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Research Article

Optimal fishing mortality assignment for southern hake *Merluccius australis* in Chile

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ABSTRACT. Since 1979, southern hake (*Merluccius australis*) has been exploited in Chile from the Bio Bio to the Magallanes regions, between the parallels 41°28.6'S and 57°S. There is evidence of a constant fishing effort and a sustained reduction of the fish population, consistent with a progressive decrease in total annual catches. Management strategies based on the maximum sustainable yield (MSY) and quota assignment/ distribution criteria have not been able to sustain acceptable biomass levels. A non-linear optimization model with two objective functions was proposed to determine an optimal total catch quota for more sustainable exploitation of this fishery. The first function maximizes the total catch over time in response to an optimal assignment of fishing mortality rates per fleet; the second function maximizes the total economic benefit associated with the total catch. The dynamics of the fish population were represented with the equations of a predictive age-structured model. Decision variables were fishing mortality rates and annual catch quotas per fleet, subject to constraints that guarantee a minimum level of biomass escape over a long-term period. The input parameters were obtained from the last stock evaluation report carried out by the Instituto de Fomento Pesquero (IFOP) of Chile. The historical background data of the fishery and the regulatory framework were relevant aspects of the methodology. Five scenarios were evaluated with the two objective functions, including a base scenario, which considered the referential mortality rate as input data as the average mortality rate per fleet from 2007 to 2012. Total economic benefits fluctuate between 102 and USD 442 million for total catches in the range of 108 to 421 thousand tons, which were obtained from maximizing the economic and biological objective functions. Economic benefit/catch ratios were reduced for scenarios with higher constraints on catch limits, and they were more efficient from a biological point of view. Situations with lighter constraints showed in general higher economic benefits and better performance ratios than those with stronger restrictions. The use of optimization models may provide a useful tool to evaluate the effect of regulations for adequate conservation and economical utilization of a limited resource.

Keywords: *Merluccius australis*, southern hake; non-linear programming, optimal assignment; total allowable catch quota; quota distribution; MSY

INTRODUCTION

Commercial fishing depends on hydrobiological resources that, in the 1950s, were considered abundant and inexhaustible (Hawthorne & Minot, 1954). Several collapsed fisheries have been reported. They included the North Atlantic deep-sea cod (*Gadus morhua*) (Froese & Quaas, 2012), with a historical lower spawning biomass level reported in 2006, and the Peruvian anchovy (*Engraulis ringens*) that collapsed in the early 1970s with a combination of overfishing and environmental disturbances like El Niño (Clark, 1976; Aranda, 2009). However, in the late 1990s, anchovy biomass recovered in stock abundance (Gutiérrez *et al*., 2012).

The economic growth of any nation is strongly related to the sustainable exploitation of its natural renewable resources (Riekhof *et al*., 2018). One of Chile's main economic activities is the fishing and aquaculture industry, which accounts for 18% of the

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annual exports (ProChile, 2018). According to SUBPESCA (Subsecretaría de Pesca y Aquicultura), in 2018, the national fishing activity accumulated 2.65 million tons, from which 0.83 million tons were destined to international markets (SUBPESCA, 2018). This activity generated exports of USD 4.053 million, which increased by 11.1% compared to the year 2017. In 2016, Chile was ranked as the 12th largest producer of fish by-products by the FAO report State of Fisheries and Aquaculture in the World (SOFIA, 2018), with a total fish capture of 1.50 million tons in the year 2016. A similar report issued a decade earlier (2006), ranked Chile as the sixth largest producer of fish by-products globally, which shows that the Chilean fishing industry had lost its strategic position during that period. The National Fisheries Report for the year 2018, issued by SUBPESCA in March 2019, indicated that from a total of 44 Chilean fisheries, 27 have a biological reference point (BRP). Eight were in full exploitation condition, 11 were overexploited, eight were depleted, and the other 17 fisheries did not define a formal BRP. They were considered in full exploitation conditions under permanent supervision. (Thorpe *et al*., 2000a,b).

Southern hake (*Merluccius australis*) is a fish with demersal habits (Hutton & Hector, 1872). It is widely distributed in the southern hemisphere and can be found in Argentina, New Zealand, and Chile (Céspedes *et al*., 1996; García de la Rosa *et al*., 1997; Cousseau & Perrotta, 1998; Flores *et al*., 2019). The commercial catch of southern hake was formally established in Chile in 1977, between parallels 41°21'S and 57°S (Céspedes *et al*., 1996; Flores *et al*., 2019). The fishery was operated mainly by an industrial trawl fishing fleet from 1979 to 1983, catching an average of 39 thousand tons per year. In 1984, artisanal fishing fleets began to catch southern hake, mainly in the fjords of southern Chile and the industrial longliner fishing fleet (Lillo *et al*., 2015). Currently, three fishing fleets catch southern hake in Chile, including an industrial longliner fleet (ILF), an industrial trawler fleet (ITF), and an artisanal fleet (ARF). The artisanal fishing fleet has the largest share of catch quota allowed for southern hake (60% of total quota). A constant pressure over this fishery has led to a reduction in total catches due to sustained decreases in the abundance of the population (Quiroz *et al*., 2013). In 2014, a historical minimum catch of 12.3 thousand tons for southern hake was reported in Chile (Fig. 1).

Quiroz *et al*. (2013) concluded that the southern hake fishery remained in a safe zone of exploitation from 1977 to 1985. For the following years, the annual fishing mortality rates were always above the threshold that determines the BRP ($F_{MSY} = F_{45\%SBPR\ F=0}$), establishing a condition of permanent overfishing. Since 2012, spawning biomass (*SB*) was always below those values that determinate BRP ($SB_{MSY} = 40\%SB_0$), being in a constant overexploitation condition (Quiroz, 2014). Current management strategies for commercial fishing in Chile allocate and distribute the total catch between all fleets following political and socio-economic approaches, including historical share per fleet and constant proportions among industrial and artisanal fleets. The local authorities always use the highest possible value from an acceptable biological range of catch recommended by the Technical Scientific Committees. The lack of long-term policies for sustainable fishing could be responsible for the overfishing and overexploitation condition of this natural resource today.

In Chile, all sea extractive activities, including fisheries, are regulated by the National Law N°18,892 of 1989. In 2001, a maximum annual catch quota per shipowner was established for each fleet. For the industrial fleet, the catch quota was given according to its historical share over the total catch (*i.e*., percentage of each ship owner catch over the total annual catch). For the artisanal fleet, an extraction regime was created, which consisted of a fixed fraction over the global catch quota allocated either by area, fishing cove, boat size, artisanal fishermen union, or individual fishers. In 2012-2013, important amendments were introduced to this law, including special fishing licenses to fisheries subjected to total allowable catch (TAC) (SUBPESCA, 2013). The amendment of 2013, incorporated the concept of maximum sustainable yield (MSY) introduced by Graham (1934), as a target to achieve for all Chilean fisheries, concept that is widely used to these days by researchers for fisheries research and management.

Current Chilean fishing law establishes as a general management objective of achieving the maximum sustainable yield. However, the concept of MSY for fisheries management has been too widely criticized due to the limited information and an inadequate implementation to prove its theoretical framework (Russell, 1931; Graham, 1934; Gordon, 1954; Schaefer, 1954; Larkin, 1977; Finley, 2007; Legovic *et al*., 2010; Mesnil, 2012; Finley & Oreskes, 2013; Kar & Gosh, 2013, Steadman *et al*., 2014). Wiff *et al*. (2016) indicate that the MSY-based management strategies applied to Chilean fisheries do not provide certainty about the specific stock productivity since the BRP is estimated from fixed parameters of stock-recruit relationship (*h*) and natural mortality (*M*). This limitation for most fisheries exploited in Chile is due to the lack of available information to determine *h*. Authors concluded that even if enough data was available to determine *h*, the uncertainty remains when

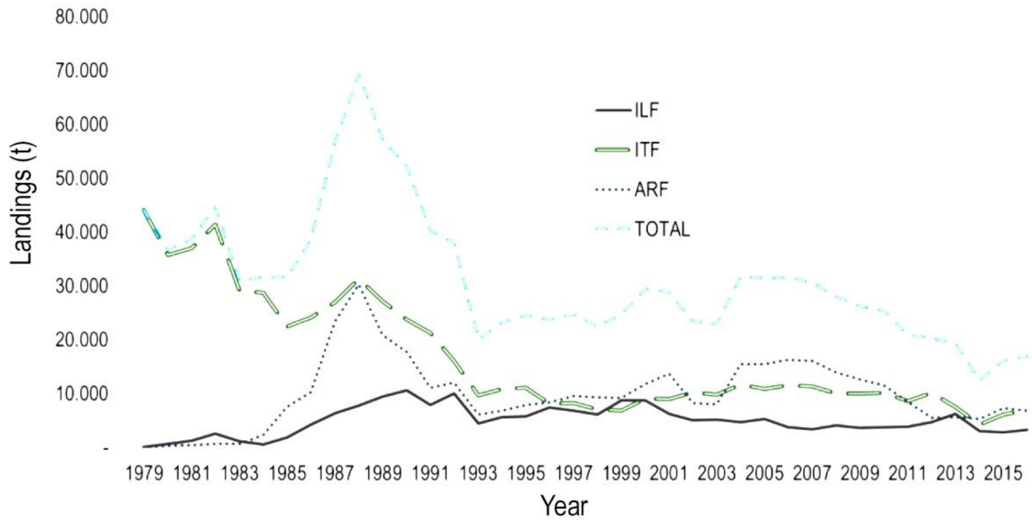

Figure 1. Total landings per fleet and global catch per year of southern hake *Merluccius australis* in Chile for years 1979-2016. ILF: longliner fleet; ITF: trawler fleet and ARF: artisanal fleet (source: SERNAPESCA).

establishing a BRP based on the MSY approach, which may negatively affect the sustainability and conservation of the stocks.

Alternative fishery management approaches have been proposed, including strategies based on the recommendations of the FAO code of conduct for responsible fisheries [1995; Article 2 (a)] and the US Magnuson-Stevens fishery conservation and management act (1996, Title III Sec 301. 104-297). Cunningham (1980) proposed an optimum sustainable yield (OSY) approach, which was once recommended by the International Council for the Exploration of the Sea (ICES) to replace the MSY approach. The OSY approach recommends lower fishing mortality levels than MSY, which allows the stock to recover above the BRP levels for MSY. Hoshino *et al*. (2018) reviewed the implementation of a maximum economic yield (MEY) principle in management policies for a multiple-species fishery in Australia to obtain the maximum economic benefit from exploiting the stocks. However, this approach requires large quantities of data to estimate the reliable values of each BRP (Mardle *et al*., 2002).

Today, the ICES provides recommendations and guidance based on several international agreements and policies, including the MSY as a target to reach high long-term yields for fisheries management. As long as there are necessary conditions, a plan/strategy agreed by the management parties, knowledge, and data for stock dynamics supports its implementation. However, the BRP for the MSY should be subjected to regular reviews and valid only in the mid-term due to permanent changes in conditions that affect the parameters that are assumed constant by the models used to estimate MSY.

Another approach for fishery management used for mixed or multispecies stocks is the pretty good yield (PGY) developed by Hilborn (2010). PGY was used to reach an acceptable percentage of the MSY when it was impossible to simultaneously reach the main targets as the F_{MSY} for all species. The use of optimization methods for catch quota assignment and optimal control rules have been proposed in the literature in order to improve the management strategies of specific hydrobiological resources (Katsukawa, 2004; Albornoz *et al*., 2006a,b; Albornoz & Canales, 2006, 2013). Studies recommend considering population dynamics and biological models and economic models to manage fisheries (Bjørndal *et al*., 2004, 2012; Weintraub *et al*., 2007).

The determination of catch quotas that guarantee optimal exploitation of each fishery is a complex task because of the combination of economic, social, and biological criteria (Richter *et al*., 2018). In Chile, the allocation of catch quotas among stakeholders (industrial and artisanal) is based on stock assessment studies carried out by the IFOP and recommendations from a Technical Scientific Committees, which proposes a range of biologically acceptable catch quotas to the local authority, for a specific stock, to achieve the MSY as a precautionary approach. However, the authorities driven by social pressure from artisanal and industrial fishing companies allocate the maximum possible catch quota (upper limit), underestimating the precautionary approaches and ignoring the limitations of the MSY concept. This approach has not effectively protected the southern hake fishery due to its steadily decreasing stock trend during the past two decades (Quiroz *et al*., 2013; Quiroz, 2014). Therefore, there is an opportunity to try a different approach to assign catch quota to preserve and restore this resource.

A non-linear optimization model was proposed to evaluate different catch allocation strategies to recover southern hake biomass levels close to MSY. The model can be useful to test different alternatives for catch quota allocation as a tool for improving the current management of southern hake fishery in Chile. The first function maximizes the global catch for all fleets (industrial and artisanal) by optimal allocation of fishing mortality rates per fleet, which was considered an objective biological function. The second function maximizes the global economic benefits associated with the total catch as an economic objective function. The dynamics of the fish population were represented in the model using the equations of a predictive age-structured biological model. Constraints include catch limits per fleet, minimum levels of spawning biomass, and total biomass for long-term preservation of the resource.

MATERIALS AND METHODS

Optimization model

A non-linear optimization model with two objective functions was developed to evaluate the long-term response of the southern hake (*Merluccius australis*) population, assuming mortality and recruitment conditions constant over time. The model was based on the Thompson & Bell (1934) model, which predicts different fishing efforts on the fish stocks in the future, fundamental for developing bio-economic predictive models. The optimization model's formulation with a biological approach is as follows:

$$Max \sum_{i=tr,\ t=1}^{i=tm,\ t=T} Y_{i,t}^{ilf} + Y_{i,t}^{itf} + Y_{i,t}^{arf} \quad (1)$$

Subject to:

$$N_{i,t} = N_{i-1,t-1}\, e^{-Z_{i-1,t-1}}$$
$$i = tr+1,\dots,tm\ ;\ t = 2,\dots,T \quad (2)$$

$$Z_{i,t} = M + \sum_{f=1}^{3} F_{ref}^{f}\, S_{i}^{f}$$
$$i = tr,\dots,tm\ ;\ t = 1,\dots,T \quad (3)$$

$$SB_t = \sum_{i=tr}^{tm} N_{i,t}\ W_i\ O_i\, e^{(-\,0.6667\ Z_{i,t})}$$
$$t = 1,\dots,T \quad (4)$$

$$Y_{i,t}^{f} = \frac{N_{i,t}\ F_{i,t}\ \left(1 - e^{(-Z_{i,t})}\right) W_i}{Z_{i,t}}$$
$$t = 1,\dots,T \quad (5)$$

$$SB \geq SB_{MSY} \qquad t = 1,\dots,T \quad (6)$$

$$SB_{MSY} \geq 40\%\ SB_0 \qquad t = 1,\dots,T \quad (7)$$

$$F_t^{ilf} \geq 0,\ F_t^{itf} \geq 0,\ F_t^{arf} \geq 0$$
$$t = 1,\dots,T \quad (8)$$

The basic parameters used in the model are defined according to the following notation:

Parameters

- T: total number of periods (years) of the planning horizon (15 years)
- tr: age at which a recruit is incorporated at the beginning of each period (2 years)
- tm: maximum age that the resource can reach (24 years)
- W_i: average weight at age i in Kg.
- O_i: sexual maturity at age i
- F^f_{ref}: referential fishing mortality rate per fleet f
- S^f_i: exploitation pattern or selectivity per fleet at age i
- M: instantaneous natural mortality rate
- SB_0: virginal spawning biomass
- Δt: the proportion of the year where the spawning occurs (for the case of southern hake, this happens in August; therefore, $\Delta t = 8/12 = 0.6667$).

Variables of population dynamics

- $N_{i,t}$: the total population of the age group i for a period t
- $Z_{i,t}$: the total instantaneous mortality rate of age group i for a period t
- SB_t: spawning biomass at the end of period t
- $\bar{R}$: average recruitment
- $Y_{i,t}^{ilf}$: catch in weight of age group i for a period t for the industrial longliner fishing fleet
- $Y_{i,t}^{itf}$: catch in weight of age group i for a period t for the industrial trawl fishing fleet
- $Y_{i,t}^{arf}$: catch in weight of age group i for a period t for the artisanal fishing fleet.

Decisions variables

- F^{ilf}: fishing mortality rates for the industrial longliner fishing fleet
- F^{itf}: fishing mortality rates for the industrial trawl fishing fleet

- F^{arf}: fishing mortality rates for the artisanal fishing fleet.

The objective biological function (Equation 1) corresponds to the maximization of the sum of annual catch in weight for the three fleets over 15 years. In restriction (Equation 2), it is assumed that the number of individuals for an age range decreases exponentially as a function of the resulting mortality rate defined in (Equation 3). Considering the sum of the instantaneous natural mortality rate (*M*), and the instantaneous fishing mortality rate (*F*) per fleet, for each age group *i*. Restriction (Equation 4) represents the spawning biomass level at the end of each period, resulting from the sum of the fraction of adults of each cohort that survive after spawning. Restriction (Equation 5) establishes the relationship between fishing mortality rates, natural mortality rates, abundance, and catch volumes for a given period and age. Restrictions (Equations 6 and 7) impose minimum escape levels for the spawning biomass for the conservation of the stock during the assessment period. Equation 8 is the non-negativity restriction.

For the formulation of the optimization model with an economic approach, the objective was to maximize the total economic benefit associated with the total catch as a response to an optimal assignment of fishing mortality rates per fleet. The following term gives this benefit:

$$E_t^f = \frac{Y_{i,t}^f\ (\lambda_f - c_f)}{(1+\rho)^t} \quad (9)$$

where:

- λ_{ilf}: sale price per ton for industrial longliner fleet, USD 3,050
- λ_{itf}: sale price per ton for industrial trawl fleet, USD 3,121
- λ_{arf}: sale price per ton for the artisanal fleet, USD 2,482
- c_{ilf}: operational cost per ton for industrial longliner fleet, USD 550
- c_{itf}: operational cost per ton for industrial trawl fleet, USD 821
- c_{arf}: operational cost per ton for the artisanal fleet, USD 231
- ρ: annual discount rate, 12% (Albornoz *et al*., 2006a)
- E_t^f: economic benefit per fleet for a period *t*
- $Y_{i,t}^f$: catch in weight per fleet of age group *i* for a period *t*
- t: year.

Therefore, the economic objective function is defined as follows:

$$Max \sum_{i=tr,\ t=1}^{i=tm,\ t=T} E_t^{ilf} + E_t^{itf} + E_t^{arf} \quad (10)$$

The sale prices and operational costs were obtained from local industrial fishing companies in the region and were standardized by fleet type (industrial) and by weight (t). Variables and restrictions are the same as those proposed for the model with a biological approach in (Equations 2-8).

The parameters used in both objective functions were obtained from the Instituto de Fomento Pesquero (IFOP) of Chile. The parameters for population dynamics such as exploitation patterns by fleet (S_i^f), referential fishing mortality rate (F^f_{ref}), the instantaneous natural mortality rate (*M*), average weight at age (W_i), sexual maturity at age *i* (O_i) and virginal spawning biomass (SB_0) were obtained from Quiroz (2014) and are summarized in Table 1. This input data was the result of a stock assessment analysis, which considers a statistical model based on age that uses the age structure of the fish captured by the three fleets. Also, the analysis considered abundance index time-series based on catch per unit of fishing effort (CPUE) and a time-series of abundance index derived from hydroacoustic research cruises.

Virginal spawning biomass (SB_0) was estimated at 394.3 thousand tons, and virginal recruits (R_0) were 155 million individuals. Recruits of age 2 during the first year of the planning horizon was 90.9 million, and the stock-recruit relation (*h*) was 0.75 (Quiroz, 2014).

The generalized reduced gradient method was used for solving the non-linear model (Lasdon *et al*., 1973; Facó, 1988, 1989). The minimum resolution time was 0.25 s, and the maximum time was 0.47 s. Both objective functions were evaluated under six different scenarios, including a base scenario. They were subjected to different subsets of constraints on catch limits per fleet and minimum escape spawning biomass (Table 2). The baseline scenario considered as input data the referential mortality rate, as the average mortality rate per fleet, from 2007 to 2012, data obtained from Quiroz (2014), where: $F_{ref}^{ilf} = 0.108$; $F_{ref}^{itf} = 0.228$ and $F_{ref}^{arf} = 0.073$.

RESULTS

With a biological approach, the optimization model allocated fishing mortality to all fleets in three out of the five scenarios evaluated. Scenarios 1 and 4, under a biological approach, allocated all fishing mortality to

Table 1. Input parameters for the population dynamics of southern hake *Merluccius australis* in Chile. (Quiroz, 2014).

Age	Weight (W_i)	Msex (O_i)	S_i^{ilf}	S_i^{itf}	S_i^{arf}
2	0.25	0.000	0.000	0.000	0.002
3	0.42	0.000	0.000	0.001	0.007
4	0.64	0.000	0.001	0.002	0.019
5	0.92	0.001	0.001	0.005	0.045
6	1.22	0.008	0.003	0.010	0.099
7	1.52	0.045	0.007	0.019	0.193
8	1.81	0.170	0.012	0.035	0.335
9	2.12	0.350	0.032	0.060	0.521
10	2.40	0.537	0.059	0.099	0.723
11	2.73	0.742	0.104	0.156	0.897
12	3.10	0.882	0.171	0.233	0.993
13	3.46	0.945	0.266	0.333	1.000
14	3.78	0.971	0.387	0.451	0.990
15	4.24	0.982	0.530	0.583	0.972
16	4.61	0.988	0.681	0.716	0.945
17	4.94	0.991	0.822	0.838	0.911
18	5.25	0.993	0.932	0.933	0.870
19	5.66	0.995	0.992	0.989	0.824
20	6.09	0.996	1.000	1.000	0.773
21	6.28	0.997	1.000	1.000	0.719
22	6.60	0.998	1.000	1.000	0.663
23	7.07	0.999	1.000	0.999	0.605
24	7.36	1.000	1.000	0.999	0.548

the artisanal fishing fleet (ARF) with a total yield of 328.8 thousand tons in both scenarios, which could be explained since this fleet did not have catch restrictions. Given the selectivity pattern of this fleet, this may have a better performance than the industrial fleets in terms of expected impact level over the stock regarding the fish sizes due to the type of fishing gear used.

On the other hand, the optimization model with an economic approach, in two scenarios (1 and 5) allocated as much as possible fishing mortality to the most productive fleet, in terms of the cost-benefit relationship, which in this case was the industrial trawler fleet (ITF). These results were more productive than the baseline scenario in terms of the average price/ton relationship (Table 5).

Scenario 5 in the biological approach, shared the fishing mortality between the ITF and the ARF, which could be explained due to the constraint limiting the ARF quota fraction up to 30% of Y_T forcing allocation of the rest of the fishing mortality to the fleet with a better cost-benefit relationship. The total fishing mortality rate per scenario follows a similar trend to total catch volumes and economic benefits. Although the allocation of fishing mortality showed a high dispersion among scenarios, the total catch values and economic benefits were similar. Without considering the baseline scenario, the highest fishing mortality value (0.357) was obtained in scenarios 1 and 5 from an economic approach. The lowest fishing mortality value (0.0429) was obtained in scenario 3 when the function with a biological approach was selected.

Table 3 shows the total catch and total economic benefits by the fleet for the six scenarios evaluated. In scenarios without catch restrictions (scenarios 1 and 5), the model with an economic approach maximized the total benefit by allocating the total catch to a single fleet (ITF), due to its better cost-benefit relationship than the other fleets and comparing these results to the 2018 global catch quotas assigned by the local authority, the model, under an economic approach allocated in scenarios 1 and 5, a catch for the industrial trawl fishing fleet equal 101.3% of the quota assigned for this fleet in the year 2018.

For the two other fleets, the results proposed a 100% catch reduction over the quota assigned in 2018 and a 19.4% reduction of total quota (Table 4). By allocating catch to the other fleets (ILF and ARF), the overall economic benefit from this resource will be reduced even if the total global catch is maintained. An indicator that the economic objective function is strongly influenced by the cost-benefit relationship rather than the selectivity pattern. Nevertheless, the model results did not consider other factors, such as the social and economic implications of allocating catch to the artisanal and longliner fleets. In scenarios where limits on catch volumes were imposed, the model always allocates the maximum possible catch to the artisanal fishing fleet. The remaining catch volume was allocated in equal proportion to both industrial fleets for scenario 2 (economic and biological) and scenario 4 under an economic approach. In scenario 3, under a biological approach, both industrial fleets share the same catch quota proportion. However, under an economic approach, the model allocated more catch quota to ITF than ILF due to differences in the cost-benefit relationship.

In scenarios 1 to 5, for both biological and economic approaches, the catch volumes allocated for each fleet during the first year were always lower than the current catch quota assigned by the authority in the year 2018 (Table 4), with a 12.3% reduction of Y_T in scenarios where ARF had no catch limits and a 78.6% reduction for scenarios with the most restrictions (catch limits for all fleets). When no specific catch limits were imposed, catch allocations were subjected to maintaining a minimum *SB* level for the whole evaluation period. It is interesting to note that if the average fishing mortality rates of recent years are maintained, the total catch allocation increases by 27.6% compared to the 2018 quota. Figure 2 shows a summary of the *SB* projections

Table 2. Configuration of different optimization scenarios applied on southern hake *Merluccius australis* in Chile. The non-negativity constraint (Equation 8) was included in all scenarios.

Scenario	Configuration
S0 (baseline)	As defined earlier
S1	$SB_t/SB_0\ \geq 40\%;\ \ t\ \geq 10$
S2	As S1 plus catch constraints by fleet; $Y^{ilf}/Y_T\ \leq 20\%\ Y_T$; $Y^{itf}/Y_T\ \leq 20\%$; $Y^{arf}/Y_T\ \leq 60\%$
S3	As S1 plus catch constraints by fleet; $Y^{ilf}/Y_T\ \leq 15\%\ Y_T$; $Y^{itf}/Y_T\ \leq 15\%$; $Y^{arf}/Y_T\ \leq 45\%$
S4	As S1 plus catch constraints by fleet; $Y^{ilf}/Y_T\ \leq 10\%\ Y_T$; $Y^{itf}/Y_T\ \leq 10\%\ Y_T$
S5	As S1 plus catch constraints by fleet; $Y^{arf}/Y_T\ \leq 30\%\ Y_T$

Table 3. Total catch (*Y*), distribution of catch per fleet, and economic benefits (*E*) per fleet and total for the evaluation period.

Scenarios		Y_T (t)	Y^{ilf}/Y_T (%)	Y^{itf}/Y_T (%)	Y^{arf}/Y_T (%)	E^{ilf} (USD million)	E^{itf}	E^{arf}	E_T
Baseline	Biological approach	421,388	14	38	47	66.5	182.8	193.5	442.9
	Economic approach	421,388	14	38	47	66.5	182.8	193.6	442.9
Scenario 1	Biological approach	328,806	0	0	100	0.0	0.0	315.5	315.5
	Economic approach	320,328	0	100	0	0.0	345.6	0.0	345.6
Scenario 2	Biological approach	325,988	20	20	60	68.8	70.2	186.9	325.8
	Economic approach	319,294	20	20	60	67.1	68.5	182.8	318.5
Scenario 3	Biological approach	108,675	15	15	70	15.9	16.3	70.2	102.4
	Economic approach	297,241	20	24	56	62.2	74.9	158.8	295.9
Scenario 4	Biological approach	328,806	0	0	100	0.0	0.0	243.0	315.5
	Economic approach	327,719	10	10	80	34.5	35.2	251.0	320.7
Scenario 5	Biological approach	323,583	0	70	30	0.0	244.1	92.6	336.7
	Economic approach	320,328	0	100	0	0.0	345.6	0.0	345.6

Table 4. Total catch for the first year of the planning horizon, and increment/reduction percentages regarding the catches quota for the year 2018.

Scenarios		Y_T (year 1) (t)	Variation of Y_T over the total catch quota 2018 (%)	Variation of (Y^{ilf}+Y^{itf}) over industrial catch quota 2018 (%)	Variation of Y^{arf} over artisanal catch quota 2018 (%)
Baseline	Biological approach	25,923	27.64	72.64	-2.36
	Economic approach	25,923	27.64	72.64	-2.36
Scenario 1	Biological approach	17,806	-12.33	-100.00	46.11
	Economic approach	16,354	-19.48	101.31	-100.00
Scenario 2	Biological approach	16,668	-17.93	-22.98	-14.56
	Economic approach	16,154	-20.46	-25.75	-16.94
Scenario 3	Biological approach	4,344	-78.61	-87.37	-72.77
	Economic approach	14,493	-28.64	-27.67	-29.29
Scenario 4	Biological approach	17,806	-12.33	-100.00	46.11
	Economic approach	17,128	-15.67	-62.35	15.46
Scenario 5	Biological approach	16,406	-19.22	38.83	-57.93
	Economic approach	16,354	-19.48	101.31	-100.00

relative to virginal spawning biomass (SB_0). Results show scenarios (excluding baseline) and objective functions. The 40% SB_0 attained at year 10 was an imposed restriction on the model. Besides, more than 50% of SB_0 was attained in most scenarios at the end of the planned horizon. Baseline scenario did not achieve 40% of SB_0 at year 10, instead of at the end of the evaluation period in year 15. This scenario was simulated using averaged referential mortality rates, and no restrictions were applied.

Table 5. Long-term performance ratio (benefit-to-catch ratio) for all scenarios.

Scenarios		Y_T (thousand tons)	E_T (USD million)	Average price (USD t^{-1})
Baseline	Biological approach	421.39	442.86	1,051
	Economic approach	421.39	442.86	1,051
Scenario 1	Biological approach	328.81	315.54	960
	Economic approach	320.33	345.57	1,079
Scenario 2	Biological approach	325.99	325.80	999
	Economic approach	319.29	318.48	997
Scenario 3	Biological approach	108.68	102.35	942
	Economic approach	297.24	295.92	996
Scenario 4	Biological approach	328.81	315.54	960
	Economic approach	327.72	320.67	978
Scenario 5	Biological approach	323.58	336.67	1,040
	Economic approach	320.33	345.57	1,079

Table 5 shows the long-term productive performance ratio between the economic benefits and global catch for all six scenarios throughout the evaluation period. The lowest benefit/catch ratio was USD 942 per ton and occurred in scenario 3 for the model with the biological approach. However, the total mortality rate in this scenario represented only 10% of the baseline scenario's total mortality. Therefore, the lowest catch and economic benefit occurred in scenario 3, representing only 25.7% of the total catch and 23.1% of the total economic benefit achieved in the baseline scenario.

The highest benefit/catch ratio was USD 1,079 per ton and occurred in scenarios 1 and 5 for the model under the economic approach. The total mortality rate represented 87% of the total mortality rate of the baseline scenario. The total catch in these scenarios represented 76% of the total catch and 78% of the total economic benefit achieved in the baseline scenario.

DISCUSSION

Short-term benefits *vs*. sustainable catch

The artisanal fishing fleet currently has the predominant quota of southern hake *Merluccius australis* in Chile, which can be explained by factors, including social, economic, and political pressure. When the priority is to attain economic benefits, the baseline scenario (business as usual) in both approaches shows a slow increase in SB_0, barely achieving $SB_{MSY} \geq 40\%$ of SB_0 at the end of the evaluation period. The baseline scenario considers as input that F is constant over time, and it can be assumed a constant effort over the stock and the SB, which may eventually be recovered to the MSY level within 15 years. Nevertheless, the steady population decline and current allocation of catch quotas suggest that F has been increasing over time, not allowing SB_{MSY} to be achieved within 15 years, leading to an imminent collapse of the southern hake stock in the long-run. The local authority increases the total catch quotas (fishing mortality) every year, despite the biological implications behind these decisions. Scenario 3, under the economic approach, may show fewer economic benefits in the short-term. However, it could provide more sustained exploitation of the resource in the long-term, achieving 43.2% of SB_0 by the 4th year and 74.4% by year 15 (Fig. 2). Despite its overfishing and overexploitation condition, a progressive increment of fishing mortality rate shows how poorly southern hake fishery has been managed in Chile.

The constant need for immediate economic relief to local fishers may discourage the local authority to substantially reduce the current mortality rates (total catch volumes), to allow southern hake to recover fully, providing a more sustainable operation and economic benefit for a more extended period. However, immediate economic benefits could not be achieved, since 40% *of* SB_0 is achieved just before year 10. It is unlikely to see a significant reduction in current fishing mortality rates without significant changes in the management strategy of this resource. Therefore, the quota distribution and the management principle may remain today, because let SB_{MSY} to be achieved in 10 years seems to maximize and justify immediate benefits.

The model results suggest that it is not sustainable to maintain current mortality rates (base scenario) since the projected values for SB would remain below the

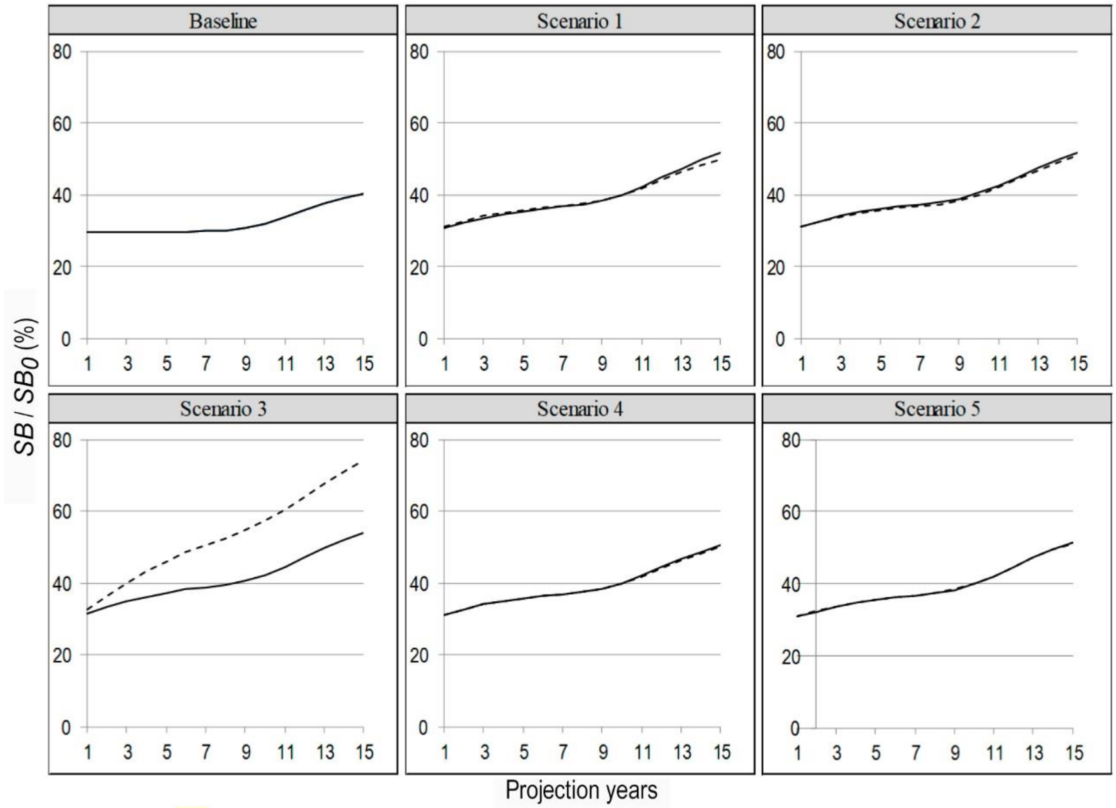

Figure 2. Projection of SB percentage regarding SB_0 for all scenarios with a biological (dotted line) and economic (solid line) approach.

threshold that defines a stock under an overexploitation condition for at least 15 years. Current criteria for assigning quota and quota distribution that superimpose immediate economic benefits over the resource's sustainability could lead to permanent overfishing, overexploitation, or even the collapse of southern hake in Chile.

The results of scenario 1 without catch restrictions provided the best result for total yield (biological function) and best result in terms of total benefits (economic function) by allocating the total catch to one fleet as the optimal solution. However, this allocation is not realistic since the other two fleets did not share the resource. Scenario 1 was also solved by restricting the solution to achieve $SB \geq 40\%$ SB_0 in the years 3 and 9; the results showed that when $SB \geq 40\%$ of SB_0 was attained in the year 3, the total yield was 113,66 thousand tons (biological function) and for the economic function the total benefit was USD 113 million. On the other hand, when the target was achieving $SB \geq 40\%$ of SB_0 in year 9, the total yield was 308.37 thousand tons for the biological function. For the economic function, the total benefit was USD 321 million.

Quota assignment

For the model under economic function, scenarios 1 and 5 maximized the economic benefits by allocating 100% of the catch to the industrial trawl fishing fleet (ITF) and leaving the other two fleets (ILF and ARF) without a catch. This scheme is improbable to be implemented since it requires a large fleet capacity for the ITF to fulfill this task, and more importantly, it may cause conflicts and social impacts among the artisanal fishermen. They currently have entitled 60% of the total catch quota of this resource. Scenarios 1 and 4 under the biological approach maximized the total catch by assigning 100% of the quota to ARF and leaving the industrial fleets (ILF and ITF) without a catch. This allocation is not feasible to implement in the short-term since the artisanal fishing fleet (ARF) does not have the technical capacity to capture the entire quota and the subsequent losses of jobs for the industrial fleets that impact the entire local fishing industry. Scenarios 2 and 3, for both biological and economic function, provided a solution by maximizing total catch and economic benefits by including a constraint that forces the solution to allocate fishing quotas to all fleets. The strategy of assigning fishing quotas to each fleet may reduce the overall yields (total catch and economic benefits) of this fishery and reduce the economic utilization of this limited resource.

Constraints

The model was proposed to evaluate different catch allocation strategies for Chile to recover southern hake biomass close to the MSY. Scenarios 1 to 5 considered constraints aimed to cap the global annual catch by restricting catch quotas and then acting fishing fleets regardless of the type of fishing vessels. These constraints were imposed to prevent not exceeding key parameters established by the SB_0 and BRP to recover a minimum southern hake biomass level over a specified period. From a strategic point of view, the authority or regulator in Chile should address these restrictions to prevent an imminent collapse of this valuable resource.

Richter *et al.* (2018) proposed a model to determine a total acceptable catch (TAC) for different ship segments. TAC was established by a group of scientists, subject to a set of institutional constraints. They limited the commercialization of individual transferable quotas (ITQs) between different boat segments and restricted the access of new boats to this fishery. Richter *et al*. (2016) evaluated the losses of economic welfare from a strategy that considered only biological restrictions for pursuing MSY and concluded that economic welfare should also be considered in fishery management policies. In general, there are several choices to fix a fishing quota where the objectives are declared explicitly by all participants, including the optimal harvest approach, as have been considered in this research. In most recent decades, several harvest control rule concepts have been formulated into a management strategy evaluation-MSE (Punt *et al.*, 2016). This approach permits simulate all fishery management components in order to identify the most robust control rule for making decisions. Scientific Committee proposes the limit catch (quota) for southern hake fishery based on a long-time biomass projection (SUBPESCA/CCT-RDZSA, 2019). In this analysis, a single management objective has been considered. A constant reference fishing mortality rate is applied (F_{MSY}) independently to the current population status, being this the probable reason has not permitted effective population recovery. A population rebuilding plan could consider an "optimal harvest" approach proposed in this work considering this situation and be analyzed under an MSE analysis.

Limitations of the models

The model outcomes from this research should be considered as a preliminary approach for establishing a management strategy for limited hydrobiological resources. It would require more data for economic and social impact assessments to establish the implications of regulating and allocating catch quotas for southern hake fishery among different fleets in Chile. More detailed information for operational costs, market prices, and job opportunities for each type of fleet and vessels would improve the ability of the model to estimate changes in the economic welfare for this fishery. Sensitivity analysis using different discount rates and variable operational costs should be considered for future work to assess how this variation could influence the results.

Finally, updating some of the biological parameters of southern hake should be considered, including the selectivity patterns of each fleet, the sexual maturity and the average weights at different ages in the stock. Values for these parameters were obtained from the last stock assessment from 2012 (Quiroz, 2014). Therefore, it is considered pertinent to conduct new surveys and studies when updating these biological parameters since they provide useful information for this research.

CONCLUSIONS

This research combines non-linear optimization models with population age-structured dynamic models to provide a useful tool for assessing the biological and economic implications approaches for an optimal allocation of the total catch for the southern hake *Merluccius australis* fishery in Chile. As a preliminary approach, the model was successfully run to test the effect on total yields and economic benefits, applying different constraints on this fishery. These included catch limits per fleet and biomass minimum scape levels (precautionary approach) for sustainable economic exploitation of this fishery, given that the southern hake population has declined over the past two decades. The current fishing policy of Chile is not capable of reversing this condition.

The model results suggest that it is not sustainable to maintain current mortality rates (base scenario) since the projected values for *SB* would remain below the threshold that defines a stock under an overexploitation condition for at least 15 years. Scenarios 1 and 4, under a biological approach, allocated all fishing mortality to the artisanal fishing fleet (ARF) with total yields of 328.8 thousand tons. This fleet did not have catch restrictions and had a better selectivity pattern.

The model with an economic approach, in two scenarios (1 and 5) allocated as much as possible fishing mortality to the most productive fleet, in terms of the cost-benefit relationship, which in this case was the industrial trawler fleet (ITF) with a total economic benefit of USD 345.6 million in both scenarios. However, this allocation is not realistic since the other two fleets did not share the resource.

The imposed restriction of maintaining $SB_{MSY} \geq$ 40% of SB_0, provided results that achieved the precautionary approach for the optimal fishing mortalities rates assigned. The use of optimization models may provide a useful tool to evaluate changes in fishing policies for adequate conservation and economical utilization of fisheries. Further studies may include a more detailed analysis of local economic welfare and the environmental impacts of this fishery's economic utilization. A more comprehensive economic analysis may include multiple factors. These include operational cost splits into fixed and variable components, external and internal market prices, direct and indirect jobs, permissions fees, and other regulatory costs.

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