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Improving Hydroacoustic Assessment of Chilean Jack Mackerel (*Trachurus murphyi*): Sampling Design and Bayesian Spatial Modelling for Density Estimation

Chile

IMPROVING HYDROACOUSTIC ASSESSMENT OF CHILEAN JACK MACKEREL (*Trachurus murphyi*): SAMPLING DESIGN AND BAYESIAN SPATIAL MODELLING FOR DENSITY ESTIMATION

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ABSTRACT

Hydroacoustic surveys provide an important fishery-independent source of information for estimating the distribution and relative abundance of pelagic resources. However, the accuracy and comparability of acoustic indices depend on both the spatial coverage and configuration of the sampling design and the statistical methods used to account for unsampled areas. This study evaluates methodological improvements for the hydroacoustic assessment of Chilean jack mackerel (*Trachurus murphyi*) in northern and central-southern Chile, focusing on sampling design and spatial modelling.

A Bayesian spatial and spatio-temporal framework based on INLA-SPDE was applied to separate the probability of occurrence from positive acoustic density, while accounting for spatial and temporal autocorrelation of the data. Model performance was evaluated using WAIC, and predictions were performed over a common inference area to improve interannual comparability. Alternative sampling designs were tested through 1,000 simulated surveys for each scenario, comparing the different numbers and configurations of transects for each scenario in terms of precision, uncertainty and survey effort.

Results showed substantial interannual variability in the spatial distribution and acoustic density of jack mackerel. Spatial dependence improved model performance in a relevant proportion of the analysed years, although its contribution varied between areas, years and model components. The results also indicated that spatial coverage strongly influences the uncertainty of density estimates. In northern Chile, the current sampling design provided an adequate balance between spatial coverage and precision, although a 16-transect design represents a viable alternative under operational constraints. In central-southern Chile, a 16-transect adaptive design with increased sampling effort in the oceanic sector achieved uncertainty levels comparable to those of a 32-transect design, but with substantially lower survey effort.

Our results highlight the importance of integrating spatial modelling and simulation-based sampling design assessment to improve the precision, efficiency, consistency and robustness of hydroacoustic surveys. Sampling strategies should be designed based on the spatial structure of the resource and the operational characteristics of each assessment area.

Keywords: *Trachurus murphyi*, Chilean Jack Mackerel, hydroacoustic, sampling design, acoustic density, geostatistics, Bayesian models, INLA-SPDE, uncertainty and precision.

1. INTRODUCTION

Chilean jack mackerel (*Trachurus murphyi*) is one of the main exploited pelagic resources in the Southeast Pacific. Its broad and dynamic spatial distribution poses significant challenges for its scientific assessment (Serra, 1991; Elizarov *et al.*, 1993; Gerlotto *et al.*, 2012; Gretchina, 1998). In this context, hydroacoustic surveys provide an important fishery-independent source of information for estimating the density and abundance of pelagic resources. However, the quality and comparability of hydroacoustic estimates depend on several factors, including spatial coverage, transect intensity and configuration, and the methods used to estimate density in unobserved areas (Simmonds and MacLennan, 2005).

A historical review of hydroacoustic surveys conducted to assess Chilean jack mackerel in the Northern and Central-Southern areas of Chile revealed differences among surveys in terms of the spatial coverage, the extent of the surveyed areas, and transect configuration. These differences may affect the comparability of time series and complicate the interpretation of interannual changes in the spatial distribution and density of the resource. In addition, hydroacoustic data are characterized by a high proportion of zero observations and a markedly skewed distribution of positive values, requiring methodological approaches capable of adequately representing the spatial and temporal variability of the resource. To address this issue, spatial and spatio-temporal models were implemented within a Bayesian framework based on INLA-SPDE (Rue *et al.,* 2009; Lindgren *et al.,* 2011).

This Working Paper addresses two complementary components aimed at improving hydroacoustic assessments of Chilean jack mackerel in Chile: (i) the evaluation and optimization of the hydroacoustic sampling design by applying Bayesian spatio-temporal models, and (ii) the application of simulation-based sampling design scenarios to improve the precision and accuracy of mean density and its associated uncertainty. Integrating these two components enables a joint assessment of the ability of the sampling design to adequately represent the spatial distribution of the resource and the contribution of spatial modelling to estimating mean density across the surveyed area.

2. MATERIALS AND METHODS

2.1. Study Area

The analysis considered two hydroacoustic research areas for Chilean jack mackerel in Chilean waters: the Northern Area and the Central-Southern Area (Figure 1).

Both areas were analyzed independently due to differences observed in the spatial structure of the resource, the scale of aggregations, and the historical development of the sampling designs.

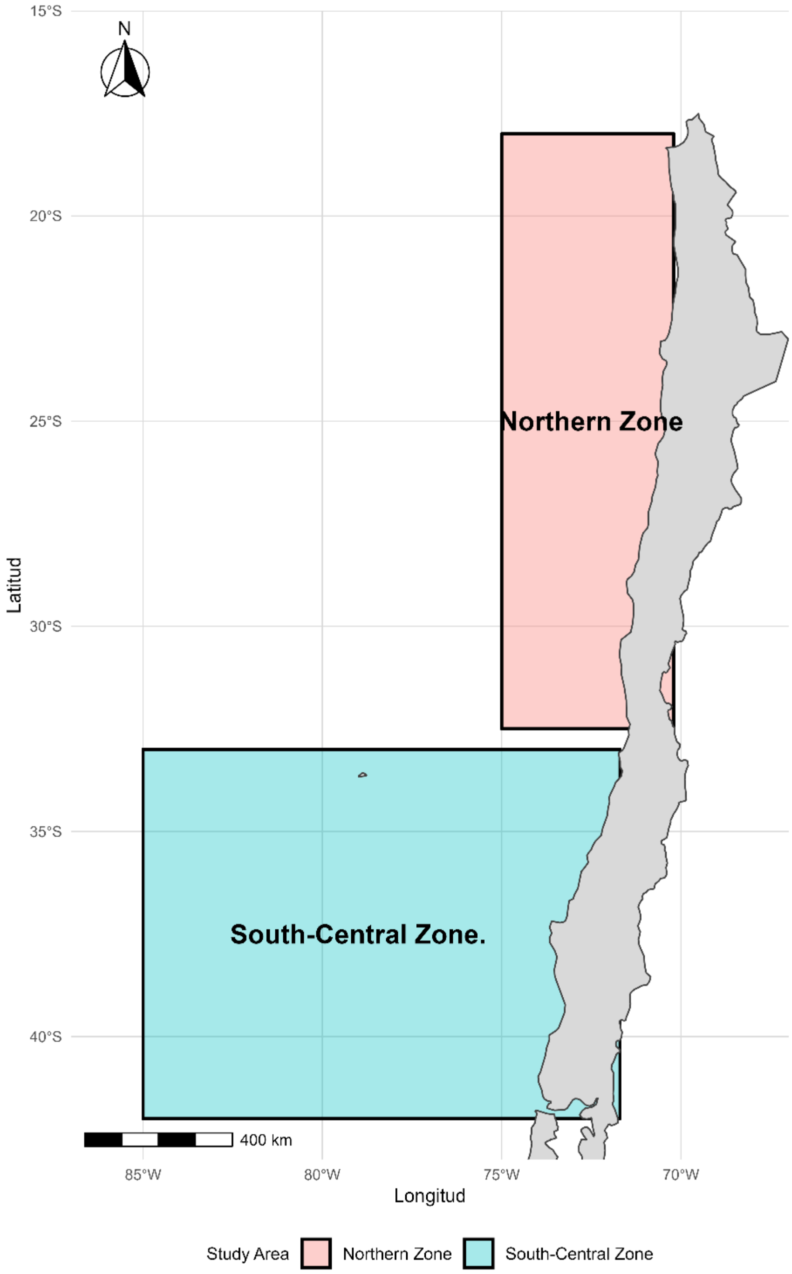

Figure 1. Study area and historical coverage of Chilean jack mackerel hydroacoustic surveys in the Northern and Central-Southern areas.

2.2. Hydroacoustic Data

The analysis considered two assessment regions in Chile: The Northern and Central-Southern Areas. A common analytical framework was applied to both regions; however, the historical time series differed substantially in terms of temporal continuity and spatial coverage. In the Northern Area, the standardization analysis included acoustic surveys conducted between 2006 and 2024, with no survey conducted in 2022. The database contained 133,906 georeferenced observations, including 127,509 zero-density observations and 6,397 positive-density observations. For the Central-Southern Area, the standardization analysis covered the period 1997–2023, with no direct observations from acoustic surveys in 2013–2016, 2018–2019, and 2022. The database contained 183,211 observations, including 162,016 zero-density observations and 21,195 positive-density observations (Table 1).

Table 1. Characteristics of the acoustic databases used for spatio-temporal standardization.

Region	Analysis period	Total observations	Zero density	Positive density	Zero proportion
Northern Chile	2006–2024	133,906	127,509	6,397	95.2%
Central-southern Chile	1997–2023	183,211	162,016	21,195	88.4%

Note: Years without direct acoustic surveys were retained as latent temporal steps in the spatio-temporal models and were not interpreted as years with observed acoustic indices.

An important characteristic of the databases was the high frequency of observations with zero density. This feature was explicitly incorporated into the models through a delta approach.

2.3. Development and Evaluation of a Bayesian Approach for Chilean Jack Mackerel Density Estimation and Uncertainty

A geostatistical approach was applied considering the distribution and density responses as separated, independent and random stationary processes following the framework proposed by Roa-Ureta and Niklitschek (2007). Chilean jack mackerel occurrence was defined as a dichotomous (presence-absence) response defined by a density threshold (>0.1 t·nmi^{-2}). The prediction of this process corresponded to jack mackerel probability of presence. Conditional density corresponded to density values within jack mackerel aggregations modelled using a Gamma distribution. Spatial and temporal variability were incorporated separately, considering year as the temporal dimension and a Matérn spatial correlation structure over a regular mesh, together with a first-order autoregressive temporal structure (AR1), following the approach of Niklitschek and Skaret (2016).

Inference was conducted using a Bayesian framework implemented by applying the Integrated Nested Laplace Approximation (INLA) and the Stochastic Partial Differential Equation (SPDE) approach (Lindgren et al., 2011), where both distribution and density processes were assumed as Gaussian Markov Random Fields (GMRF) (Rue and Held, 2005). Due to the computational cost associated with simultaneously fitting spatial and temporal dependencies, a sequential strategy was adopted, initially estimating the temporal structure and subsequently using its results to characterize spatial dependence.

Based on the posterior distributions of the probability of occurrence and conditional density, a Relative Biomass Index (RBI) was estimated for each sampling scenario by integrating both components over the spatial domain of the assessment area. Scenario performance was evaluated based on the posterior distribution of the RBI, considering its mean, standard deviation, credible intervals, and coefficient of variation (CV). Comparison of the alternatives allowed the trade-off between precision, uncertainty, and spatial representativeness to be assessed, using the reduction in CV as one of the main criteria for determining the relative improvement in the sampling design.

2.3.1. Bayesian Spatial Modelling Using INLA-SPDE

Bayesian spatial modelling was implemented using the Integrated Nested Laplace Approximation (INLA), with the Stochastic Partial Differential Equation (SPDE) approach used to represent the latent spatial structure of both processes. This approach approximates a spatially continuous Gaussian random field using a Gaussian Markov Random Field (GMRF) defined over a triangular spatial mesh, thereby reducing the computational complexity associated with estimating large-scale spatial models (Lindgren *et al.*, 2011).
In general terms, the spatial structure of the model can be expressed as:

$$Y(s)=\mu(s)+\omega(s)+\varepsilon(s)$$

where $Y(s)$ represents the observation at location s, $\mu(s)$ corresponds to the structural component or mean trend, $\omega(s)$ represents the latent spatial effect, and $\varepsilon(s)$ corresponds to the residual error.

The SPDE approach represents the spatial field as a linear combination of basis functions defined on a triangular mesh:

$$\omega(s)=\sum_{k=1}^{K}\psi_k\,(s)w_k$$

where $\psi_k(s)$ are basis functions associated with the mesh nodes and w_k corresponds to the spatial weights. This formulation allows continuous spatial structures to be approximated using a finite number of parameters while taking advantage of the sparse structure of the precision matrices characteristic of GMRFs, thereby improving computational efficiency (Lindgren *et al.*, 2011).

The INLA approach was used to obtain approximate posterior distributions for the model parameters, hyperparameters, and spatial predictions, avoiding the intensive use of MCMC simulation methods and reducing the computational requirements for Bayesian inference (Rue *et al.*, 2009). Within this framework, the INLA-SPDE combination allowed the spatial dependence of the resource to be explicitly incorporated and predictions to be generated over a common spatial mesh, providing a consistent basis for estimating mean density and comparatively evaluating the sampling scenarios.

2.3.2. Model Selection and Evaluation

Spatial models were selected using the Watanabe-Akaike Information Criterion (WAIC), comparing models that incorporated spatial components with null (interecept-only) models.

WAIC was used as a criterion for relative comparison, with lower values indicating more support by the data and better expected predictive performance.

The analysis allowed assessment of whether the explicit incorporation of spatial structure contributed to explaining the observed variability in occurrence and positive-density processes.

2.4. Historical Review and Evaluation of the Sampling Design

The historical review of Chilean jack mackerel hydroacoustic surveys in the Northern and Central-Southern areas considered transect configuration and orientation, transect spacing, spatial coverage, and the extent of the surveyed areas. This information was used to characterize the evolution of the sampling designs and establish a common basis for evaluating alternative optimization strategies in both study areas.

To improve the sampling design, methodological approaches for analysing data with spatial and spatio-temporal dependence were reviewed. Based on this review, a Bayesian approach based on the Integrated Nested Laplace Approximation (INLA) was evaluated, using the spatio-temporal information from the scientific survey time series to construct a predicted reality representative of jack mackerel distribution.

On this basis, a simulation procedure was implemented to compare the performance of different sampling designs and intensities, considering scenarios with different numbers of transects arranged parallel to the coastline. Using Bayesian kriging and resampling of historical information, 1,000 virtual seascapes were generated and subsequently sampled according to the survey trajectories defined for each scenario. For each replicate, mean density and its associated uncertainty measures were estimated, allowing the precision and accuracy of the designs to be comparatively evaluated.

Scenario performance was evaluated considering the predicted mean density, credible intervals, the Relative Biomass Index (RBI), standard error, and coefficients of variation (CV). Design selection aimed to identify alternatives capable of reducing uncertainty and maximizing estimation precision, using CV as one of the main comparison criteria, following the methodology applied by Canseco *et al.* (2025).

Additionally, a relative approximation of the operational cost of each scenario was incorporated by estimating transect survey time, assuming a constant vessel speed of 10 knots. Survey time was calculated from the total distance travelled along transects and expressed as navigation days. This estimate considers only the effective time required to complete the transects and therefore excludes travel between transects and navigation time to and from port. Once the sampling design has been selected, the total survey duration should also include travel between transects and complementary survey activities, including oceanographic stations, plankton sampling, and fishing operations intended for species identification, collection of biological samples, and validation of acoustic records.

3. RESULTS

3.1. Development and Evaluation of a Bayesian Approach for Chilean Jack Mackerel Density Estimation and Uncertainty

3.1.1. Northern Area

The application of the Bayesian approach allowed the probability of Chilean jack mackerel presence and density conditional on occurrence to be estimated separately, with both components subsequently integrated to obtain corrected mean density estimates over a constant inference area. The results showed marked interannual variability in both the probability of presence and estimated density.

The predicted probability of presence ranged from 0.04 to 0.19, whereas corrected mean density ranged from 41 to 696 $t \cdot nmi^{-2}$. The lowest density was estimated in 2009 (41 ± 15 $t \cdot nmi^{-2}$), whereas the highest values corresponded to 2023 (696 ± 217 $t \cdot nmi^{-2}$) and 2024 (568 ± 152 $t \cdot nmi^{-2}$). Substantial increases were also observed in recent years, particularly in 2019, 2020, and 2021 (Table 2).

The uncertainty associated with the estimates showed substantial interannual variability. The coefficient of variation (CV) of corrected density ranged from 2% to 81%, with the highest values occurring in years characterized by lower survey spatial coverage. In contrast, the lowest levels of uncertainty were obtained in years with broader spatial coverage. This pattern highlights the influence of spatial representation of the study area on the precision of density estimates (Table 2).

The spatial distribution of predictions showed that the highest densities were concentrated mainly in the central-southern sector of the inference area, whereas the northern sector generally exhibited lower values (Figures 2 and 3). This pattern demonstrated that mean density estimates depend strongly on the spatial coverage achieved by each survey. Years with lower coverage tended to exhibit lower mean estimates and greater uncertainty, indicating that a reduction in the surveyed area may generate a negative bias in the estimation of the Relative Biomass Index and increase associated uncertainty.

Table 2. Predicted values of probability of occurrence and corrected acoustic density obtained from Bayesian models for the Northern Area.

Year	PP	PP.ee	Corrected Density ($t \cdot nmi^{-2}$)	CD.ee	CV (%)
2006	0.10	0.013	50	7	14
2007	0.05	0.003	148	45	30
2008	0.04	0.005	54	18	33
2009	0.09	0.008	41	15	37
2010	0.07	0.026	95	24	25
2011	0.07	0.037	154	125	81
2012	0.05	0.012	69	24	35
2013	0.05	0.016	73	27	37
2014	0.09	0.037	47	26	55
2015	0.08	0.023	143	40	28
2016	0.08	0.003	87	11	13
2017	0.08	0.012	157	18	11
2018	0.08	0.004	58	7	12
2019	0.10	0.005	424	96	23
2020	0.11	0.006	181	11	6
2021	0.12	0.009	190	40	21
2023	0.13	0.002	696	217	31
2024	0.10	0.008	568	152	27

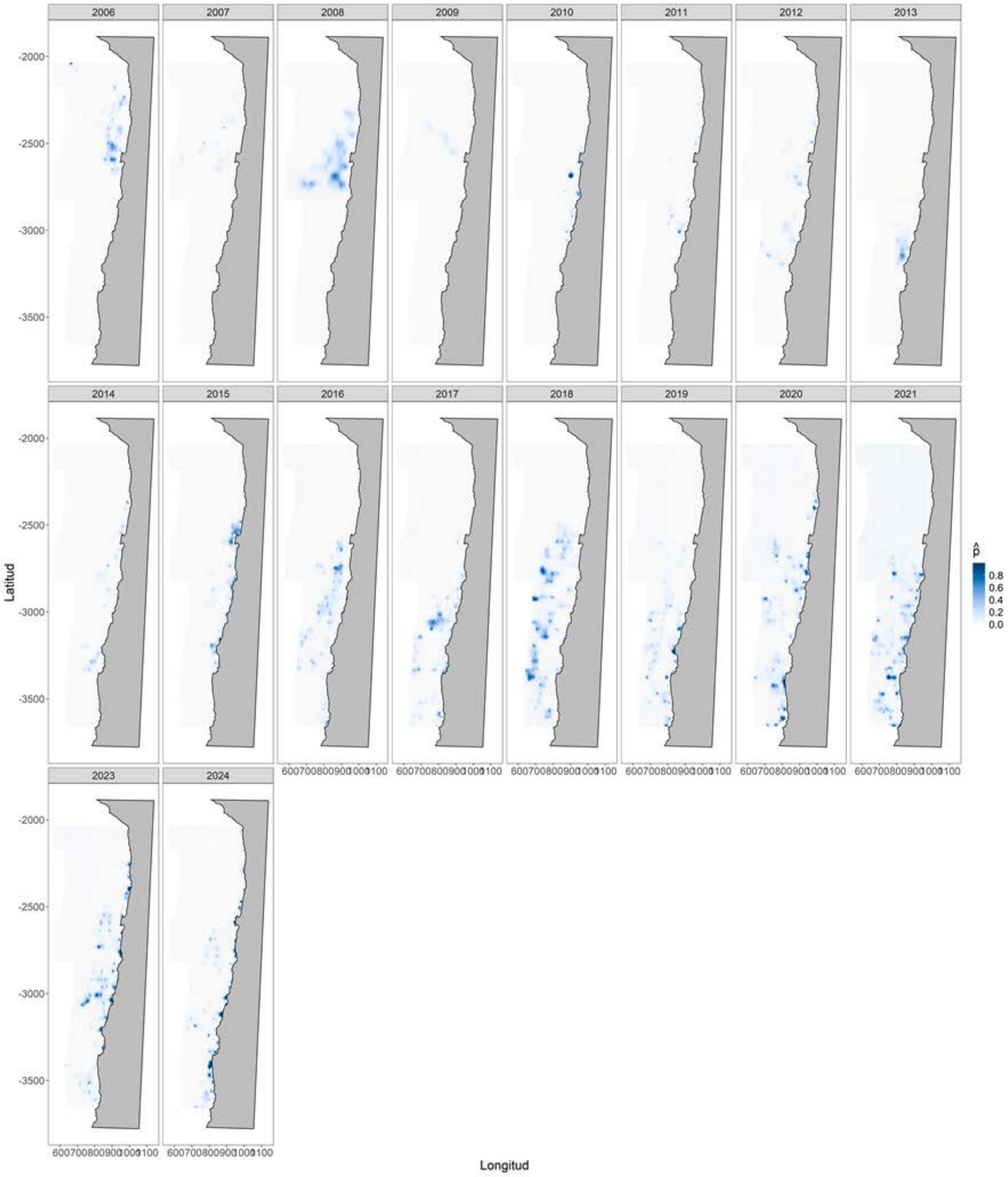

Figure 2. Predicted probability of occurrence obtained by fitting spatial models with a binomial distribution family for each survey conducted in the Northern Area, using a fixed inference area between 2006 and 2024.

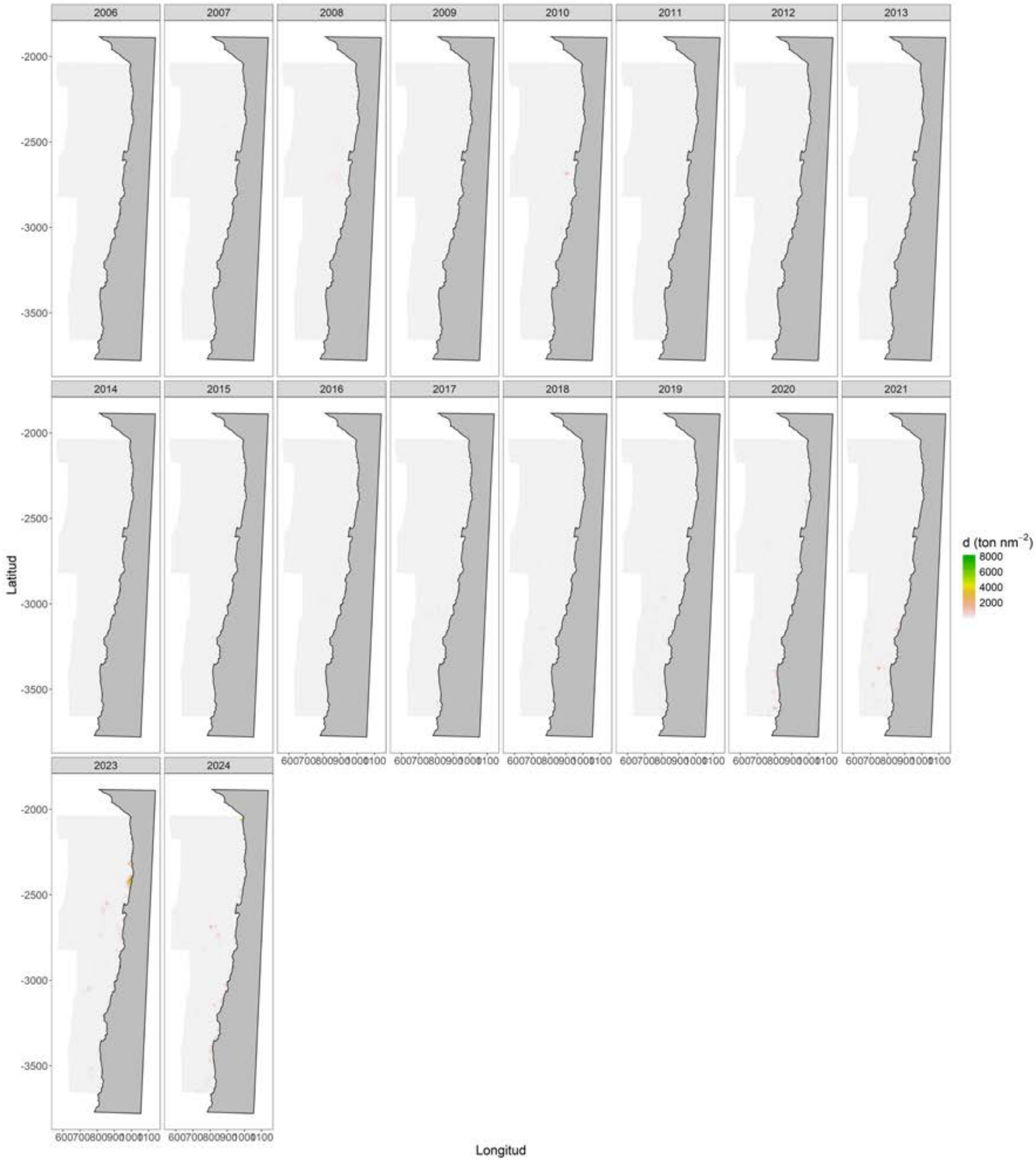

Figure 3. Corrected density estimated using spatial models fitted with a Gamma distribution family for each survey conducted in the Northern Area, considering a constant inference area between 2006 and 2024.

3.1.2. Central-Southern Area

In the Central-Southern Area, the Bayesian approach allowed the probability of presence and corrected mean density to be estimated over a constant inference area, facilitating comparisons among surveys conducted between 1997 and 2023 (Table 3). The probability of presence showed considerable interannual variability, ranging from 0.01 to 0.25. The highest values were estimated in 2003 (0.25), 2010 (0.23), and 2002 (0.22), whereas the lowest values corresponded to 2012 (0.01) and 2011 (0.02) (Table 3).

Corrected mean density also exhibited high temporal variability, ranging from 11 ± 7 t·nmi^{-2} in 2009 to 345 ± 121 t·nmi^{-2} in 2020. Relatively high values were also observed during the early years of the time series, such as in 1997 (211 ± 264 t·nmi^{-2}) and 2000 (140 ± 72 t·nmi^{-2}) (Table 3).

The spatial distribution of the probability of occurrence and corrected mean density showed marked interannual variability, reflecting changes in the spatial distribution and intensity of Chilean jack mackerel aggregations within the inference area (Figures 4 and 5). Overall, the predictions showed that the distribution of Chilean jack mackerel was not constant among surveys, with changes in spatial occupancy and in the concentration of the highest densities within the inference area.

CV values ranged from 9% to 125%, with the highest levels of uncertainty mainly associated with years with limited spatial coverage or lower representation of the resource distribution (Table 3). In this context, the results show that coverage of the inference area is an important factor affecting estimation precision, reinforcing the importance of maintaining consistent spatial coverage among surveys.

Table 3. Predicted values of probability of occurrence and corrected mean density obtained from Bayesian models for the Central-Southern Area.

Year	PP	PP.ee	Corrected Density (t·nmi^{-2})	CD.ee	CV (%)
1997	0.18	0.02	211	264	125
1998	0.16	0.04	104	52	50
1999	0.18	0.03	97	17	18
2000	0.14	0.02	140	72	51
2001	0.17	0.02	118	21	18
2002	0.22	0.04	61	14	23
2003	0.25	0.06	127	40	31
2004	0.20	0.05	107	16	15
2005	0.08	0.01	54	7	13
2006	0.18	0.00	85	8	9
2007	0.12	0.02	87	37	43
2008	0.04	0.01	13	7	54
2009	0.05	0.02	11	7	64
2010	0.23	0.07	13	2	15
2011	0.02	0.01	15	9	60
2012	0.01	0.00	29	18	62
2017	0.13	0.01	31	15	48
2020	0.12	0.01	345	121	35
2021	0.07	0.02	92	29	32
2023	0.06	0.03	26	6	23

Figure 4. Predicted probability of occurrence obtained by fitting spatial models with a binomial distribution family for each survey conducted in the Central-Southern Area, using a fixed inference area between 1997 and 2023.

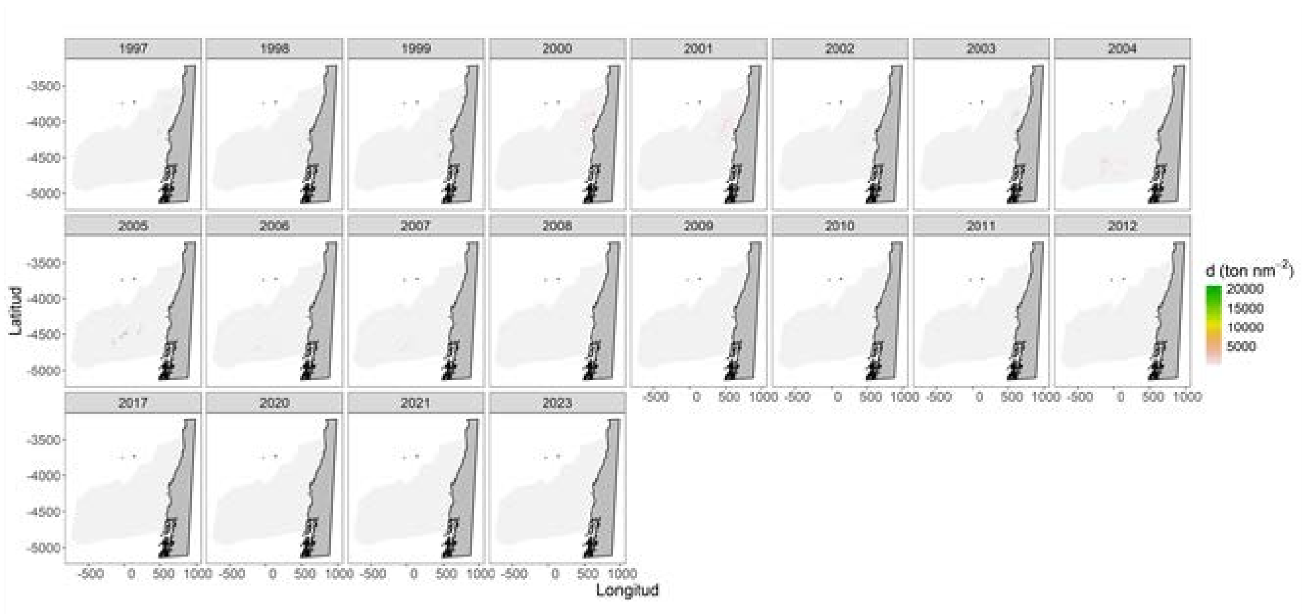

Figure 5. Corrected density estimated using spatial models fitted with a Gamma distribution family for each survey conducted in the Central-Southern Area, considering a constant inference area between 1997 and 2023.

The results showed a relationship between survey spatial coverage and estimation precision. In particular, years with lower coverage of the inference area exhibited higher coefficients of variation, indicating that a substantial proportion of the uncertainty is associated with the ability of the sampling design to represent the spatial distribution of the resource. In this context, it is recommended that surveys cover the entire potential distributional area, either through a smaller number of extended transects or through a greater number of transects distributed homogeneously throughout the study area.

3.1.3. Comparison of Spatial Structure Between Areas

INLA-SPDE modelling identified a differentiated spatial structure between the probability of presence and conditional density, as well as differences in the spatial structure between the Northern and Central-Southern areas. In both areas, the spatial ranges associated with the probability of presence were generally larger than those estimated for the conditional density, suggesting that the overall distribution of the resource exhibits a larger-scale spatial structure upon which more localized high-density aggregations develop.

In the Northern Area, the largest spatial range estimated for the binomial process was approximately 218 km, whereas the maximum range for the Gamma process was approximately 62 km. In the Central-Southern Area, the maximum values were approximately 475 km for the probability of presence and 72 km for conditional density (Table 4). These results suggest a greater spatial extent in the presence-absence structure in the Central-Southern Area, whereas the spatial scales associated with conditional-density aggregations were relatively similar between the two areas.

Table 4. Comparative summary of Bayesian spatial modelling results for the Northern and Central-Southern areas.

Area	Component	Approximate maximum spatial range	Main result
Northern	Probability of presence (Binomial)	218 km	Large-scale spatial structure and interannual variability
Northern	Conditional density (Gamma)	62 km	Aggregations with a more localized spatial structure
Central-Southern	Probability of presence (Binomial)	475 km	Larger spatial scale of the overall distribution
Central-Southern	Conditional density (Gamma)	72 km	Spatially structured aggregations at an intermediate scale

Comparison using WAIC (Table 5) showed that incorporating spatial structure improved predictive performance in a substantial proportion of the years analysed, although the magnitude of this improvement varied among surveys and between the probability of presence and conditional density components. In the Northern Area, the contribution of the spatial structure was particularly relevant to the probability of presence in several recent years, whereas in the Central-Southern Area the Gamma process showed more consistent evidence in favour of incorporating spatial autocorrelation.

These results indicate that the spatial structure of Chilean jack mackerel is not constant among years or areas; therefore, the incorporation of spatial effects should be explicitly evaluated for each dataset. The use of the WAIC criterion allowed this assessment to be conducted objectively, identifying formulations that provided better predictive performance.

Table 5. Summary of model evaluation using WAIC.

Area	Component	Overall result	Implication
Northern	Binomial	The spatial model showed better performance in a substantial proportion of years	The spatial distribution of the resource provides relevant predictive information
Northern	Gamma	Spatial structure frequently improved model performance	Aggregations exhibit spatial dependence
Central-Southern	Binomial	Results varied among years	The spatial structure of the probability of presence changes interannually
Central-Southern	Gamma	More consistent evidence in favour of the spatial model	Aggregations exhibit a relatively stable spatial structure

3.1.4. Synthesis of Results from the Bayesian Approach

Overall, the results obtained for the Northern and Central-Southern areas demonstrate that the Bayesian approach based on INLA-SPDE models allowed the spatial structure of Chilean jack mackerel to be explicitly represented and the processes associated with the probability of presence and aggregation intensity to be separated. The use of a constant inference area also reduced the influence of differences in spatial coverage among surveys and provided a more consistent basis for temporal comparisons.

A common result in both areas was that the spatial structure associated with the probability of occurrence was generally larger than that corresponding to the conditional density. However, the Central-Southern Area exhibited a greater spatial extent of the occurrence structure, with maximum ranges considerably larger than those estimated for the Northern Area. In contrast, the spatial structure of the density aggregations were more similar between the two areas.

Comparison using WAIC supported the usefulness of incorporating spatial dependence into the modelling of Chilean jack mackerel distribution, although the relative contribution of this structure varied among years and between the two processes. This result indicates that the spatial structure of the resource is dynamic and that its statistical representation should account for temporal variability.

Finally, the results show that the precision of mean density estimates is closely related to the ability of the sampling design to represent the spatial distribution of the resource. In this regard, the Bayesian modelling framework developed here provides the statistical basis for subsequently evaluating alternative sampling designs, allowing assessment of how different configurations and levels of spatial coverage may affect the precision and uncertainty of acoustic density estimates.

3.2. Results of the Historical Review and Sampling Design Evaluation

3.2.1. Northern Area

The historical review of Chilean jack mackerel hydroacoustic surveys in the Northern Area revealed interannual variation in transect configuration, extent, and spatial coverage. These differences in the intensity and distribution of sampling effort provided the basis for evaluating alternative designs through simulation, considering configurations with different numbers of transects and transect spacing.

To establish a reference scenario for evaluating the different designs, a spatio-temporal model was fitted using all available surveys from the Northern Area. A mean density of 20 t·nmi^{-2}, with a coefficient of variation (CV) of 7%, was used as the reference. Based on the spatial and temporal structure estimated from the historical time series, 1,000 independent replicates were generated for each sampling scenario. The designs evaluated included 6, 10, 16, and 32 transects, as well as two alternatives involving 16 transects with adaptive sampling in areas of projected high density.

The results showed a general decrease in uncertainty as the number of transects increased. The 6-transect scenario yielded an estimated mean density of 35.7 t·nmi^{-2}, with a mean CV of 19%, whereas with 10 transects the mean density decreased to 28.2 t·nmi^{-2} and the CV to 12%. The 16-transect scenario yielded a mean density of 32.2 t·nmi^{-2} and a CV of 12%, whereas the 32-transect design yielded a mean density of 29.3 t·nmi^{-2} and the lowest mean CV, at 6%. However, increasing sampling intensity did not result in a proportional improvement in estimation accuracy, as even the 32-transect scenario remained positively biased relative to the reference value of 20 t·nmi^{-2} (Table 6; Figures 6 and 7).

The 16-transect adaptive designs yielded mean densities of 33.5 and 33.4 t·nmi^{-2}, respectively, and mean CVs of 9% in both cases. Therefore, intensifying sampling in areas of higher projected density did not produce relevant improvements in accuracy or substantial reductions in uncertainty relative to the systematic designs (Table 6; Figures 6 and 7).

Operational results showed a substantial increase in effort associated with increased sampling intensity. Estimated transect survey time increased from 4 days with 6 transects to 23 days with 32 transects (Table 6).

Table 6. Performance of the sampling scenarios evaluated in the Northern Area.

Scenario	Mean density (t·nmi^{-2})	CI 95%	SD	Mean CV (%)	CI 95% CV	DE CV	Duration (days)
6 transects	35.7	28.0–45.8	4.7	19	5–40	10	4
10 transects	28.2	23.9–33.4	3.0	12	4–28	6	7
16 transects	32.2	28.3–38.7	2.9	12	3–32	7	11
32 transects	29.3	27.0–32.9	1.6	6	1–14	4	23

16 transects, oceanic adaptive	33.5	29.3–39.3	2.8	9	2–26	7	19
16 transects, oceanic and coastal adaptive	33.4	29.7–40.7	3.2	9	2–22	6	20

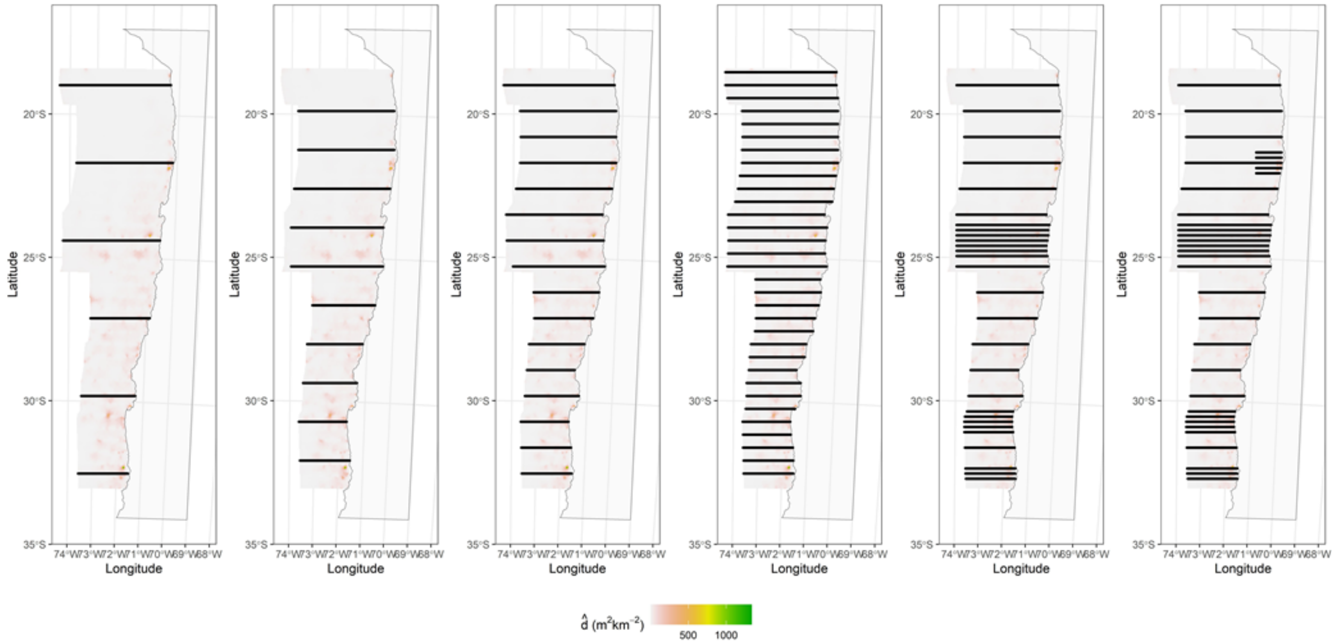

Figure 6. Predicted acoustic density obtained by fitting a model incorporating temporal and spatial correlation for the following scenarios: (a) 6 transects, (b) 10 transects, (c) 16 transects, (d) 32 transects, (e) 16 oceanic adaptive transects, and (f) 16 oceanic and coastal adaptive transects. For each scenario, 1,000 resampling replicates were conducted to identify the sampling strategy that reduced uncertainty (lower CV) for surveys in the Northern Area.

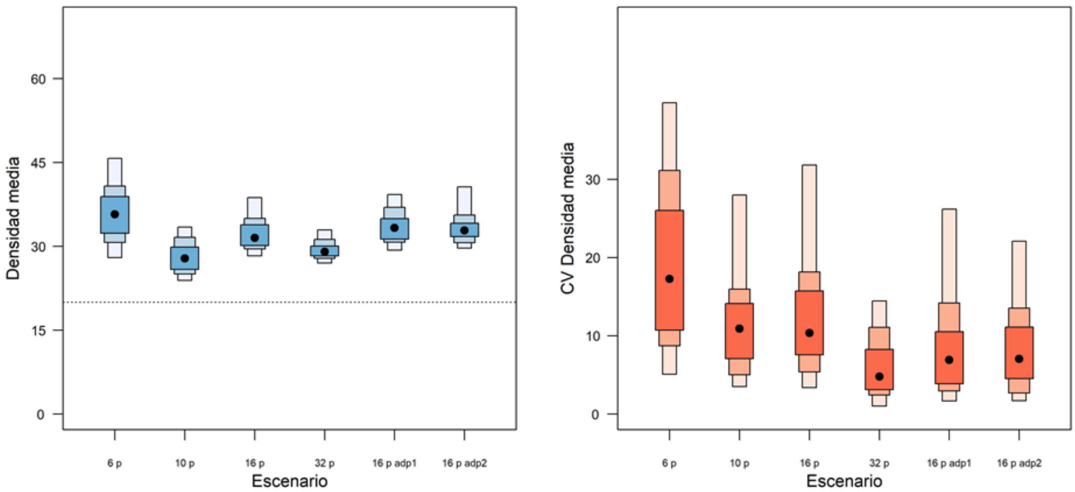

Figure 7. Predicted acoustic density obtained by fitting a model incorporating temporal and spatial correlation, with 1,000 resampling replicates conducted to identify the sampling strategy that reduced uncertainty (lower CV) for surveys in the Northern Area.

Considering the balance between precision and operational effort, we propose maintaining the sampling design currently used in the Northern Area, as it provides adequate spatial coverage of the resource and uncertainty levels compatible with the objectives of the assessment. As an alternative under operational or budgetary constraints, the 16-transect scenario represents a viable option, maintaining adequate spatial coverage while approximately halving survey duration (11 days versus 23 days; Table 6).

It is also recommended that the systematic design be complemented by an adaptive sampling component in areas where major Chilean jack mackerel aggregations are detected. Overall, the current design adequately represents the spatial distribution patterns of the resource, although some transects in the central sector of the study area should be extended to improve coverage of areas potentially occupied by Chilean jack mackerel (Figure 8).

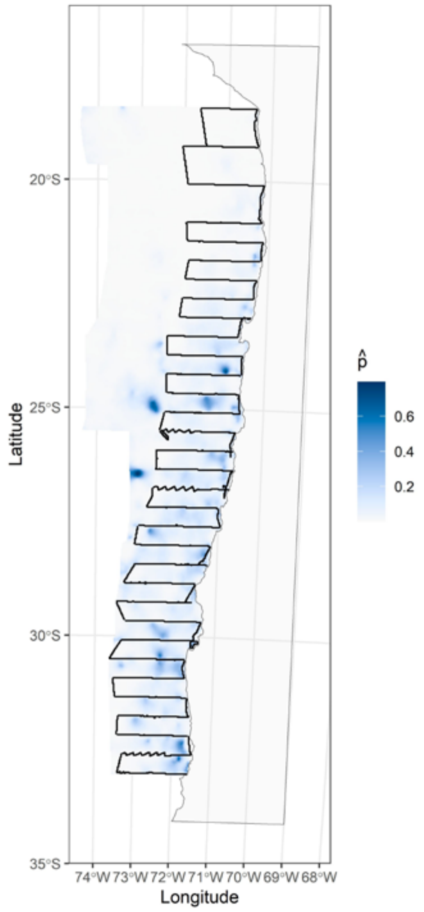

Figure 8. Predicted acoustic density obtained by fitting a model incorporating temporal and spatial correlation to the current sampling design used in surveys in the Northern Area.

3.2.2. Central-Southern Area

In the Central-Southern Area, the historical review revealed a greater spatial extent of the surveyed areas and a sampling structure that included both coastal and oceanic sectors. Based on the historical time series, seven configurations were evaluated: 6, 10, 16, and

32 systematic transects; 16 transects with adaptive sampling in oceanic sectors; 16 transects with adaptive sampling in oceanic and coastal sectors; and a stratified design with a variable number of transects between the coastal and oceanic sectors.

As in the Northern Area, a spatio-temporal model was fitted using all available surveys from the Central-Southern Area to establish a reference scenario for evaluating the different designs. A mean density of 56 $t \cdot nmi^{-2}$, with a CV of 78%, was used as the reference. A total of 1,000 independent replicates were generated for each scenario, allowing the precision, accuracy, and potential bias of estimates obtained under the different sampling configurations to be comparatively evaluated.

The results showed a progressive reduction in uncertainty as sampling intensity increased. The 6-transect scenario yielded an estimated mean density of 195.3 $t \cdot nmi^{-2}$, with a mean CV of 9%, whereas the 10-transect scenario yielded 72.5 $t \cdot nmi^{-2}$ and a CV of 8%. With 16 transects, mean density decreased to 54.5 $t \cdot nmi^{-2}$ and the CV to 5%. The 32-transect scenario yielded a mean density of 45.1 $t \cdot nmi^{-2}$, with a mean CV of 4%, representing the scenario with the lowest uncertainty among the systematic alternatives evaluated (Table 7; Figures 9 and 10).

The 16-transect adaptive designs showed results similar to the 32-transect scenario in terms of uncertainty (Table 7; Figures 9 and 10). The oceanic adaptive design yielded a mean density of 46.7 $t \cdot nmi^{-2}$ and a CV of 4%, whereas the alternative involving intensification in both oceanic and coastal sectors yielded 49.6 $t \cdot nmi^{-2}$, also with a CV of 4%. In contrast, the stratified design yielded a mean density of 70.4 $t \cdot nmi^{-2}$ and a CV of 8%.

Table 7. Performance of the sampling scenarios evaluated in the Central-Southern Area.

Scenario	Mean density ($t \cdot nmi^{-2}$)	CI 95%	SD	Mean CV (%)	CI 95% CV	SD CV	Duration (days)
6 transects	195.3	51.7–542.6	709.4	9	1–36	10	12
10 transects	72.5	44.5–159.5	34.3	8	2–13	4	19
16 transects	54.5	39.1–77.1	11.2	5	1–12	3	29
32 transects	45.1	40.0–55.9	4.0	4	1–7	2	58
16 transects, oceanic adaptive	46.7	38.2–58.8	5.9	4	1–10	2	38
16 transects, oceanic and coastal adaptive	49.6	41.7–74.9	8.8	4	1–11	3	40
Stratified between coastal and oceanic sectors	70.4	44.5–139.0	26.3	8	2–20	5	31

In terms of operational effort, estimated duration increased from 12 days for 6 transects to 58 days for 32 transects. The 16-transect adaptive designs had estimated durations of 38 and 40 days, respectively, whereas the stratified design required approximately 31 days (Table 7). Therefore, although the 32-transect scenario achieved the lowest CV, the improvement in precision must be weighed against the substantial increase in survey duration.

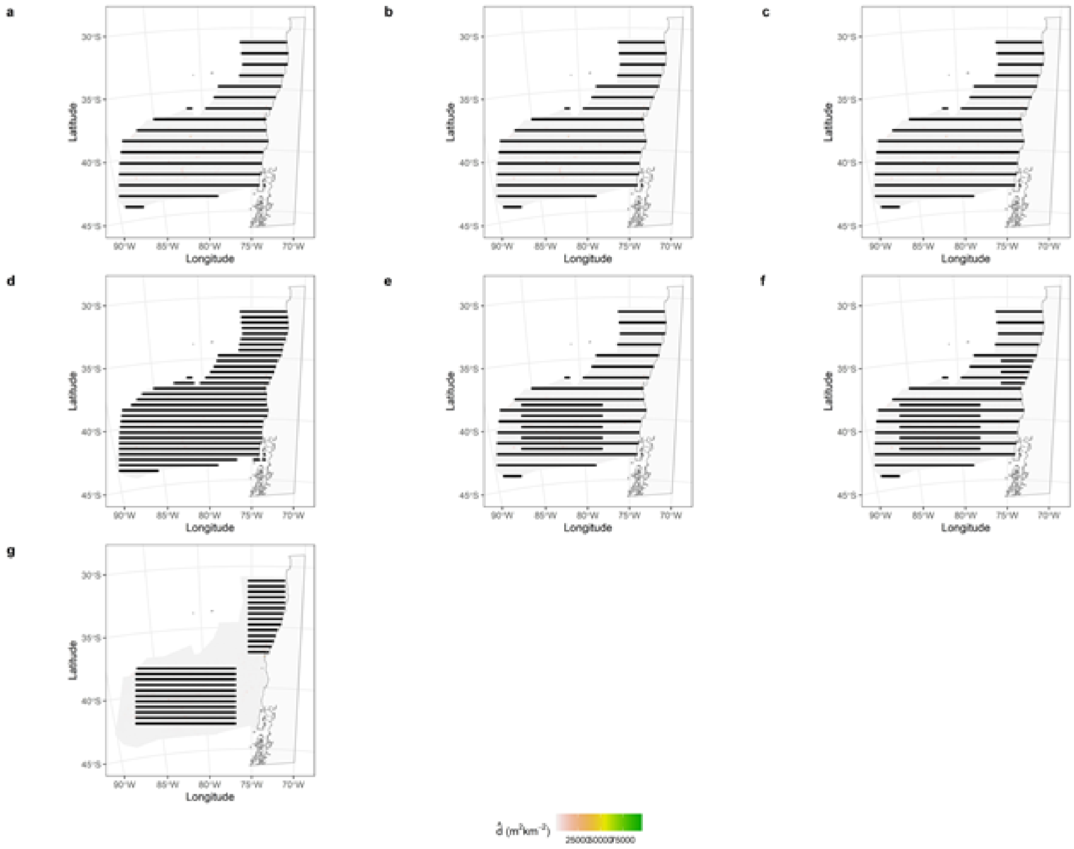

Figure 9. Predicted acoustic density obtained by fitting a model incorporating temporal and spatial correlation for the following scenarios: (a) 6 transects, (b) 10 transects, (c) 16 transects, (d) 32 transects, (e) 16 oceanic adaptive transects, (f) 16 oceanic and coastal adaptive transects, and (g) a stratified design with a variable number of transects in coastal and oceanic sectors, for surveys in the Central-Southern Area.

In this area, the results show that the 16-transect adaptive designs achieved uncertainty levels comparable to those of the 32-transect scenario, but with shorter survey durations. This indicates that spatial intensification of sampling in areas of higher projected density could represent an alternative for improving sampling-effort efficiency, although final selection should jointly consider spatial coverage, aggregation structure, and the operational requirements of the survey.

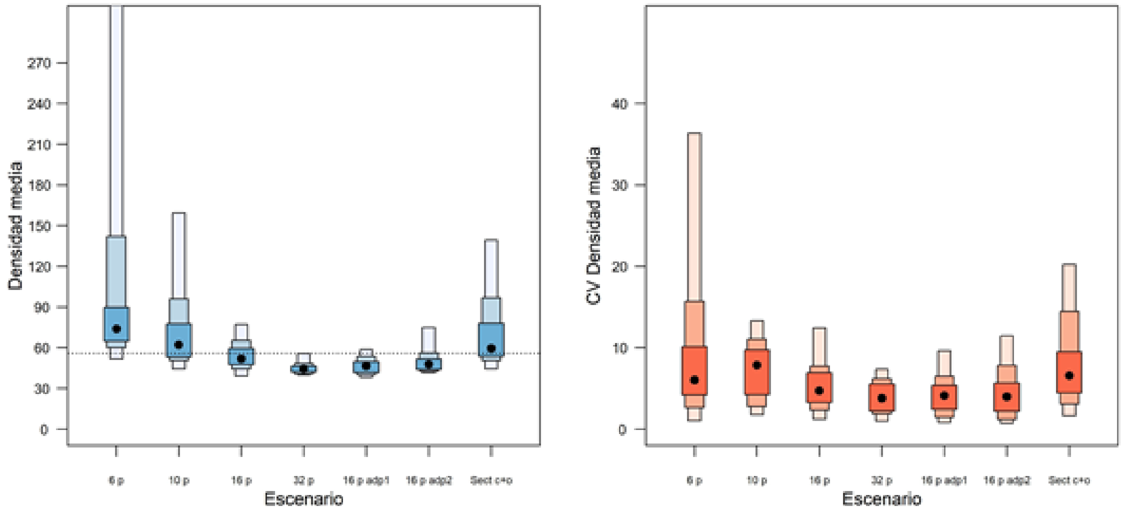

Figure 10. Predicted acoustic density obtained by fitting a model incorporating temporal and spatial correlation, with 1,000 resampling replicates conducted to identify the sampling strategy that reduced uncertainty (lower CV) for surveys in the Northern Area.

Considering the balance between statistical precision and operational cost, we propose adopting a design based on 16 transects complemented by adaptive sampling in the oceanic sector. Although the 32-transect scenario produces slightly more precise estimates, its implementation would double survey duration, from 29 to 58 days, with a consequent increase in operational and logistical costs. The proposed design would adequately capture the spatial structure of the resource, considering that the spatial autocorrelation range estimated for the historical time series was 16 nmi ($CI_{95\%}$: 15–17 nmi), supporting the spatial resolution of the recommended sampling scheme.

Furthermore, incorporating an additional adaptive component in the coastal sector did not produce relevant improvements in estimation accuracy or significant reductions in uncertainty (Figure 6, Table 2). Likewise, analysis of the historical time series suggests that the surveyed area could be reduced from 1,285,811 km² to 934,939 km², because the probability of Chilean jack mackerel occurrence in the offshore sector of the northernmost area has been persistently low. This optimization would reduce both survey duration and the costs associated with survey implementation, without compromising the ability to detect the resource (Figure 11).

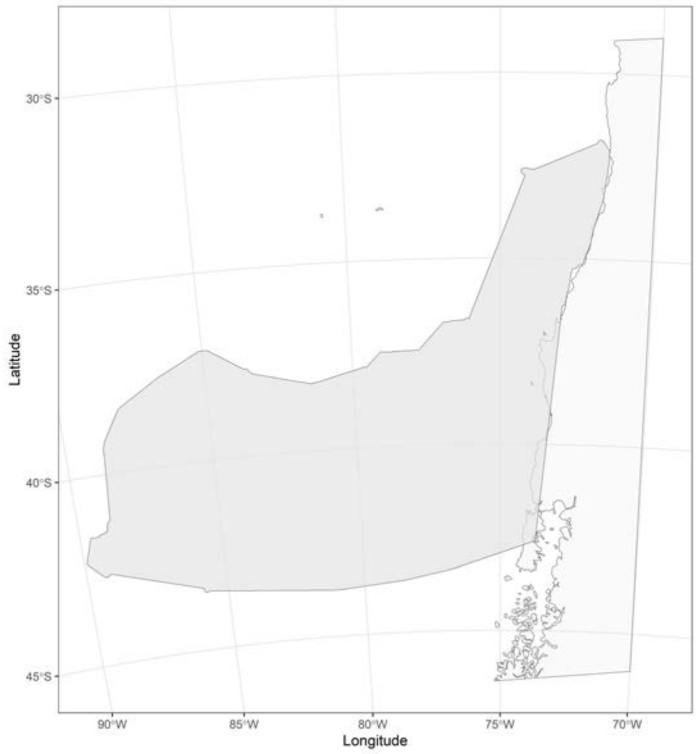

Figura 11. Area to be covered by the Chilean jack mackerel assessment survey in the Central-Southern Area.

3.2.3. Synthesis of Sampling Design Evaluation

The evaluation of the scenarios showed that increasing sampling intensity tends to reduce uncertainty in acoustic density estimates in both areas, but with diminishing marginal benefits relative to the increase in operational effort. In the Northern Area, the 32-transect scenario achieved the lowest CV, although it remained positively biased relative to the reference density and required considerably longer survey time. In the Central-Southern Area, the 16-transect adaptive designs achieved CV values similar to those of the 32-transect design, with a shorter estimated survey duration.

Consequently, the results support the usefulness of evaluating sampling designs through simulations based on the estimated spatial and temporal structure of the resource. This procedure allowed alternatives to be identified that balance estimation precision, associated uncertainty, and operational effort, providing a quantitative basis for selecting sampling designs specific to each assessment area. The comparison was conducted independently for the Northern and Central-Southern areas, considering their respective spatial and operational characteristics, without assuming that an optimal configuration in one area is necessarily applicable to the other.

4. CONCLUSIONS

1. The distribution of Chilean jack mackerel exhibited marked spatial heterogeneity and interannual variability, highlighting the need to explicitly incorporate the

spatial and temporal structure of the resource when estimating mean acoustic density and its associated uncertainty.

2. The Bayesian approach implemented through INLA-SPDE spatial and spatio-temporal models allowed the spatial dependence of the resource to be represented and estimates to be generated over a common inference area, providing a consistent methodological basis for comparing density among years and areas.
3. Model comparison using WAIC showed that incorporating spatial structure improved model performance in a substantial proportion of cases, although its contribution varied among years and areas, indicating a dynamic spatial structure.
4. The use of a constant inference area helped reduce the effect of historical differences in survey spatial coverage and supported more consistent comparisons of interannual estimates.
5. Simulations showed that increasing the sampling intensity reduces uncertainty in mean density estimates, but with diminishing benefits relative to the increase in operational effort. Therefore, design selection should jointly consider precision, uncertainty, spatial coverage, and survey effort.
6. In the Northern Area, the current design provides an adequate balance between spatial coverage, precision, and operational effort. The 16-transect scenario represents a viable alternative under operational constraints, provided that sufficient coverage of the area potentially occupied by the resource is maintained.
7. In the Central-Southern Area, the 16-transect design with an adaptive sampling component in the oceanic sector achieved uncertainty levels comparable to those obtained with the 32-transect design but with lower operational effort, supporting its consideration as an alternative for future surveys.
8. The results demonstrate that there is no single optimal sampling design for the entire assessment area and that the strategy should be adapted to the spatial and operational characteristics of each area. In this context, the integration of spatial models and sampling design simulations represents a useful tool to support the continuous improvement of hydroacoustic assessments of Chilean jack mackerel.

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