MARINE AND FISHERY SCIENCES 35 (2): 287-306 (2022)
https://doi.org/10.47193/mafis.3522022010508

ORIGINAL RESEARCH

A data-limited approach to determine the status of the artisanal fishery of sea silverside in southern Chile

PAULO MORA[1, 2], GUILLERMO FIGUEROA-MUÑOZ[1, 3, 4], LUIS A. CUBILLOS[1, 5, *] and POLIANA STRANGE-OLATE[1]

[1]Programa de Magíster en Ciencias Mención Pesquerías, Facultad de Ciencias Naturales y Oceanográficas, Universidad de Concepción, Chile. [2]Instituto de Fomento Pesquero, Almte. Manuel Blanco Encalada 839 - Valparaíso, Chile. [3]Núcleo Milenio INVASAL and Genomics in Ecology, Evolution and Conservation Laboratory (GEECLAB), Departamento de Zoología, Facultad de Ciencias Naturales y Oceanográficas, Universidad de Concepción, Concepción, Chile. [4]Departamento de Ciencias Biológicas y Químicas, Facultad de Recursos Naturales, Universidad Católica de Temuco, Rudecindo Ortega 02950, Temuco, Chile. [5]Centro COPAS COASTAL, Departamento de Oceanografía, Facultad de Ciencias Naturales y Oceanográficas, Universidad de Concepción, Casilla 160-C, Concepción, Chile.
ORCID *Paulo Mora* https://orcid.org/0000-0002-8172-1533, *Guillermo Figueroa-Muñoz* https://orcid.org/0000-0001-7446-9934, *Luis A. Cubillos* https://orcid.org/0000-0003-0641-3722

*Correspondence:
lucubillos@udec.cl

Marine and Fishery Sciences MAFIS

OPEN ACCESS

Received: 9 March 2022
Accepted: 28 April 2022

ISSN 2683-7595 (print)
ISSN 2683-7951 (online)

https://ojs.inidep.edu.ar

Journal of the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP)

ABSTRACT. Artisanal fisheries are essential, but for most the status of the stock supporting the fishing activity remains unknown due to lack of data and difficult access to sampling. For example, the artisanal fishery of sea silverside *Odontesthes* (*Austromenidia*) *regia*, in Los Lagos administrative region in Chile, requires a data-limited approach to determine its status because the fishery administration has not invested in its monitoring. The approach consisted of estimating the spawning potential ratio (SPR) from length-frequency data collected in 2019 using length-based spawning potential ratio (LBSPR) and biological reference points using the only-catch optimized method (OCOM) to catch data covering the period from 1960 to 2020. In addition, five age-structured sea silverside populations were simulated considering uncertainty in recruitment and utilizing life-history parameters estimated by FishLife. According to LBSPR, the SPR was 0.58 (95% confidence intervals: 0.5-0.7), suggesting a fully exploited fishery status. The OCOM result was inconsistent with the life-history parameters and was discarded as a valid sea silverside stock assessment. The age-structured population simulations indicated evidence of a reduction in the spawning stock biomass close to 75% of the unexploited condition in 1960. Thus, the underexploited status reached a probability close to 49.4%, and the fully exploited status was 41.2%. The framework for a data-limited stock-assessment approach and results obtained here for the sea silverside are starting essential steps that may be emulated in other artisanal data-limited fisheries.

Key words: Data-poor, assessment, small-scale fishery, simulations, life-history.

Un enfoque de datos-limitados para determinar el estatus de la pesquería artesanal de pejerrey de mar en el sur de Chile

RESUMEN. Las pesquerías artesanales son esenciales, pero para la mayoría de ellas se desconoce el estado de las poblaciones que sustentan la actividad pesquera debido a la falta de datos y al difícil acceso a los muestreos. Por ejemplo, la pesquería artesanal del pejerrey de mar *Odontesthes* (*Austromenidia*) *regia*, ubicada en la región administrativa de Los Lagos de Chile, requiere un enfoque con datos limitados para determinar su estado debido a que la administración pesquera no ha invertido en su monitoreo. El enfoque consistió en estimar la razón de potencial de desove (SPR) a partir de datos de frecuencia de talla recolectados en 2019, utilizando la relación de potencial de desove basada en la talla (LBSPR) y puntos biológicos de referencia utilizando el método optimizado de solo-captura (OCOM) sobre los datos de captura entre 1960 y 2020. Además, se simularon cinco poblaciones de pejerrey de mar estructuradas por edad bajo incertidumbre en el reclutamiento y utilizando parámetros de historia de vida estimados por FishLife. Según el LBSPR, el SPR fue de 0,58 (intervalos de confianza del 95%: 0,5-0,7), lo que sugiere un estado de explotación plena. El resultado del OCOM fue inconsistente con los parámetros de historia de vida y se descartó como una evaluación válida del *stock* de pejerrey de mar. Las simulaciones de la poblacionales estructurada por edades mostraron una reducción en la biomasa desovante cercana a 75% de una condición no explotada en 1960. Así, el estado subexplotado alcanzó una probabilidad cercana a 49,4%, y el estado de explotación plena de 41,2%. El marco para un enfoque de la evaluación de *stock* con datos limitados, y los resultados obtenidos aquí para el pejerrey de mar, están iniciando pasos esenciales que podrían emularse en otras pesquerías artesanales limitadas en datos.

Palabras clave: Datos limitados, evaluación, pesquería artesanal, simulaciones, historia de vida.

INTRODUCTION

Global total marine catches were 84.4 million metrics tons in 2018, from which 78.7% came out from biologically sustainable stocks. In 2017, this fraction reached 65.8%, and stocks fished biologically unsustainably were 34.2% (FAO, 2018). Unfortunately, there are problems with artisanal fisheries, either because they are difficult to sample or because information on them is generally incomplete, or both, increasing the uncertainty of global fishery statistics. Nevertheless, artisanal fisheries are essential mainly because they are not only an indispensable source of food for human consumption, but also generate employment for fishers, providing economic well-being for all agents involved in the socio-ecological system resulting from these fisheries (Salas et al. 2007; Pomeroy and Neil 2011).

In Chile, artisanal fisheries contributed almost 38% to the national landings in 2020, industrial fisheries 21% (mainly pelagic fish) and aquaculture 41% (mainly salmon and mussel aquaculture) (SERNAPESCA 2020). Almost 61% of the artisanal fisheries landings are fish, 29% seaweed, 6% mollusks, and the rest are crustaceans, sea urchin, and tunicates (SERNAPESCA 2020). The silverside *Odontesthes* (*Austromenidia*) *regia* Humboldt, 1821, is a small pelagic fish that supports an artisanal fishery, inhabiting marine coastal waters in the Humboldt Current System, from northern Peru to southern Chile (Brian and Dyer 2006; Arellano and Swartzman 2010; Deville et al. 2021). Silversides are small, slender and elongated fish which live between 1 and 4 years, and their spawning season lasts between two and five months (Pajuelo and Lorenzo 2000; Moresco and Bemvenuti 2006; Arrieta et al. 2010). Thirteen species of silversides have been described in Chile, with representatives of the subgenus *Austromenidia* (including *Odontesthes regia*) being the most abundant in the marine ecosystem (Dyer and Gosztonyi 1999). Sea silverside has high genetic diversity and at least two co-distributed genetic groups (Deville et al. 2021). The species can inhabit diverse marine environments, such as estuaries, beaches, sandy bottoms, and moves in small schools near the coast, between 0 and 50 m depth (Cifuentes et al. 2012).

In Los Lagos administrative region, southern Chile, the sea silverside is a species of great commercial interest for artisanal fishers, where landings represent 90% of the total landings of the species (SERNAPESCA 2020). Overall, the main fishing gear used for the silverside fishery corresponds to gillnets (2-3 m deep, 3-4 cm mesh size), which are positioned in the coastal zone (SUBPESCA 2003). The official records of sea silverside artisanal landings in Chile increased from 58 t in 1960 to 661 t in 2020. In Los Lagos, landings started in 1965 attaining peaks of 4,420 t and 3,271 t in 1990 and 1999, respectively. However, after the last peak, sea silverside landings declined to only 4 t in 2011 and started to recover until 2020 (Figure 1).

There are concerns about the status of the artisanal sea silverside fishery. Therefore, a data-limited approach was used to determine the status of

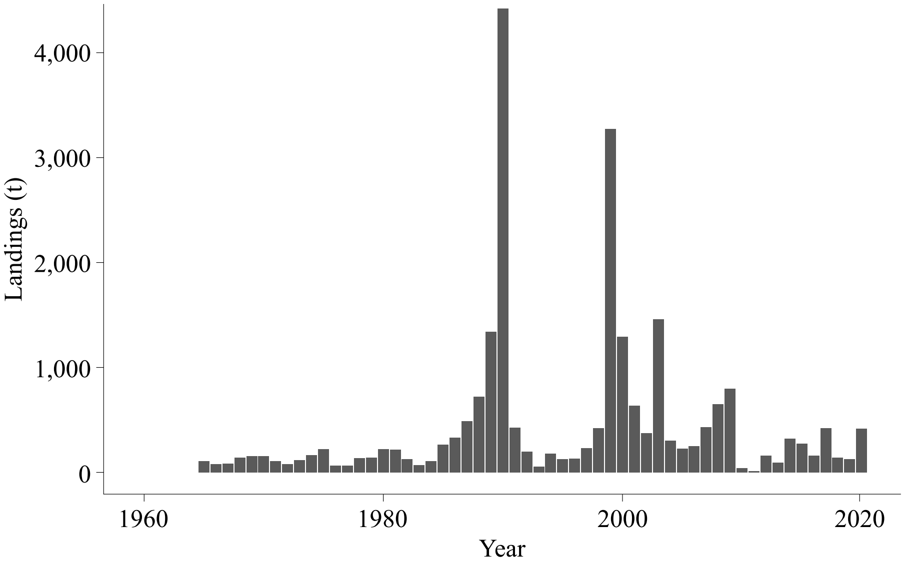

Figure 1. Landings of sea silverside in Los Lagos administrative region in Chile during the period 1960-2020.

the fishery in the Los Lagos Region. The sea silverside reproductive aspects, age, and growth were studied in Peruvian waters by Villavicencio and Muck (1984), Gómez Alfaro et al. (2006), Arrieta et al. (2010), and Campos León et al. (2020). Plaza et al. (2011) described sea silverside as an asynchronous multiple-spawner with an extensive spawning season in Chile. Pavez et al. (2008) studied biological and fishery aspects of sea silverside in Los Lagos administrative region. These authors concluded that catches were supported by the spawning stock, particularly reproductive aggregations near shore, and the fishery could be affecting the reproductive potential since sea silverside is a low-fecundity species.

Most data-limited stock assessment methods consider commercial catch (Free et al. 2020; Ovando et al. 2022), body length data (Hordyk et al. 2014a, 2014b; Prince et al. 2015; Hordyk et al. 2016), or both. The performance of data-limited methods is usually evaluated by simulation considering uncertainty in the population dynamics (Zhou et al. 2017a; Carruther and Hordyk 2018; Free et al. 2020; Sharma et al. 2021). This paper evaluates the sea silverside status in Los Lagos administrative region, uses length-frequency data to compute the spawning potential ratio, and evaluates the models' performance by simulating the population dynamics.

MATERIALS AND METHODS

Study area and data sources

The study area is referred to as Los Lagos administrative region in Chile. Total landings were obtained from official records of the Servicio Nacional de Pesca y Acuicultura (SERNAPESCA, https://sernapesca.cl). Biological data were obtained by sampling the artisanal activity in four fishing zones during 2019. Punta Quillahua and Amortajado have zones exposed to the sea along the continental coast. The other two, Bahía Ancud and Golfo de Quetalmahue, are semi-enclosed fishing zones in northern Chiloé island (Figure 2). The fishing zones are associated with Ancud as the main port for landings. A total number of 552 sea silversides were sampled. For

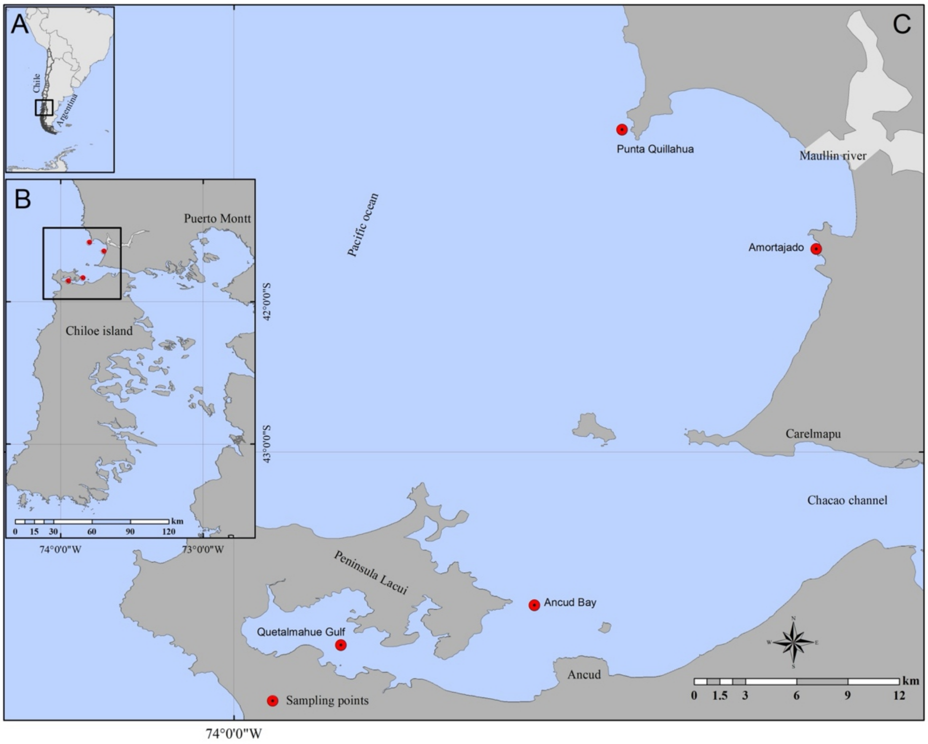

Figure 2. Study area in Chile (A) showing sampling locations in northern Chiloé island, and (B) zoom of sampled locations during 2019 (C).

each individual, total mass (W) was measured using a scale Pesamatic Model WTB 2000 (± 0.01 g) and total length (TL) with a board meter (± 0.1 cm). Sex of individuals (males, n = 338; and females, n = 214) was determined through macroscopic observation of gonads, after dissection.

Biological data analysis

Biological data were grouped according to the following austral seasons: summer (January-March), autumn (April-June), winter (July-September), and spring (October-December). Then, the average, standard deviation, and range of total length (cm) and body weight (gr) were computed by season and sexes. Besides, parameters of the length-weight relationship (LWR) were determined, in which the body is a potential function of total length (Froese 2006):

$$W = aL^b$$

where W is the total body weight, L is the total length (cm), and a and b are unknown parameters to be estimated. Although the LWR is a non-linear model and the parameters could be estimated through a non-linear least-square approach, the body weight violates the linearity and homoscedasticity. Froese (2006) and Ogle (2016) stated that bodyweight follows a log-normal distribution, and therefore a multiplicative error term could be a better choice. Hence, linearizing the equation by applying logarithms makes the error additive, stabilizes the variance, and the unknown parameters can be estimated using a linear model. The log-normal and gamma distributions were fitted to observed body weight data using maximum likelihood estimation implemented in the function fitdistr of the R-package MASS (Venables and Ripley 2002). According to the log-likelihood and Akaike information criterion (AIC) (Akaike 1974), body weight of sea silverside follows a gamma distribution (log-likelihood = -2206.2, AIC = 4416.4) rather than a log-normal distribution (log-likelihood = -2209.7, AIC = 4423.4). Therefore, unknown parameters (*a* and *b*) of the LWR were estimated using a generalized linear model (GLM) with gamma family and natural logarithm as link function. The following linear predictor was used:

$$W = \alpha + \beta \cdot \mathrm{SEX} \cdot \mathrm{SEASON} \cdot \log L + \mathrm{SEX} + \mathrm{SEASON}$$

where α is the intercept, β the slope, SEX is a factor for males and females, SEASON is a factor for summer, autumn, winter, and spring. The R-package (DHARMa) (Harting 2022) for residual diagnostics was utilized, which uses a simulation-based approach to create standardized residuals for a fitted GLM. After testing residuals, normal residuals followed. An ANCOVA was used with a *Chi*-squared test to evaluate significant effects of fixed groups, i.e. SEX and SEASON (Lai and Helser 2004). A submodel consisted of removing one of the fixed factors resulting non-significant and represented by a model with different intercepts and fixed slope (model 1), a model with changes in the slope and fixed intercept (model 2), and a model with changes in both the intercept and slopes simultaneously (model 3) (e.g. Nahdi et al. 2016). The best submodel was selected with AIC (Akaike 1974), and the Nagelkerke pseudo-r^2 (Nagelkerke 1991) was computed. The R-package MASS was utilized to fit GLMs (Venables and Ripley 2002) and the R-package rcompanion (Mangiafico 2015) for computing the Nagelkerke pseudo-r^2.

Once LWR was analyzed, the condition factor among seasons and sexes was studied. The relative condition factor (Le Cren 1951) was computed as $K_n = W/L^b$, where K_n is the allometric condition factor, W is the body weight, L is the total length, and b is the allometric exponent of the LWR (Nahdi et al. 2016).

Status of the fishery

Length-based spawning potential ratio

Annual length-frequency data were utilized to apply the length-based spawning potential ratio (LBSPR) model of Hordyk et al. (2014a, 2014b). The LBSPR is a steady-state stock assessment model that estimates the spawning potential ratio as an index of status. In addition, the method also estimates the parameters of a logistic selectivity curve (Hordyk et al. 2016). The input is one or more length-frequency data, the von Bertalanffy (VB) asymptotic length (l_∞), the ratio between the natural mortality (M) and the VB growth coefficient (M/k) (Prince et al. 2015), and the length at first maturity (l_m) obtained from Pavez et al. (2008) (Table 1).

Catch data analysis

The only-catch stock assessment model called OCOM (Optimized Catch-Only Method) of Zhou et al. (2017a) as implemented in the package 'datalimited2' (Free 2018) for the software R (https://www.r-project.org) was applied to determine the status of the sea silverside artisanal fishery in Los Lagos administrative regions. As mentioned, landing data covered the period from 1960 to 2020 (Figure 1) assuming they are a proxy of the catch since landings could be less or equal to the catches.

The OCOM uses Schaefer's logistic surplus production:

$$B_{i+1} = B_i + rB_i\left(1 - \frac{B_i}{K}\right) - C_i$$

where B_i is the biomass at the beginning of the year i, r is the intrinsic growth rate, K is the carrying capacity, and C_i is the observed catch during year i. The unknown parameters to be estimated are r and K, and the estimation procedure utilizes a prior for r to solve K through the ratio B_i/K or stock saturation, i.e. $s = B_i/K$. The prior for r is based on natural mortality (M), and prior for the stock saturation is based on a boosted

Table 1. Life-history parameters estimated for sea silverside according to Pavez et al. (2008), and life-history parameters estimated by FishLife. Additional derived parameters needed for simulation of a population dynamics highlighted by an asterisk (see text).

Process	Parameter	Symbol	Units	Pavez et al. (2008)	FishLife
Growth	Asymptotic length	l_∞	cm	24.0	29.0
	Asymptotic weight	w_∞	g	95.0	241.0
	Growth coefficient	k	year^{-1}	1.047	0.597
		t_0	year	0.632	-0.274*
	Coefficient of variation of length at age	CV_L	-	n.a.	0.05*
Mortality	Natural mortality rate	M	year^{-1}	1.2	1.1
	Maximum age	t_{max}	year	3 +	5
Maturity	Age at maturity	t_m	year	n.a.	1.3
	Length at maturity	l_m	cm	15.8	16.9
	Shape maturity at length	δ	cm	2.0	0.5*
	Spawning time	τ	-		0.583*
Stock-recruitment	Steepness	h	-	-	0.815
	Standard deviation of recruitment deviations	σ_R	-	-	0.567
	Autocorrelation of recruitment deviations	ρ_R	-	-	0.352
Length-weight relationship (LWR)	Intercept LWR	a	g cm^{-b}	0.0050	0.0098*
	Allometry coefficient LWR	b		3.1	3*
Average temperature	Temperature	T	°C	12.6	18.1

regression trees (BRTs) model developed by Zhou et al. (2017b). The estimation considered n = 10,000 values for *r* and *s*, and the optimization function solved viable *r*-*K* pairs to set upper and lower *K* values, which are not part of a prior range. Derived quantities are MSY = $rK/4$ and $F_{MSY} = r/2$ based on optimized *r*-*K* pairs.

Simulation of sea silverside age-structured populations

In addition to the known life-history parameters of Pavez et al. (2008) for the sea silverside, other life-history parameters were obtained by applying the FishLife package developed by Thorson et al. (2017) and Thorson (2020) for the software R. FishLife is an efficient method to estimate life-history parameters for little-studied species. It is based on a multivariate model that utilizes a comprehensive evolutionary model of life-history parameters fitted to longevity, growth, natural mortality, maturity, and temperature data from FishBase (Froese and Binohlan 2000; Froese and Binohlan 2003; Froese and Pauly 2022). FishLife utilizes stock-recruitment parameters and population parameters from the RAM Legacy Database (https://www.ramlegacy.org) (Ricard et al. 2012). According to a multivariate normal distribution, the model predicts a vector of life-history parameters along phylogenetic lineages, with lower taxonomic levels having more precise parameters than higher levels.

Based on FishLife, additional derived parameters were obtained for sea silverside such as the von Bertalanffy age at length zero (Pauly 1983), the assumed coefficient of variation of length at age, shape of maturity (based on 95% maturity, Pavez et al. 2008), the spawning time as year fraction (i.e. the month starting the reproductive period according to Plaza et al. 2011), and the length-weight parameters based on cube law (Froese 2006) (Table 1). Once all the parameters were obtained, five age-structured sea silverside population models were simulated for the period 1965-2020 (Table 2). The simulations considered uncertainty in unexploited recruitment level and interannual variability. The unexploited recruitment (R_0) scales the population level, specifically the unexploited spawning stock biomass (SSB_0) at the beginning of 1965. The interannual variability is a process error impacting the trajectory of the population from 1965 to 2020, given the observed catch history. The steepness (h), standard deviation of deviations of log recruitment (σ_R), and autocorrelated annual deviations (ρ_R) allowed us to estimate the stock-recruitment model of Beverton and Holt parameterized by Punt and Cope (2019), as:

$$R_i = \frac{R_0 SSB_{i-1}}{SSB_0} \frac{4h}{(1-h)+(5h-1)SSB_{i-1}/SSB_0} \exp(\varepsilon_i - 0.5\sigma_R^2)$$

where ε_i are the annual deviations of recruitment, which are autocorrelated, as:

$$\varepsilon_i = \rho_R \varepsilon_{i-1} + \sqrt{1-\rho_R^2}\,\eta_i$$

where ρ_R is the serial correlation coefficient and $\eta_i \sim \mathrm{N}(0, \sigma_R^2)$ (Thorson et al. 2014; Hawkshaw and Walters 2015). The simulation approach consisted of selecting the lower limit for R_0, on a log scale ($\log R_0$), and projecting forward from 1965 to 2020, while solving the fishing mortality rate (F_i) given the observed catch, selectivity (v_j), and the projected vulnerable biomass (V_i) of the population (Table 2). The Baranov catch equation was utilized to compute the fishing mortality rate through the Newton-Raphson algorithm (Gulland 1965; Quinn and Deriso 1999). The basic idea that underlies each simulation is to reconstruct possible trajectories of stock change from the start of the fishery to the most recent year, given population dynamics (i.e. the stock-recruitment model, recruitment variability, and survival) (Table 2), selectivity (v_j), and observed catches.

Once R_0's lower limit was determined, R_0's upper range was defined using two times σ_R^2. Five sea silverside populations were simulated, each with 1,000 alternative and equally probable trajectories of recruitment, and hence for the state variables of the population. Invalid trajectories, e.g. those resulting in extinction before 2020, were discarded. With valid trajectories, the ratio between the spawning biomass in 2020 and the unexploited spawning biomass, i.e. SSB_i/SSB_0, allowed to estimate the following status condition: depletion ($SSB_i/SSB_0 < 0.25$), overexploitation ($0.25 \leq SSB_i/SSB_0 < 0.4$), fully exploitation ($0.4 \leq SSB_i/SSB_0 < 0.75$), and under exploitation ($SSB_i/SSB_0 > 0.75$). The status categories are in agreement with the Chilean Law (Payá et al. 2014) and consider a target reference point to be 50% of the unexploited spawning biomass, i.e. $SSB_\mathrm{target} = 0.5SSB_0$, with a range between 0.4 and 0.75 of SSB_0. The limit reference point was the half of the target, i.e. $SSB_\mathrm{lim} = 0.25SSB_0$.

RESULTS

Biological data

The total length of sea silverside ranged between 14.8 and 24.0 cm for females and 15.4 and 23.4 cm for males, showing similar total length and weight averages and standard deviations (Table 3). Nevertheless, the length-frequen-

Table 2. Equations of the age-structured simulation model for sea silverside in Los Lagos region, Chile.

Process or state	Equation	Number
Length at age	$L_j = l_\infty(1 - \exp(-k(j - t_0))$	1
Maturity at size *l*	$m_l = 1/(1 + \exp((l_m - l) / \delta)$	2
Maturity at age *j*	$m_j = \sum_{l=1}^{L} m_l \left(\frac{1}{L_j CV_L \sqrt{2\pi}}\right) \exp\left(-\frac{(l - L_j)^2}{2(L_j CV_L)^2}\right)$	3
Selectivity at size *l*	$v_l = \left(1 + \exp(-\frac{\log(19)\ (l - l_{50})}{d}\right)^{-1}$, where $d = l_{95} - l_{50}$	4
Selectivity at age *j*	$v_j = \sum_{l=1}^{L} v_l \left(\frac{1}{L_j CV_L \sqrt{2\pi}}\right) \exp\left(-\frac{(l - L_j)^2}{2(L_j CV_L)^2}\right)$	
Weight at age	$w_j = aL_j^b$	5
Abundance	$N_{i,j} = \begin{cases} R_i,\ j = 1 \\ N_{i,j-1} \exp(-M),\ 1 < j < t_{max};\ i = 1 \\ N_{i-1,j-1} \exp(-M - v_{j-1} F_{i-1}),\ 1 < j < t_{max};\ i > 1 \end{cases}$	6
Total biomass at *i* beginning of year	$B_i = \sum_{j=1}^{t_{max}} N_{i,j} w_j$	7
Spawning biomass	$SSB_i = \sum_{j=1}^{t_{max}} m_j w_j N_{i,j} \exp(-\tau Z_{i,j})$	8
Vulnerable biomass	$V_i = \sum_{j=1}^{t_{max}} v_j w_j N_{i,j} \exp(-0.5 Z_{i,j})$	9
Unexploited spawning biomass	$SSB_0 = \varphi_0 \,.\, R_0$	10
Reproductive potential without fishing	$\varphi_0 = \sum_{j=1}^{t_{max}} m_j w_j s_j \exp(-\tau M)$; where $s_j = \begin{cases} 1 & j = 1 \\ s_{j-1} \exp(-M) & j = 2, ..., t_{max} \end{cases}$	11
Reproductive potential *F* at fishing mortality	$\varphi_F = \sum_{j=1}^{t_{max}} m_j w_j s_j \exp(-\tau (M + v_j F)$; where: $s_j = \begin{cases} 1 & j = 1 \\ s_{j-1} \exp(-(M + v_j F) & j = 2, ..., t_{max} \end{cases}$	12

Table 3. Summary of total length, body weight, and minimum (min) and maximum (max) values of sea silverside. Standard deviation shown in parenthesis.

			Total length (cm)			Body weight (g)		
Sex	Season	n	Mean (cm)	Min	Max	Mean (g)	Min	Max
Female	Summer	61	20.2 (2.4)	14.8	23.8	59.1 (20.1)	23	94
	Autumn	46	20.3 (1.1)	18.6	23.4	52.7 (9.3)	39	78
	Winter	45	20.9 (1.3)	17.4	23.9	61.8 (12.3)	36	95
	Spring	62	20.1 (1.4)	17.6	24.0	54.6 (12.5)	37	89
	Annual	214	20.3 (1.7)	14.8	24	57.0 (14.9)	23	95
Male	Summer	76	19.6 (2.0)	15.4	23.4	54.0 (15.1)	23	82
	Autumn	43	20.2 (1.1)	17.5	22.3	52.5 (8.7)	38	70
	Winter	68	20.4 (1.0)	18.5	22.8	57.9 (10.1)	41	85
	Spring	151	19.6 (1.1)	17.2	23.2	49.9 (8.9)	34	84
	Annual	344	19.8 (1.4)	15.4	23.4	52.8 (11.2)	23	85
Both	Annual	558	20.0 (1.5)	14.8	24	54.4 (12.9)	23	95

cy evidenced the most extensive range of sea silverside specimens in summer, from 15 to 24 cm (Figure 3).

The general model for the length-weight relationship (LWR) showed no significant differences between males and females. Indeed, the factor sex showed no effects in the intercept (SEX, $P = 0.083$), nor in the slopes (SEX · log$L$, $P = 0.334$), neither in the intercept among sex by season (SEX · SEASON · log$L$, $P = 0.547$) or in the slope by season (SEX · SEASON . log$L$, $P = 0.070$). Discarding SEX from the general model and considering only seasonal effects, the AIC values for models 1, 2, and 3 were 3008.2, 3007.4, and 3008.7, respectively. Although the AIC was close among competing models, the best model for the LWR was model 2 (Table 4), with a fixed intercept and different slopes among seasons (Nagelkerke pseudo-$r^2 = 0.921$). The highest expected weight at a given length occurred in summer and the lowest in autumn for fish larger than 20 cm (Figure 4 A). This result was a consequence of different seasonal slopes for the LWR, with a slope higher in summer and lower in autumn (Table 4). According to the standard error, the slope was not different from 3, and the lowest 95% confidence interval was 2.901 while the highest equaled 3.058. Accordingly, the allometric condition factor (K_n) did not show significant differences among seasons for males and females, but females showed a lower range in autumn and larger in spring (Figure 4 B).

Status of the fishery

Length-based spawning potential ratio

The fit of the steady-state LBSPR model to the annual length-frequency of sea silverside performed well (Figure 5 A). The resultant spawning potential ratio (SPR) was 0.58, with 95% confidence intervals (CI) between 0.5 and 0.7. The ratio fishing to natural mortality (F/M) was 3.1 (CI: 1.9-4.3), and the logistic selectivity parameters were $L_{50} = 19.7$ cm (CI: 19.1-20.2 cm), and $L_{95} = 22.6$ cm (IC: 21.8-23.4 cm). The resultant selectivity curve was to the right of the maturity ogive (Figure 5 B), suggesting that on average a significant proportion of fish were spawning before being caught.

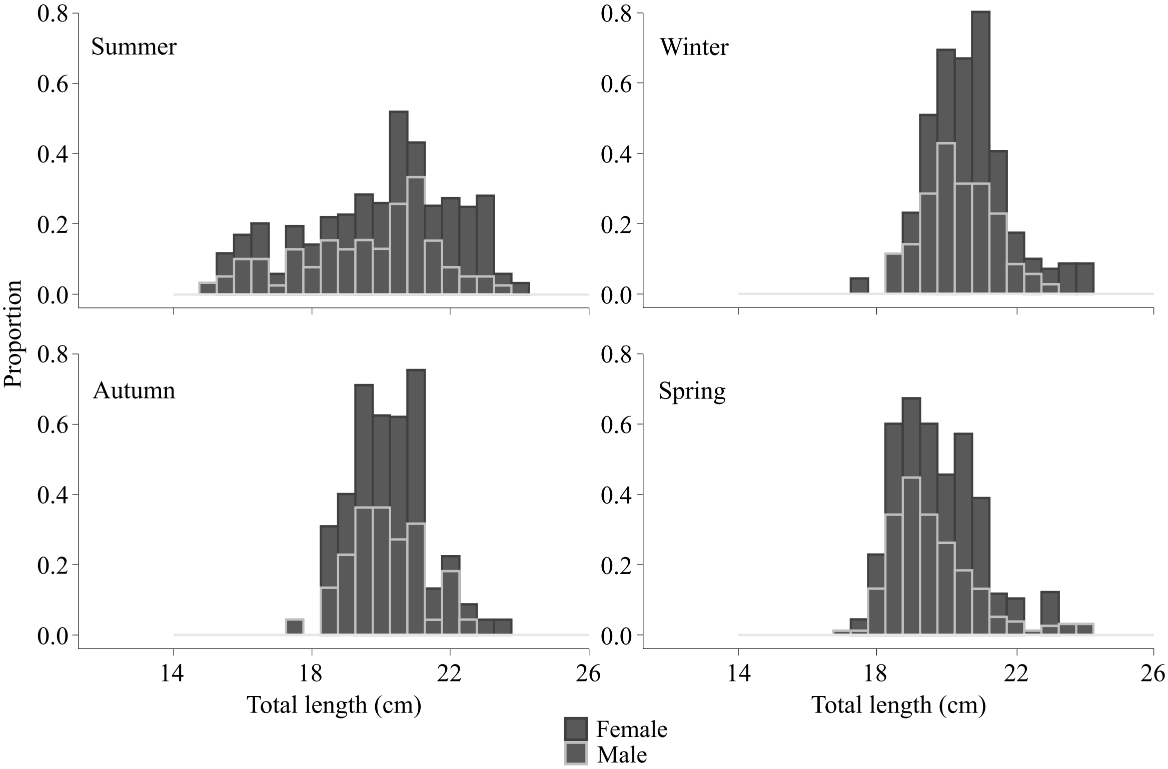

Figure 3. Length-frequency data of sea silverside by sex and seasons during 2019.

Table 4. Coefficients for the best model describing the length-weight relationship of sea silverside. Model 2 estimated by generalized linear model, family gamma and natural logarithm as link function. Nagelkerke pseudo-$r^2 = 0.921$, likelihood ratio test: -708.5 ($p < 0.01$).

Coefficients	Estimate	Standard error	t-value	P-value
Intercept	-4.926	0.114	-43.39	< 0.01
Length*Summer	2.983	0.038	78.43	< 0.01
Length*Autumn	2.953	0.038	78.06	< 0.01
Length*Winter	2.976	0.038	79.15	< 0.01
Length*Spring	2.971	0.038	77.90	< 0.01

The only-catch stock assessment model

Population parameters and biological reference points obtained using the optimized only-catch model (OCOM) indicated a median carrying capacity (*K*) of 8,197 t and a median intrinsic growth rate (*r*) of 0.342 (Table 5). The maximum sustainable yield (MSY) was 700 t, and the fishing mortality rate at MSY (F_{MSY}) was 0.171 (IC: 0.083-0.542). Finally, the saturation (B_{2020}/K) showed a reduction of 0.313 in biomass in 2020, slightly above the limit biomass and equivalent to $B_{2020}/B_{MSY} = 0.575$ (IC: 0.192-1.175) (Figure 6 C).

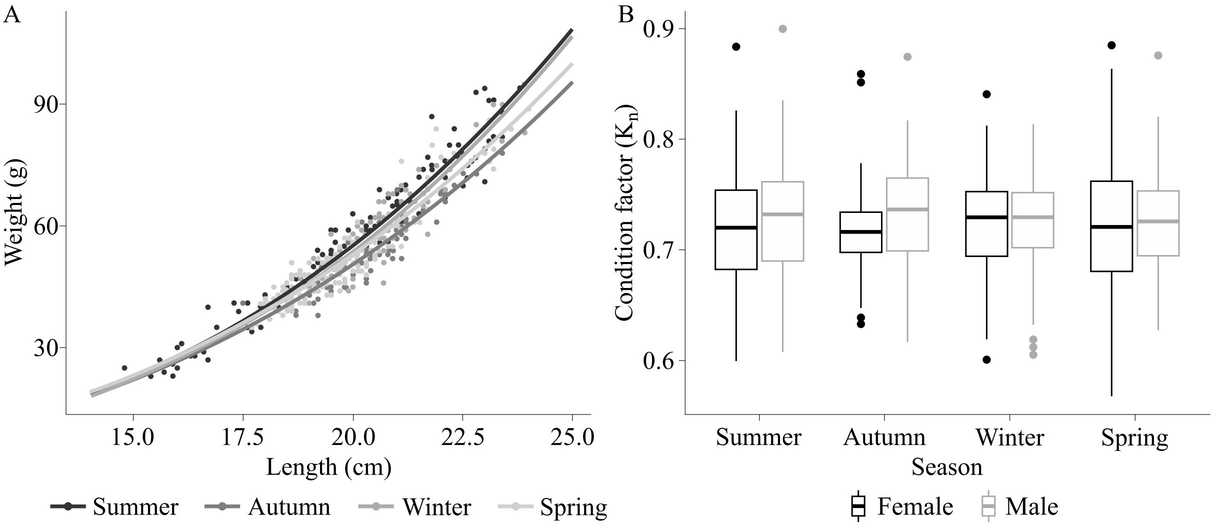

Figure 4. A) Length-weight relationships by seasons. B) Condition factor by sex and seasons of sea silverside (2019).

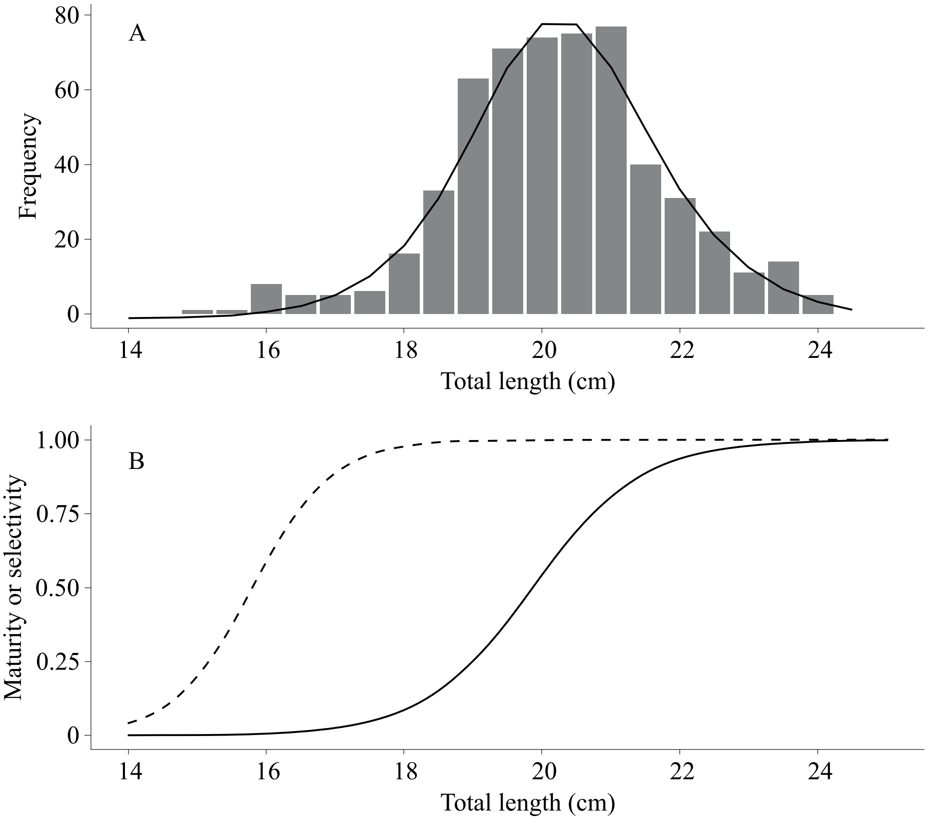

Figure 5. A) LBSPR fitted (continuous line) to the annual length-frequency data (bar). B) The logistic selectivity curve (continuous line) obtained and compared with the maturity ogive (segmented line) of Pavez et al. (2008).

Table 5. Estimates of the logistic surplus production model (r, K) and biological reference points for sea silverside based on the OCOM model applied to the catch history in Los Lagos region, Chile (1960-2020).

Parameter	Median	Lower limit	Upper limit
r	0.342	0.014	0.463
K	8,197	7,007	13,625
MSY	700	466	812
B_{MSY}	4,098	3,504	6,813
F_{MSY}	0.171	0.133	0.232
B_{2020}/K	0.313	0.222	0.583

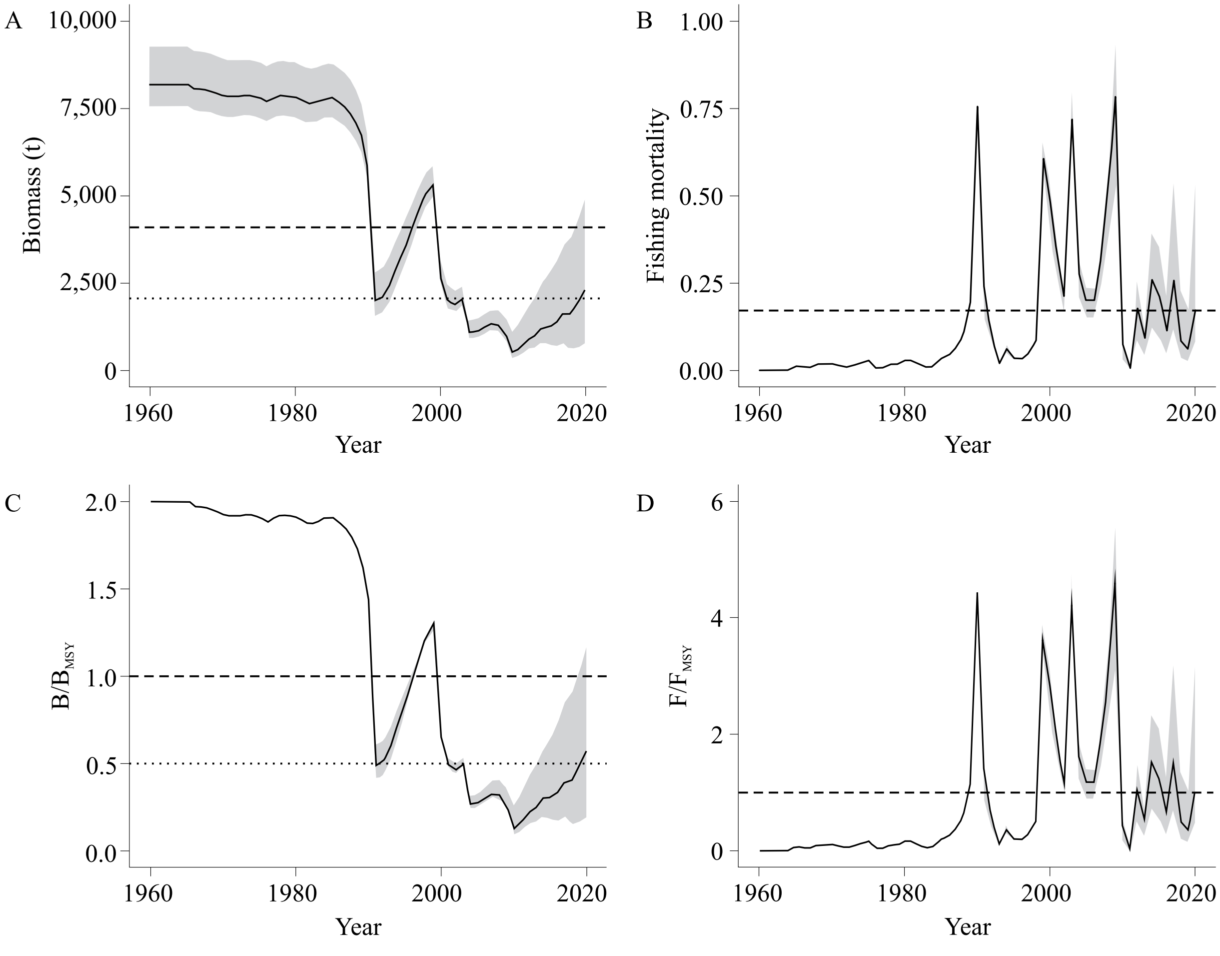

Figure 6. A) Results of the only-catch optimized method: changes in sea silverside biomass. B) Fishing mortality. C) Relative changes in biomass. D) Relative changes in fishing mortality regarding the target biological reference points (segmented line) associated with the logistic surplus production maximum sustainable yield. The dotted line in panel A and C is the limit biological reference point.

According to the selected r-K pairs, biomass trajectories revealed no effect of fishing between 1960 and 1990. However, overfishing occurring in 1989-1990 impacted the sea silverside population negatively (Figure 6). After that, a slight recovery occurred until 1999, but the overfishing between 1999 and 2005 determined a depletion. Eventually, the sea silverside exhibited a recovery from 2005 to 2020 with increased uncertainty.

Simulations of age-structured sea silverside populations

The minimum value for the unexploited recruitment ($\log R_0$) was 4.8, and according to $\sigma_R = 0.567$, the upper limit for $\log R_0$ was 5.6 (Figure 7). From this range, the level of unexploited recruitment was selected at random. Simulations of the state variables were summarized by utilizing the percentile at 10, 50, and 90%. The five populations share identical life-history parameters (Table 2), and they differed only in R_0 and interannual recruitment variability (Figure 7 A). Higher catches in 1990, 1999-2000, and 2003, negatively affected the total biomass (Figure 7 B), particularly the spawning stock biomass (Figure 7 C).

The spawning potential ratio, SSB_i/SSB_0, showed similar performance in the five simulated populations (Figure 8). The status in 2020 was similar and fluctuated between 72.7 and 76.9% among the five simulated sea silverside populations. Considering the underlying uncertainty in the spawning stock biomass, the probabilities for under-exploited and fully exploited status were higher (Table 6).

DISCUSSION

This study aims to develop a data-limited approach to determine the status of the sea silverside stock in Los Lagos administrative region. Primary data required for such an approach rely on monitoring fishery and biological data regularly, depending on how the fishers operate within territorial, social, economic, and cultural aspects. As in most artisanal fisheries, monitoring the Los Lagos sea silverside fishery is complex due to dispersion and access to multiple fishing coves and fishing grounds in species widely distributed in a complex territory.

Biological data collected here were limited in sample size and spatially but covered all the seasons during 2019. Nevertheless, samples revealed a length structure for males and females supported by adults, matching results of Pavez et al. (2008) in 2007. These authors found sea silverside specimens ranging between 10 and 32 cm, with an average total length of 23.6 cm and average weight of 98.8 g. Although, not rigorously compared, our results suggest a reduction in the average length and average weight of sea silverside compared with Pavez et al. (2008). Fishers operated mainly with standardized gillnets (SUBPESCA 2003), and the average length comparison with data of Pavez et al. (2008) could be correct. In addition, larger specimens collected in autumn and winter could be associated with the pre-reproductive and beginning of the reproductive cycle (Plaza et al. 2011). Besides, length-weight relationships were similar between males and females, but the expected body weight was lowest in autumn and the highest in summer, coinciding with better conditions for feeding (Iriarte et al. 2007, 2011) and with results reported by Gómez-Alfaro et al. (2006) in Pisco, Peru. Regarding to the condition factor (CF) of sea silverside, it did not change among seasons, but the wider CF occurred in females during spring, which coincided with the reproductive cycle and the transition to higher concentrations of phytoplankton biomass in the coastal waters (Iriarte et al. 2007).

As mentioned, length-frequency data are one of the primary data to determine the fish population status (Hordyk et al. 2014a, 2014b). Thus, the annual length frequency of sea silverside

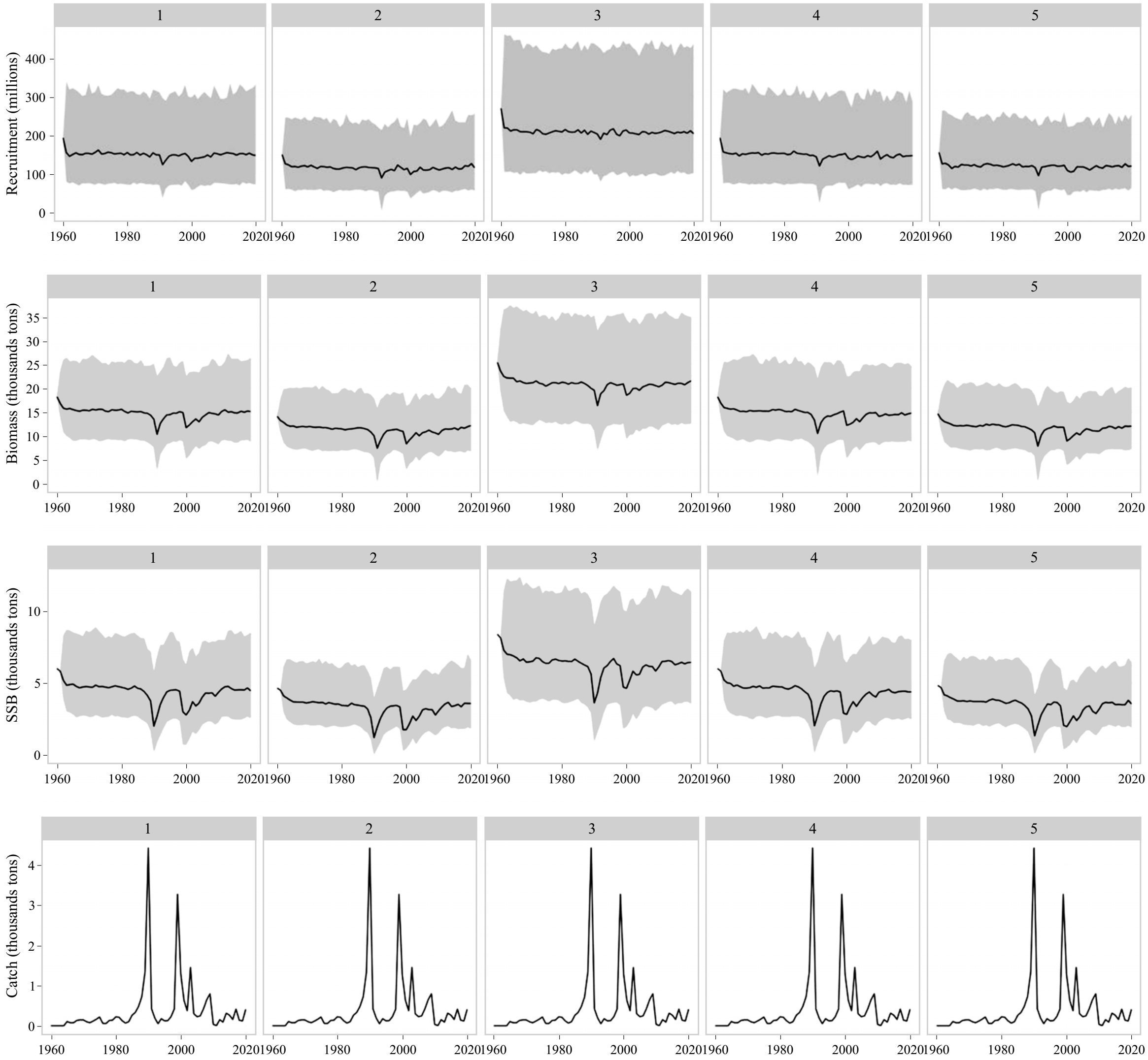

Figure 7. Simulations of age-structured of sea silverside populations (columns) based on the uncertainty in recruitment (A), resulting total biomass (B), spawning stock biomass (SSB) (C), conditioned to the observed catch history (1960-2020) (D). The grey area represents percentile intervals at 90%, and the continuous line indicates the median of simulations per recruitment scenarios (columns).

obtained here is fundamental to estimate the spawning potential ratio (SPR), resulting in 58% with confident intervals between 50 and 70%. These results mean that the sea silverside would be fully exploited in Los Lagos administrative region. The fishing gear utilized by fishers varies, but in Los Lagos, the gillnet is the main fishing gear used by fishers (SUBPESCA 2003), followed by beach seine pulled by hand to the beach (personal observations). The length at first capture estimated here was 19.7 cm, i.e. the length at 50% selectivity. Thus, the length at first capture was higher than maturity length (l_m = 15.8 cm, Pavez et al. 2008). Furthermore, the selectivity curve obtained with LBSPR allows a significant fraction of sea silverside to spawn prior to be cap-

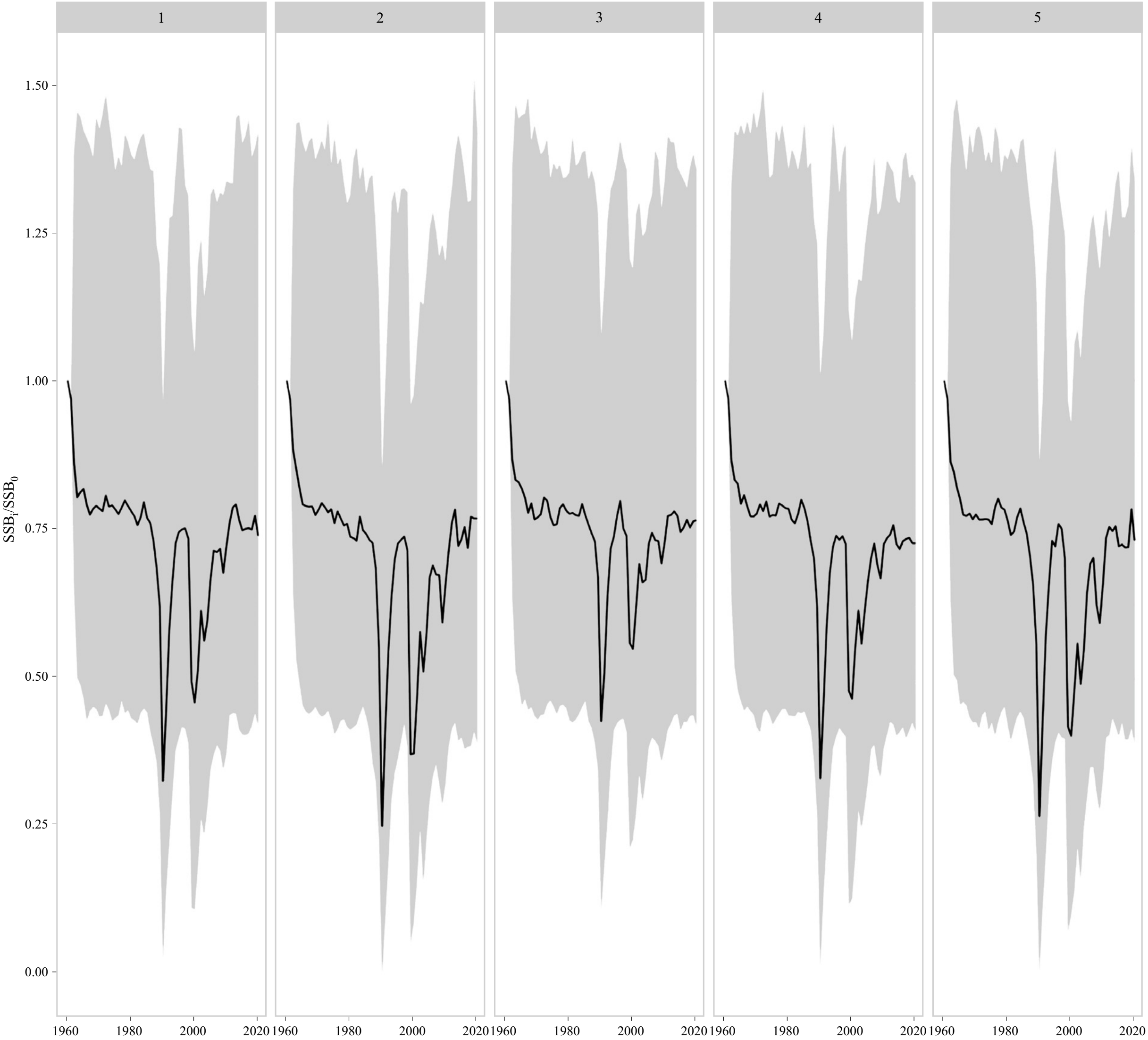

Figure 8. Reproductive potential indicator for sea silverside status, consistent in the ratio between the spawning stock biomass in a given year (SSB_i) and its unexploited level (SSB_0). The grey area represents percentiles at 90%, and the continuous line is the median of alternative and equally probable spawning biomass trajectories.

tured. Therefore, although sea silverside aggregates close to the coast to spawning, raising its vulnerability to fish activity, there is no evidence that the fishery affects the reproductive potential, as suggested by Pavez et al. (2008).

Nevertheless, the reduction in average total length from 23.6 in 2007 to ca. 20 cm in 2019 would indicate a sensible reduction in fecundity due to the repetitive removal of larger female individuals in the past. Partial fecundity as a function of total length was demonstrated for sea silverside in the study area by Plaza et al. (2011), and for the sea silverside in Peru (Gómez Alfaro et al. 2006). However, the reduction in the SPR to 58% (IC: 50-70%) obtained by applying the LBSPR method should consider the caveat of this

Table 6. Performance of the simulated age-structured population model under uncertainty during the recruitment process of sea silverside given by the observed catch history (1960-2020). The effective number of viable population trajectories shown in parenthesis.

		Populations simulated					
	Indicator	1 (723)	2 (419)	3 (924)	4 (695)	5 (462)	Weighted average
Status	SSB_{2020}/SSB_0	73.9	76.9	76.6	72.7	73.2	74.7
Collapse	$\Pr[SSB_{2020}/SSB_0 < 0.25]$	0.6	1.7	0.9	1.3	2.6	1.3
Overexploitation	$\Pr[0.25 \leq SSB_{2020}/SSB_0 < 0.4]$	8.2	9.3	7.9	7.6	7.6	8.0
Fully exploitation	$\Pr[0.4 \leq SSB_{2020}/SSB_0 < 0.75]$	42.3	37.7	39.5	43.9	42.2	41.2
Under exploitation	$\Pr[SSB_{2020}/SSB_0 > 0.75]$	49.9	51.3	51.6	47.2	47.6	49.4

data-limited stock assessment model. Indeed, the LBSPR is a steady-state or equilibrium model, and therefore the length-frequency data must be representative of average conditions. Furthermore, although sea silverside is a small pelagic fish with a short life cycle, the recruitment variability should be influencing the abundance and length structure like in the summertime. However, the fishery is supported by larger adults, and hence, the length structure is not influenced by fluctuations in recruitment. In addition, the fishing effects in the length structure are represented in the descending arm of the length-frequency histogram. That is the reason why the LBSPR estimated a ratio F/M = 3.1 (IC: 1.9 to 4.3).

In terms of the catch history, the Only-Catch Optimized Method (OCOM) (Zhou et al. 2017a; Free 2018) revealed a different status for the sea silverside artisanal fishery in Los Lagos region. Indeed, the OCOM showed that the sea silverside population was recovering from the lowest depleted biomass ($B/B_{MSY} = 12.9\%$) from 2010 to 2020 ($B/B_{MSY} = 57.5\%$). In 2020, however, the uncertainty represented by the confidence interval was vast from a depleted to a fully exploited status. In addition, the median value for r was 0.342, which according to the natural mortality estimates the r value seemed to be lower than expected. Indeed, the estimates of natural mortality (M) ranged between 1.1 and 1.2, and hence $F_{MSY} = 0.87M = 0.96\text{-}1.0$ (Zhou et al. 2012), and $r = 2F_{MSY} \approx 2$. Therefore, the OCOM results seemed to be inconsistent with the sea silverside biology and considered invalids. In order to proceed to a more formal stock assessment with surplus production models, it will be necessary to collect fishery data and obtain catch per unit effort as a relative abundance index.

Age-structured simulations showed that the spawning stock biomass would be reduced to approximately 75% from the unexploited condition in 1960. The underexploited status reached a probability close to 49.4%, and the fully exploited status was 41.2%. The underexploited status could be a consequence of sampling recruitment from a log-normal distribution. The short life cycle of sea silverside could benefit from the low frequency of higher recruitments. Nevertheless, higher catches observed in 1990, 1999-2000 and 2003 affected the response of the stock negatively and transitorily because these higher catches were sporadic and acted as outliers. Therefore, simulations conditioned to the observed catch seemed more consistent with the LBSPR method, i.e. the sea silverside is in a fully exploited status in Los Lagos region. The approach was based on the estimated life-history parameters with FishLife rather than those known for sea silverside (Pavez et al. 2008). Parameters obtained by FishLife have the advantage that they are consistent and estimated simultaneously within a given model. Thus, the statistical uncertainty contained in the covariance can be utilized to improve the estimates when new and better data become available. Besides, the life-history parameters (mean and variance-covariance) could be sampled at random to construct operating models and evaluate the data-limited stock assessment models here utilized (e.g. Carruthers and Agnew 2016).

In the meantime, it is necessary to start with monitoring the sea silverside fishery in terms of fishing effort and catch per unit effort, and biological data. New data will facilitate estimating the fishery's status and the implementation of fishery management regulations. Therefore, the framework for a data-limited stock-assessment approach and the results obtained here for the artisanal sea silverside fishery is a starting and essential step.

ACKNOWLEDGMENTS

LAC thanks the support provided by COPAS COASTAL (ANID FB210021). PM and PSO thank the scholarship of the Dirección de Postgrado, Universidad de Concepción, Chile. GFM thanks the CONICYT-PFCHA/Magíster Nacional/2020-22200247 scholarship.

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