by retaining grid cells sampled in at least 50% of survey years. Predictions were made on a regular 4 $\times$ 4 km grid covering this common domain. The corresponding

SPDE mesh was built using a cutoff distance of 32 km, with maximum inner and outer triangle edge lengths of 64 and 320 km, respectively.

The prediction domain was held constant through time for each survey, providing a consistent spatial framework for annual biomass estimation while accommodating differences in historical survey coverage and spatial extent between regions.

Figure 3 illustrates the final SPDE meshes used for the two surveys, including the observation locations and the corresponding prediction domains.

3.3. Standardized biomass indices

Annual standardized biomass indices were obtained by predicting the fitted models over the fixed spatial domains defined for each survey series. Predictions were generated on 2 $\times$ 2 km cells for the northern survey and 4 $\times$ 4 km cells for the central-southern survey, using the same prediction domain across years within each series. This approach reduced the influence of interannual changes in survey coverage and provided a consistent spatial basis for comparison of annual biomass estimates.

Expected biomass density at each grid cell was obtained by combining the encounter-probability and positive-density components of the delta model. Annual biomass was then estimated by spatially integrating predicted biomass density using sdmTMB::get_index(). Because biomass density was expressed in t nmi^2, grid-cell areas were converted from km^2 to nmi^2 prior to integration, yielding annual biomass estimates in tonnes with associated 95% confidence intervals.

Relative biomass indices were calculated by scaling annual biomass estimates to the mean estimated biomass across years with survey observations. This standardization facilitates comparison of temporal trajectories between the two survey series independently of differences in absolute biomass magnitude and spatial extent.

3.4. Model diagnostics

Model performance was evaluated using convergence and predictive diagnostics for both survey series. Numerical convergence was assessed from the positive definiteness of the Hessian matrix, the maximum absolute gradient at convergence, and the diagnostic checks implemented in sdmTMB::sanity().

Model predictions at the observed sampling locations were compared with the corresponding acoustic observations. Diagnostic evaluation considered the encounter component, positive biomass densities, and the combined expected biomass density, together with the examination of residual patterns across years. Estimated spatial and spatio-temporal parameters, including spatial correlation ranges and AR1 coefficients, were also inspected to evaluate the spatial scales and temporal persistence represented by each model.

Finally, standardized biomass estimates were compared with the corresponding conventional survey biomass estimates to assess the effect of accounting for spatial structure, temporal dependence, and differences in survey coverage on the resulting biomass trajectories.

3.5. Model fitting and performance

The spatio-temporal delta-Gamma models converged successfully for both the northern and central-southern acoustic surveys, with no convergence warnings or evidence of numerical instability during parameter estimation. Diagnostic checks indicated positive-definite Hessian matrices and acceptable optimization gradients, supporting the numerical stability of the final model fits.

A common prediction domain was defined independently for each survey region by retaining grid cells sampled in at least 50% of the survey years. This approach ensured that annual biomass indices were calculated over a consistent spatial domain while minimizing extrapolation into poorly sampled areas. Prediction grids were generated at resolutions matching the respective survey designs (2×2 km for the northern survey and 4×4 km for the central-southern survey), providing a standardized framework for annual biomass estimation.

3.6. Spatial predictions

The fitted models produced continuous annual predictions of jack mackerel biomass density across the common prediction domains Figure 4. Predicted density fields preserved the principal spatial patterns observed during the acoustic surveys while interpolating biomass over unsampled locations within the survey domain.

Representative prediction maps illustrate substantial interannual variability in both the location and spatial extent of biomass aggregations. In the northern survey, areas of high predicted density shifted along the continental shelf and shelf break, with notable differences in the intensity and spatial continuity of biomass hotspots among years. Similarly, the central-southern survey exhibited marked temporal changes in the distribution of predicted biomass, with periods of both localized and widespread aggregations across the prediction domain.

Despite differences in spatial coverage among survey years, the modelling framework generated coherent annual prediction surfaces that provide the basis for calculating standardized biomass indices over a fixed spatial domain.

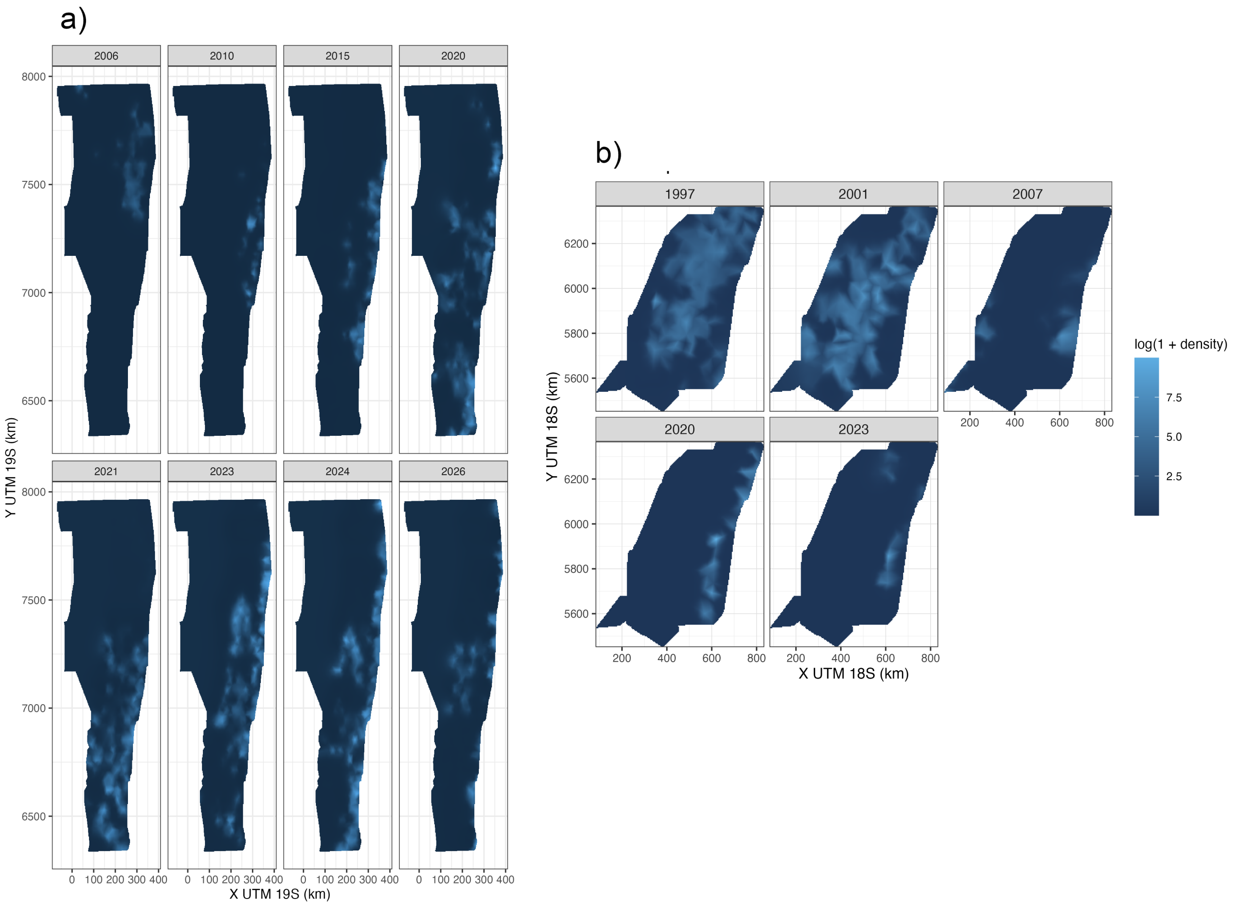

Figure 4: Representative annual spatial predictions of jack mackerel biomass density for the northern (a) and central-southern (b) acoustic surveys. Predictions were obtained from spatio-temporal delta-Gamma models and generated over the common prediction domain defined for each survey. Colours indicate the expected biomass density on a log(1 + density) scale, with a common colour scale applied within each survey to facilitate interannual comparisons.

3.7. Standardized acoustic biomass indices

The standardized biomass indices revealed contrasting temporal patterns between the northern and central-southern acoustic surveys (Figure 5). In the northern survey, relative biomass remained consistently low between 2006 and 2018, with only moderate interannual fluctuations around the long-term mean. Beginning in 2019, the index increased markedly, reaching its highest estimated values during 2023–2025 before declining in 2026. Confidence intervals were relatively narrow during the early years of the time series but increased during the period of highest estimated biomass, reflecting greater uncertainty associated with larger predicted abundance.

In contrast, the central-southern survey exhibited comparatively high relative biomass during the late 1990s and early 2000s, followed by a pronounced decline after 2001. Relative biomass remained low throughout most of the subsequent time series, with only a partial recovery observed during 2020–2021 before decreasing again in 2023. Confidence intervals generally reflected the magnitude of the estimated biomass, becoming wider during periods of higher abundance and remaining comparatively narrow during years with consistently low biomass.

Although the two acoustic surveys differ in their temporal coverage, spatial extent and sampling design, the standardized indices consistently represent relative biomass over fixed prediction domains while accounting for interannual variation in survey coverage and spatial sampling. The resulting time series provide an alternative standardized representation of relative biomass that can be compared with the indices currently available for stock assessment.

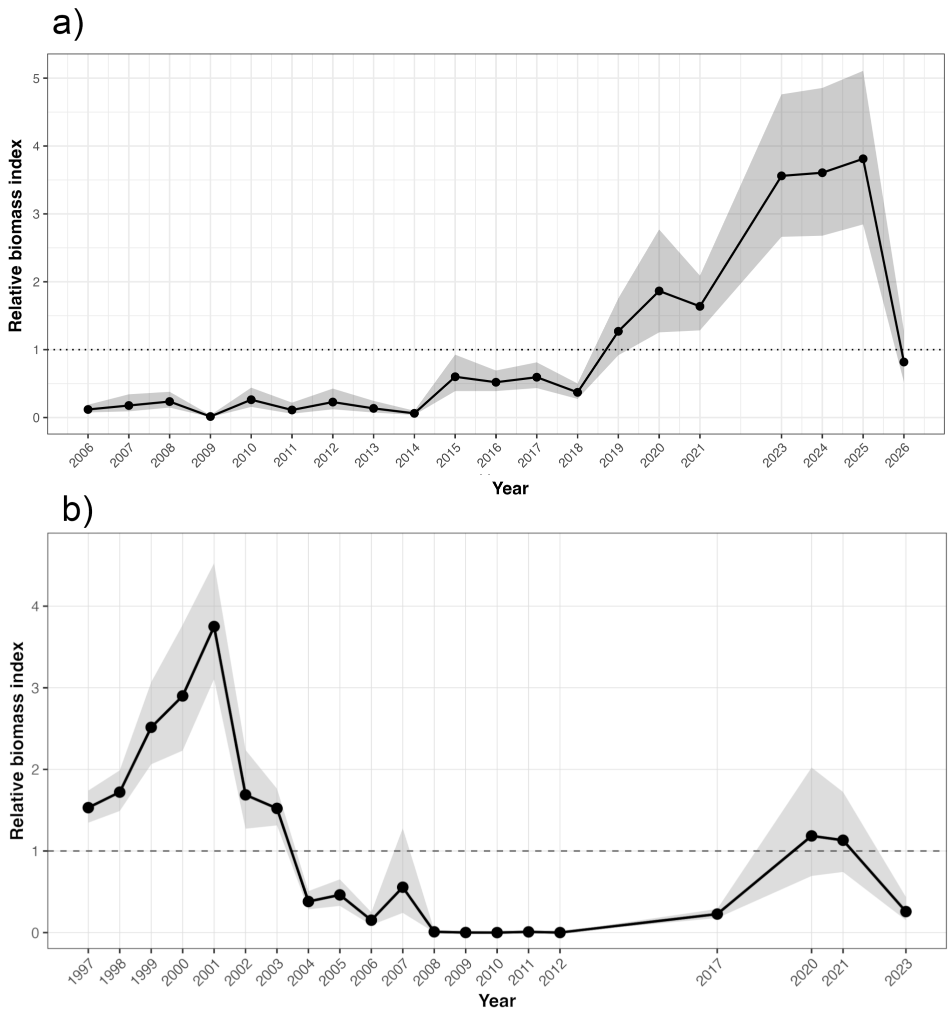

Figure 5: Standardized relative biomass indices derived from the spatio-temporal delta-Gamma models for (a) the northern Chile and (b) the central-southern Chile acoustic surveys. Indices were estimated over fixed common prediction domains using sdmTMB::getindex. Grey shaded areas indicate the 95% confidence intervals, and the horizontal dashed line denotes the long-term mean relative biomass (index = 1).

3.8. Comparison with previously available biomass indices

The standardized biomass indices reproduced the major temporal patterns observed in the previously available acoustic biomass indices for both survey regions while exhibiting differences in the magnitude of annual biomass estimates (Figure 6). Overall, both time series captured similar long-term trends, indicating that the spatio-temporal standardization preserved the principal signals of interannual biomass variability while accounting for differences in survey coverage and spatial sampling.

For the northern survey, the standardized index closely followed the temporal evolution of the historical biomass index throughout the study period. Differences between the two series were generally modest during years of relatively low biomass but became more evident during periods of increasing abundance, particularly after 2019, when the standardized estimates were consistently higher than those obtained from the historical approach. Nevertheless, both indices identified the same period of sustained biomass increase during the most recent surveys.

Similarly, the standardized biomass index for the central-southern survey reproduced the principal phases of the historical time series, including the period of relatively high biomass during the late 1990s and early 2000s, the subsequent decline, and the partial recovery observed during 2020–2021. As in the northern survey, differences between the standardized and historical series were primarily associated with the magnitude of annual biomass estimates rather than with the overall temporal pattern.

Annual biomass estimates derived from the standardized models are presented in Tables 1 and 2 for the northern and central-southern surveys, respectively. These tables provide the estimated biomass, associated confidence intervals and coefficients of variation for each survey year, constituting the standardized abundance time series generated in this study.

Overall, the comparison indicates that the spatio-temporal modelling approach preserves the principal temporal signals contained in the historical acoustic biomass indices while providing standardized annual biomass estimates that can be directly compared with the time series currently available for stock assessment.

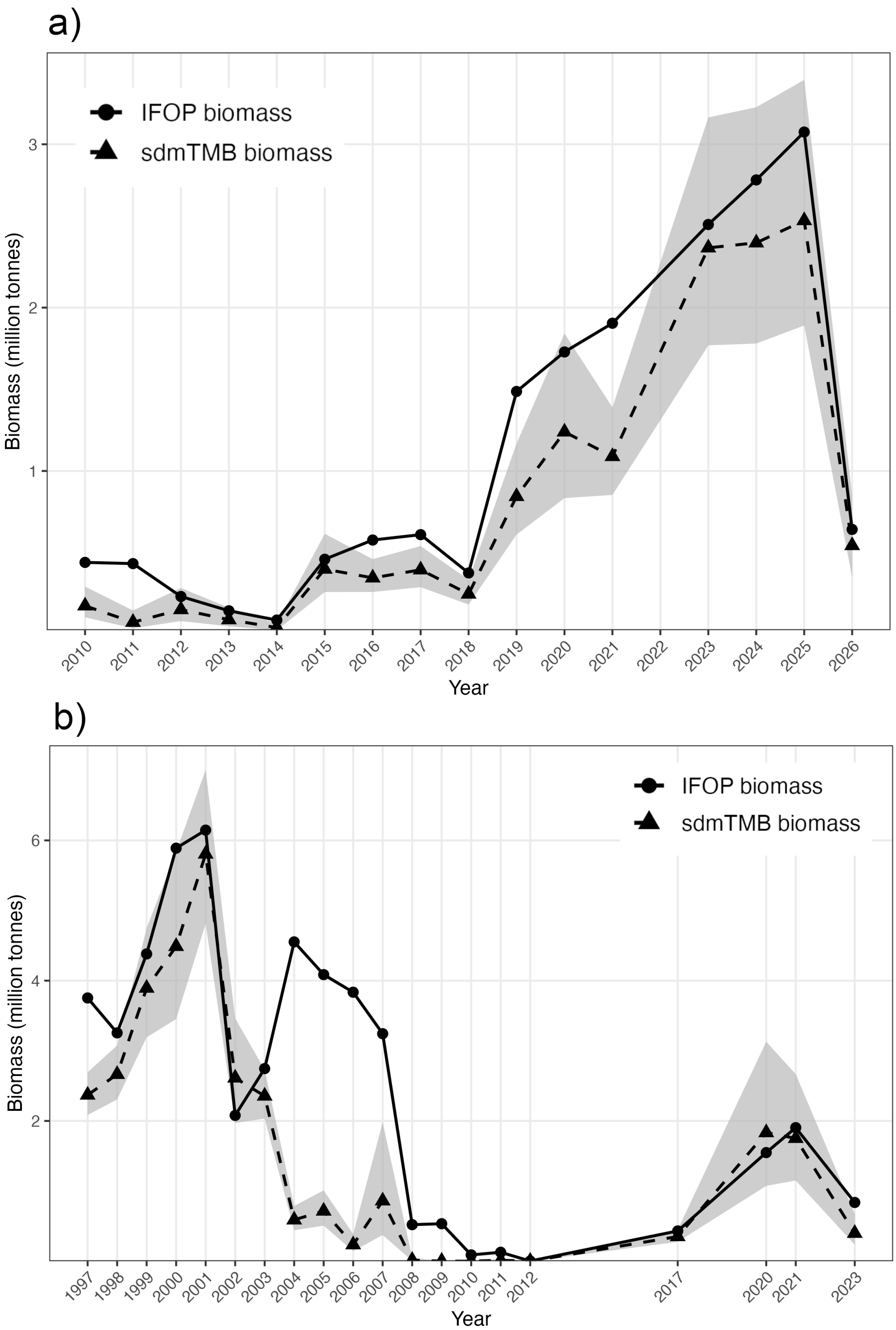

Figure 6: Comparison between the standardized biomass indices derived from the spatio-temporal delta-Gamma models (dashed lines) and the previously available acoustic biomass indices (solid lines) for (a) the northern Chile and (b) the central-southern Chile acoustic surveys. Biomass estimates are expressed in million tonnes. Grey shaded areas represent the 95% confidence intervals of the standardized biomass estimates; confidence intervals for the historical indices are omitted for clarity.

Table 1: Annual standardized biomass estimates for the northern Chile acoustic survey derived from the spatio-temporal delta-Gamma model. Biomass estimates (million tonnes), approximate 95% confidence intervals, and coefficients of variation (CV) were obtained using sdmTMB::getindex() over the fixed common prediction domain.

Year	Mean	Low	Upp
2006	78964	49839	125110
2007	117726	60939	227429
2008	156569	97179	252252
2009	9926	4219	23357
2010	174473	104146	292290
2011	73890	37407	145956
2012	151577	81053	283464
2013	89609	49166	163319
2014	41149	25518	66355
2015	399209	259059	615179
2016	345536	259397	460279
2017	394874	288562	540353
2018	246717	182584	333377
2019	844140	610473	1167246
2020	1239113	833925	1841174
2021	1088773	853476	1388938
2023	2365964	1769135	3164136
2024	2396717	1780221	3226708

Table 2: Annual standardized biomass estimates for the central-southern Chile acoustic survey derived from the spatio-temporal delta-Gamma model. Biomass estimates (million tonnes), approximate 95% confidence intervals, and coefficients of variation (CV) were obtained using sdmTMB::getindex() over the fixed common prediction domain.

Year	Mean	Low	Upp
1997	2369639	2084695	2693531
1998	2664210	2306774	3077030
1999	3893754	3192516	4749020
2000	4488571	3451836	5836682
2001	5805762	4811193	7005928
2002	2612972	1971118	3463832
2003	2355367	2033583	2728068
2004	589709	441841	787064
2005	715488	507035	1009640
2006	235175	143432	385601
2007	860752	374277	1979538
2008	14890	4576	48452
2009	1587	566	4452
2010	201	21	1885
2011	13715	5940	31670
2012	888	81	9767
2017	351553	275991	447802
2020	1833827	1074336	3130235
2021	1751652	1150496	2666923
2023	398504	235913	673153

4. Concluding remarks

The principal findings of this study can be summarized as follows:

- A common spatio-temporal modelling framework was successfully developed and applied to standardize biomass indices from the two long-term Chilean jack mackerel acoustic surveys. Despite differences in temporal coverage, spatial extent, sampling resolution and historical survey design, both surveys were analysed using a consistent methodology based on delta-Gamma models, SPDE random fields and fixed prediction domains.
- The proposed modelling framework generated coherent annual biomass surfaces and standardized abundance indices while explicitly accounting for spatial dependence, temporal autocorrelation and interannual variation in survey coverage.
- The standardized biomass indices reproduced the principal temporal patterns observed in the conventional acoustic biomass series while exhibiting differences in the magnitude of annual biomass estimates during some periods. These differences likely reflect the explicit treatment of spatial heterogeneity and changing survey coverage through time.
- The resulting standardized time series should be regarded as an alternative representation of relative biomass rather than as a replacement for the acoustic biomass indices currently used in stock assessment. Instead, they provide an additional source of information that can be evaluated alongside existing survey indices within future SPRFMO stock assessment exercises.
- The modelling framework developed in this study is readily transferable to future survey updates and may also be applicable to other long-term fishery-independent monitoring programmes where changes in survey coverage or sampling design influence the temporal consistency of abundance indices.

- Future work should focus on evaluating the sensitivity of the standardized indices to alternative model configurations, prediction domains and validation approaches, as well as assessing their performance within the SPRFMO stock assessment framework.

References

Anderson, S. C., Ward, E. J., English, P. A., Barnett, L. A., & Thorson, J. T. (2025). sdmtmb: an r package for fast, flexible, and user-friendly generalized linear mixed effects models with spatial and spatiotemporal random fields. *Journal of Statistical Software*, *115*, 1–46.