Assessing a management procedure for a benthic species with non-annual recruitment, the case of the surf clam (Mesodesma donacium, Lamarck 1888) in northern Patagonia, Chile.

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Abstract

The exploitation of benthic species by artisanal fishers in coastal management areas is expected to be sustainable when there is a management procedure (MP), in which data from direct stock assessments are the main input to estimate annual quotas. Nevertheless, the adequacy of such an MP has not been assessed for cases where recruitment does not occur or is not observed consistently in the annual surveys. One such case is the fishery for surf clam Mesodesma donacium in northern Patagonia, which thus far has been managed as though the population biomass was sustained by annual recruitment, despite the frequent lack of small-sized individuals found by stock assessment surveys. Here, we used data from annual stock assessments of M. donacium conducted in 2011-2017 at Cucao beach, to condition an operating model for the population dynamics of this species. During this period, six catch quotas were established applying the current MP, which aims to harvest 25% of the vulnerable stock. Simulations based on the operating model indicated that recruitment occurs every 2-3 years and that the current exploitation rate of 25% implies an 80% probability of future collapse. Exploitation rates below 15% are required to ensure the sustainability of this fishery. These results highlight the need to consider medium-term approaches in MPs, and to establish how often the existence of annual recruitment is a valid assumption in the management of benthic fisheries. In order to improve the MP currently utilized in most artisanal fisheries along the Chilean coast, and probably other regions, it is advisable to study alternative harvest-control rules, and to take advantage of direct annual estimates of biomass to develop integrated stock-assessment models.

Key words: data-poor fisheries, management strategy evaluation, artisanal-fisher, management areas.

Introduction

Reproductive processes strongly influence the distribution and abundance patterns of benthic species. These aspects are influenced mainly by local coastal dynamics, which can transport or retain larvae near spawning areas, modify the duration of larval development through changes in water temperature (O'Connor et al., 2007), and affect the distribution of adults (Bhaud, 1993; Giangrande et al., 1994; Grantham et al., 2003; Ospina-Alvarez et al., 2020). Moreover, the recruitment of benthic species depends on reproductive success, larval abundance and dispersal, settlement success, and post-settlement survival under environmental conditions that may be subject to anthropogenic effects (Hunt and Scheibling, 1997; Ouréns et al., 2014).

All of these factors interact at different scales, inducing high levels of spatial and temporal variability in recruitment (Pineda, 2000; Botsford, 2001; Pineda et al., 2009). At a regional scale (i.e., 10-1000 km), changes in geomorphology and coastal oceanographic regimes affect the advective loss of larvae from settlement areas and, consequently, the recruitment success of many species (Morgan et al., 2000; Lagos et al., 2008; Ebert, 2010). At smaller scales (0.1-10 km), local factors can strongly affect nearshore larval distributions (Tapia and Pineda, 2007; Shanks and Shearman, 2009), patterns of settlement (Pineda, 1994; Ladah et al., 2005), or early mortality of benthic individuals (Hunt and Scheibling, 1997).

In Chile, one of the most important and commercially exploited benthic species is the surf clam *Mesodesma donacium*. This species inhabits sandy beaches along the Chilean coast, from Arica to southern Chiloé (18-43ºS). It forms dense aggregations that are associated with morpho-dynamic beach features such as grain-size distribution, steepness, and profile (Jaramillo et al., 1994). The landing records for *M. donacium* reveal boom and bust cycles, with significant spatial and temporal fluctuations in landings, which have been described as serial depletion in the populations distributed along the Chilean coast (Thiel et al., 2007). Initially, in the 1960s and 1970s, harvesting for this species was concentrated mainly in the northern region (Matamala et al., 2008), particularly in the sandy banks of Coquimbo. During the late 1980s, banks in the southern zone near Mehuin were under significant extraction pressure. The fishery practically disappeared in the mid-1990s and started again in 1998 with the simultaneous harvesting of 10 banks in the southern Los Lagos Region (Rubilar et al., 2001; Stotz et al., 2003). The high variability observed in the harvesting of surf clam has been attributed to ENSO effects on their survival and reproductive biology (Arntz et al., 1987; Riascos et al., 2009; Carstensen et al., 2010; Ibarcena Fernández et al., 2019). Nevertheless, recruitment variability could be caused by density-dependent effects (Lima et al., 2000), and is probably associated with adult life span (Ripley and Caswell, 2006).

In recent years, the fishery for the surf clam *M. donacium* has focused on three main sections of the Chilean coast: a) Coquimbo Region (29-30ºS), with high inter-annual variability in landings, which are concentrated at two main coves (Los Choros and Peñuelas, Fig. 1); b) “Caleta Quidico” in the Biobío Region (38ºS), where most of the national landings were concentrated between 2001 and 2004, with a rapid depletion of the bank after that; and, c) Los Lagos Region (42-43ºS), with three main coves (Maullín, Mar Brava, and Cucao) accounting for landings that increased substantially in 2009-2011, and then dropped to reach a minimum in 2016 (Fig. 1).

In Chile, benthic fisheries are managed through an administrative system known as "Areas for the Management and Exploitation of Benthic Resources" (AMEBR) which is based on a Territorial User Rights for Fisheries (TURF) system, in which a geographical coastal area is allocated to artisanal-fisher organizations through temporary rights to harvest benthic species. Fishers must provide baseline information and a managing plan for target benthic species, derived from field surveys, which are often conducted by private consultants. Based on these surveys, the management agency (Undersecretariat of Fisheries and Aquaculture, SUBPESCA) authorizes to harvest a given quota for the target species, seeking to safeguard the ecosystem's natural recovery (González et al., 2006; Gelcich et al., 2010; Marín and Gelcich, 2012; Aburto et al., 2013).

In the AMEBR system, the management procedure (MP) consists of a) an annual assessment of the standing stock, which provides estimates of biomass and length-composition; b) estimation of a target fishing mortality, usually the F0.1 (Deriso, 1987) by assuming a pseudo-cohort and applying the yield-per-recruit model of Thompson and Bell (e.g., Doubleday and Esunge, 2011; Mildenberger et al., 2017); and c) estimation of a total allowable catch (TAC), which must be authorized to be harvested by SUBPESCA. This MP repeats annually without taking into account past surveys and removals and would be inadequate to ensure the sustainable exploitation of benthic species with non-annual recruitment, such as the surf clam *M. donacium*.

Unfortunately, one crucial weakness of the surf clam fishery in Chile is the incomplete recording of landings at coves and landing ports. Additionally, there is a lack of management plans that simultaneously consider the impact of users and environmental variability on the target species' availability, which increases the cost of maintaining monitoring programs (CCT-B, 2014). Often, these fisheries are data-poor, which makes it challenging to apply quantitative methods of population assessment, such as integrated statistical catch-at-length (age) analysis

(Smith et al., 2009; Punt et al., 2011). Thus, the local depletion of surf clam populations observed along the Chilean coast over the past decades has not been adequately evaluated yet due to a lack of data, which has hampered attempts to test whether local depletion was due to fishing effects or larger-scale, oceanographically driven changes in population dynamics.

At Cucao beach in northern Patagonia, data from direct stock assessments of surf clam are available annually for the seven years 2011-2017. During this period, different consultants conducted surveys and produced estimates of abundance and annual quotas under the assumption that this species recruits annually. Decisions on harvest limits for this area were taken considering those annual quota estimates. In this study, we use the 7-year data set from stock assessment surveys to implement an operating model for the population dynamics of Mesodesma donacium at Cucao beach. The implemented model allows for inter-annual variability in recruitment to be simulated, to assess the management procedure currently applied to AMEBRs, and to provide estimates of harvest rates that could achieve sustainable exploitation given the high temporal variability in recruitment detected for this fishery in the recent past.

Materials and methods

Study area and data sources

The study area is Cucao beach (24º36'S-74º08'W), located on the western shore of Chiloé island, northern Chilean Patagonia (Fig. 1). Over the past decade, Cucao has been one of the main harvesting areas for the surf clam *M. donacium*, with three organizations of artisanal fishers having territorial use rights since 2015 (Fig. 1). The data were obtained from six stock assessment surveys carried out between 2011 and 2017 (Table 1). Before 2015, the stock assessments of surf clam were carried out to establish annual catch quotas. Since 2015, data from the assessments became input information for harvesting surf clam under the AMEBR management procedure.

Evaluation of the management procedure

A simulation was implemented to evaluate the performance of the management procedure (MP) for *M. donacium* in Cucao. The simulation involved the steps of the Management Strategy Evaluation (MSE) framework (Starr et al., 1997; Cochrane et al., 1998; Punt et al., 2016; Kell et al., 2017). In this framework, one of the steps is conditioning an Operating Model (OM) based on data and knowledge for the surf clam population dynamics. The OM allowed us to evaluate the MP under uncertainty (Fig. 2), especially in terms of recruitment, which during the studied period exhibited pulses of high recruitment followed by years of low to nil recruitment. The OM allowed simulating the perceived vulnerable biomass in the stock assessment surveys for a window of 20 years into the future, along with the quota and the realized total harvest under a constant harvest rate strategy.

The simulation modeling to evaluate the MP for surf clam consisted of the steps described in the following sections: Section A describes the current MP for surf clam in Cucao. Section B describes the OM that specifies the true structure and processes modulating the surf clam population dynamics, with emphasis on conditioning the OM to the available data and knowledge (Kell et al., 2017). Section C describes the phase of projecting the operating model 20 years into the future. For each year, the OM provides a population that can be sampled in a way similar to the stock assessment surveys carried out in the field. The projected OM included the recruitment dynamics and its response to fishing and environmental forcing. Section D describes the statistics used to summarize the performance of the current and alternative management procedures for surf clam in Cucao.

Section A: The management procedure for surf clam

The management procedure corresponding to the Cucao AMEBR is shown in Figure 3. A team of technicians and professional divers carry out a stock assessment survey annually (see Table 1). The survey is designed to provide estimates of total abundance and biomass in the surveyed area. The estimate of biomass is size-structured, allowing the estimation of vulnerable biomass, which is defined by surf clams larger than 50 mm length (i.e., the minimum legal size). The stock assessment team computes yield per recruit using a Thomson and Bell model, and then $F_{0.1}$ (Deriso, 1987) to compute the quota to be harvested. Nevertheless, in practical terms, the harvest decision has resulted in a constant Quota/Vulnerable biomass ratio of approximately 25% (Table 1). Thus, the current management procedure can be simplified by formulating the following empirical harvest control rule:

1) $Q_i = 0.25V_i$

where V_i is the survey estimate for vulnerable biomass in the i-th year and Q_i is the quota of surf clam requested by the fishers organizations to the centralized management agency, i.e., the Undersecretariat of Fisheries and Aquaculture (SUBPESCA), which reviews the technical reports and approves the harvest quotas. The management procedure is essentially empirical since it uses the vulnerable biomass estimated in the survey as an indicator of the surf clam status, and the primary input to the harvest control rule (Table 1). Once SUBPESCA approves the quota, fishers can harvest the surf clam from the management area. At the time of harvest, catches are monitored and logged by the Chilean National Fisheries Service (SERNAPESCA).

Section B: The operating model

The operating model (OM) was conditioned to know life-history parameters of surf clam and total biomass and population size-structure data obtained from the direct stock-assessment surveys (Table 1 and Table 2). The OM was based on an integrative size-structured stock assessment model (Sullivan et al., 1990; Punt et al., 2013), expressed by

2) $N_{i,l} = G_{l,l'} N_{i-1,l} e^{-Z_{i-1,l}} + r_l R_i$

where $N_{i,l}$ is the abundance of length-class l at the beginning of year i, Z is the instantaneous total mortality rate, i.e., $Z = F + M$, where F is the fishing mortality, and M is the natural mortality rate (set equal to 0.3). R_i is recruitment, r_l is the distribution of recruitment by length-classes, and $G_{l,l'}$ is a growth transition matrix described by

3) $G_{l,l'} = \int_l^{l'} (l' - l)^{\alpha_j} e^{-(l'-l)/\beta_p} dl/\beta_p$

where l is the length class, and α_j and β_p are parameters describing a gamma probability function. Recruitment was estimated according to:

4) $R_i = \bar{R} e^{\epsilon_i}$

where $\bar{R}$ is the average recruitment and ϵ_i is the annual deviation, which followed a normal distribution $N(0, \sigma_R)$.

The recruitment probability at length was assumed to be normal, i.e.,

5) $r_l = \int_l^{l+1} \frac{1}{\sqrt{2\pi\sigma^2}} e^{(-(l-l_r)^2/2\sigma^2)} dl$

where l_r is the mean length at recruitment and σ^2 is the variance of length at recruitment.

The fishing mortality rate during the year i and length l ($F_{i,l}$) was computed by

6) $F_{i,l} = F_i s_l$

where F_i is the annual fishing mortality rate, and s_l is the selectivity at length l, which was defined by

7) $s_l = 0$ if $l < 50$; or $s_l = 1$ if $l \geqslant 50$

The selectivity in Eq. 7 is a 'knife-edge' function of minimum legal size ($lc = 50$ mm.

The model for observations consisted of the total annual harvest and total biomass in the surveys. Catch by number was estimated according to the Baranov catch equation, i.e.,

8) $C_{i,l} = F_{i,l} N_l (1 - e^{-Z_{i,l}})/Z_{i,l}$

where $C_{i,l}$ is the catch in the year i at length class l. The total annual harvest (Y_i) was estimated by:

9) $Y_i = \sum_l W_l C_{i,l}$

where W_l is the average weight at length class l.

Length composition in the population was estimated by:

10) $p_{i,l} = N_{i,l}/(\sum_l N_{i,l})$

The population biomass at the time of the survey (within the year) was computed by:

11) $B_i = \psi \sum_l v_l W_l N_{i,l} e^{-\tau Z_{i,l}}$

where ψ is the catchability coefficient and assumed to be equal to 0.99, v_l is the selectivity at length of the survey and assumed to be constant and equal to 1 for all length classes, and τ is the time of year in which the stock assessment survey was carried out. After that, the vulnerable biomass in the direct stock assessment surveys (V_i) was simulated according to:

12) $V_i = \psi \sum_l v_l W_l N_{i,l} e^{-\tau Z_{i,l}}$

Total biomass was computed as the sum of products between the abundance and the average weight at length, and the spawning biomass was computed by:

13) $S_i = \sum_l m_l W_l N_l e^{-T_s Z_{i,l}}$

where m_l is the female maturity ogive, T_s is the beginning of the spawning time within a year (set at 0.81). The model was conditioned to the available data and known surf clam life-history parameters and consisted of estimating the unknown parameters by fitting the population dynamics to the data. The objective function consisted of negative log-likelihood functions and penalized priors (Table 2 and Table 3). The model was conditioned through an estimation procedure implemented in ADMB (Fournier et al., 2012).

Section C: Simulation of the management procedure

Once the OM was conditioned to the data and known life history parameters, a forward projection phase of the population dynamics allowed simulating the management procedure over 20 years. The recruitment dynamics followed a Beverton and Holt stock-recruitment relationship (SRR), described by:

14) $R_i = \frac{4hR_0 S_{i-1}}{(1-h)S_0 + (5h-1)S_{i-1}} e^{\epsilon_i - 0.5\sigma_R^2}$

where R_0 is the average unexploited recruitment, assumed to be equal to the average recruitment in the period 2011-2017 (i.e., $R_0 = \bar{R}$), S_0 is the average unexploited spawning biomass that produces R_0, and h is the steepness (Francis, 1992; Dorn, 2012; Lee et al., 2012), which was set equal to 0.7 considering estimates for the surf clam *Spisula solidissima* (Powell et al., 2015; Hennen et al., 2018). In Eq. 14, recruitment is a function of both the spawning biomass and the environmental forcing, which is considered in the simulation by allowing ϵ_i to vary as a sequence of switches in the operating model, i.e.

$$15)\ \epsilon_i = E_i e^{(\delta_i)}$$

where E_i is the environmental forcing represented as a sequence of switches that are alternating between two-year periods in which recruitment is favored ($E_i = 1$) followed by two-year periods in which recruitment is not favored ($E_i = -1$). The sequence of switches was perturbed by stochastic annual deviations (δi) following a normal distribution, i.e., $N(0, \sigma_R)$. Equation 15 allowed the simulation of future recruitment as a pattern similar to the changes observed in the recruitment estimates obtained from the stock assessments of 2011-2017.

The management procedure considered the current harvest rate of 25%, but for comparison purposes, alternative values of 0, 10, 15, 20, and 30% were also considered. The exploitation rate $\mu = 0$ was implemented to simulate the unexploited surf clam population as a reference. The simulation was performed under uncertainty, sampling from the posterior of the fitted model through Markov Chain Monte Carlo (MCMC). The number of MCMC was obtained from 10,000 samples and saving every 200 by using the metropolis algorithm implemented in ADMB (Fournier et al., 2012).

Section D: Performance evaluation

The trajectory of simulated recruitment, spawning biomass, and fishing mortality resulting from the MP was summarized with confidence intervals of 90% by applying a percentile method to all realizations obtained by MCMC. Depletion was computed as the ratio between the spawning biomass in a given year and the average unexploited spawning biomass. Also, a reduction of 40% in the spawning biomass from the average unexploited value was considered as a target reference point, i.e., $S_{\text{target}} = 0.4S0$. Therefore, exploitation rates generating reductions below the target were considered unsustainable for the surf clam population. The probability of keeping the target was computed as $Pr[S_i/S_{\text{target}} > 1]$, whereas the probability of a collapse was computed as $Pr[S_i/S_{\text{target}} \leq 0.5]$. Exploitation rates generating probabilities of achieving the target above 0.5 were used as a reference for good performance.

Results

Surf clam population at Cucao beach and the operating model

In the period 2011 – 2017, the total abundance of surf clam fluctuated between 68 and 385 million individuals, with a mean of 174.2 million. Total biomass ranged between 1356 and 5407 t, with a mean of 2,994 t, whereas the vulnerable biomass fluctuated between 1261 and 5399 t, with a mean of 2716 t (Table 1).

The operating model (OM) performed well in terms of reproducing the observed changes in surf clam length composition (Fig. 4). The observed length composition showed clear modal progression for sizes > 50 mm, which was also shown by the fitted model (Fig. 4). According to the OM, the mean length at recruitment (l_r) was 8.8 mm (Table 2, last column), with specimens < 25 mm recruiting in 2013, 2014, and 2017 (Fig. 4). This finding provides evidence that the recruitment process in the surf clam population of Cucao does not occur on an annual basis, but rather with pulses of high recruitment to the population followed by periods of lower or no recruitment, approximately every $2 - 3$ years.

The population biomass showed a declining trend from 2011 to 2017 (Fig. 5A), tracking the observed total and vulnerable biomass in the surveys. The vulnerable biomass was similar to total biomass, but the spawning biomass was lower due to the maturity ogive and mortality prior to spawning within the year. The average unexploited spawning biomass (S_0) was estimated at 1,343 t, which was lower than the spawning biomass estimated for the period 2011-2017. Hence, the target spawning biomass for management purposes was estimated at 537 t. Recruitment was higher in 2011-2017, with above-average values in 2013 and 2014, followed by lower recruitment from 2015 to 2017 (Fig. 5B). The fishing mortality rate fluctuated as the harvest but was higher in 2017 (Fig. 5C).

Recruitment simulations and the performance of the management procedure

According to some realizations of the OM simulations, recruitment showed the alternating pattern between higher and lower recruitment (Fig. 6). However, that characteristic in recruitment was obscured in the total number of simulations, within the confidence limits of 90% (Fig. 7A).

The spawning biomass responded to each exploitation rate (Fig. 7B), as reflected by the approximately constant fishing mortality (Fig. 7C). The effective catch was assumed to be identical to the quota due to rigorous control of the harvest. Note that an exploitation rate of 30% produces the highest average fishing mortality, and close to that estimated in 2017 (Fig. 7C).

The current exploitation rate of 25% produced nearly 20% depletion in the spawning biomass (Fig. 8), with a probability of future collapse $>$ 80% (Fig. 9). On the other hand, an exploitation rate of 15% kept the spawning biomass close to the target, i.e., 40% of the unexploited spawning biomass (Fig. 8), with probabilities $>$ 50% once recovered the biomass (Fig. 9). Indeed, an exploitation rate of 15% was able to revert the declining trend observed in the surf clam spawning biomass (Fig. 8).

Discussion

Recruitment of benthic marine invertebrates is a highly complex process that spans a range of spatio-temporal scales (Defeo, 1996; Pineda and Caswell, 1997) and that is modulated by environmental forcing (e.g., winds, waves, physiological stress) that limits larval survival and successful settlement (Pineda, 1991; Cushing, 1995). Additionally, density-dependent factors operating at different spatial scales are prevalent in marine invertebrates (Hixon et al., 2012), leading to reduced reproductive success and survival of adults (Stephens, 1999). Adult density can positively or negatively affect recruitment success, which then determines adult density patterns (Jenkins et al., 2009). Both factors (i.e., environment and density-dependence) are not mutually exclusive, but interact to determine the densities of marine benthic populations and assemblages.

The recruitment estimates for the surf clam *M. donacium* in the period 2011-2017, and that conditioned the operating model (OM), showed the alternation of periods with high and low recruitment in the Cucao beach population, despite the short data series available. Two years with high recruitment were followed by poor recruitment in 2016, after a warm ENSO event in 2015-2016 (Jacox et al., 2016; Martínez et al., 2017).

Recruitment failures and high temporal variability are common features in the population dynamics of surf clams (Lima et al., 2000; Ripley and Caswell, 2006; Aburto et al., 2013). These are general features in the population dynamics of many species with short life cycles and can be linked to high rates of natural mortality and greater variability in growth rates (Bjørkvoll et al., 2012). These generalizations notwithstanding, the estimated lifespan of the surf clam *M. donacium* at Cucao was close to 7 years, with cohorts showing a modal progression in the size structure from 2011 to 2017. The estimated von Bertalanffy growth parameter ($K = 0.21$ year^{-1}) indicates theoretical longevity close to 15 years, i.e., $t_{max} \sim 3/K$ (Kenchington, 2014). Thus, the population's age-structure may act as a filter of recruitment variability, dampening the effects of environmental variability on population renewal, and hence reducing the influence of the environment on the stock (Planque et al., 2010).

Recruitment in *M. donacium* is hard to miss during the stock assessment surveys since post-settled individuals are easily distinguishable in the field and tend to accumulate in the swash zone and near the mouth of estuaries or small rivers (Jaramillo et al., 1994). Thus, as has been demonstrated in this study, the recruitment of surf clams at Cucao beach does not always contribute noticeably to the exploited stock biomass. Thus, settlement numbers or post-settlement mortality, or both, may vary widely from year to year, which suggests that environmental phenomena connected with the dispersal of larvae or the physiology of post-settled individuals may condition the stock's renewal. Although the information collected to date limits the inferences that can be made about environmental phenomena that may limit recruitment success in the surf clam *M. donacium*, it is likely that a specific combination of wave and wind conditions, at the right time of year, is required for competent larvae to reach the shore and settle. The total number of competent larvae that could reach the shore, in turn, is likely to depend on advective and feeding conditions in shelf waters during the weeks or months before the recruitment period.

It has been documented that environmental variability affects the abundance of *M. donacium* further north. For example, during the 1997-1998 El Niño, the collapse of the surf clam populations in Arica (18º30'S) and Huasco (28º30'S) was attributed to this phenomenon, in connection with coastal flooding and excess rainfall (Jerez et al., 1999). In Peru, high mortality of adult *M. donacium* was attributed to the increase in temperatures caused by the 1982-1983 El Niño (Arntz et al., 1987, 1988). Infrequent recruitment of surf clams has also been reported previously in northern Chile, possibly in association with environmental factors that affect the release of gametes as well as oceanographic factors affecting the survival and onshore supply of planktonic larvae (Thiel et al., 2007). It is common to hear artisanal fishers talk about a "green" surf clam with lengths of $3 - 4$ cm that is occasionally found in the exploited banks. This is consistent with the occasional appearance of juveniles in the annual surveys at Cucao beach, where small individuals (lengths $2.5 - 5.0$ cm) appeared in large numbers in only one out of seven stock-assessment surveys (2016). The inconsistent occurrence of juveniles observed in the stock-assessment surveys was not an artifact of survey mistiming (relative to recruitment), as indicated by the inter-annual consistency and progression of gaps in the size-structure data collected during surveys.

For fisheries management, the observed recruitment failures imply that, if recruitment occurs approximately once every three years, the exploitation rates should be lower than those recommended by the current management procedure ($\mu = 25\%$), and that lower exploitation rates (ţ $\leq 15\%$) are needed to ensure sustainable exploitation in the medium term. Furthermore, the current lack of knowledge on the spatial-temporal variability of settlement and recruitment in species such as the surf clam *M. donacium* puts into question the exploitation strategies that are currently considered as sustainable. Typically, it is assumed that benthic species have annual recruitment, which is not the case for *M. donacium.* Therefore, this contribution highlights an issue that warrants an even more precautionary approach to the commercial exploitation of benthic species with non-annual, or irregular recruitment.

A management procedure can be viewed as a "static" or memory-lacking process since it does not refer to either past or future observations. Indeed, annual quotas are computed from the standing stock assessed directly in the field. The size-structure data are converted into age composition data through the slicing age-class method, which is the primary input for the yield-per-recruit model of Thompson and Bell. This model assumes that age-classes are treated as a "pseudo-cohorts" without considering past recruitment to explain the current length- or age-composition. Also, the estimation of $F_{0.1}$ has an implicit economic objective because it is computed from the yield-per-recruit curve, but $F_{0.1}$ is implicitly a function of age at first catch and, hence, knife-edge selectivity (Deriso, 1987; Quinn and Deriso, 1999), which is probably adequate for the surf clam population.

Nevertheless, although $F_{0.1}$ is more conservative than F_{max}, it is questionable considering the spawning potential ratio (Shepherd, 1982; Sissenwine and Shepherd, 1987). Indeed, the realized harvest rate associated to $F_{0.1}$ was close to 25% in the management procedure and resulted in being excessive according to the surf clam population dynamics here used as an operating model. It is advisable to apply a harvest rate of 15%, which may be enough to keep the reproductive potential of the surf clam population. Furthermore, it is advisable to implement a harvest control rule in which the harvest rate declines when the spawning stock declines due to lower recruitment. The ramp-like harvest control rule could be more effective for a rapid recovery of the spawning biomass, dampening the probability of unobserved or lower recruitments in the future. Reducing exploitation as the stock declines results in added resilience against environmental variability and, eventually, climate change (e.g., Merino et al., 2017).

In general, the above described "static" or "memory-lacking" procedure management is applied to almost all of the management areas (AMEBR) in Chile, as documented in the management and exploitation plan for each target species (Gallardo et al., 2011). Our analyses revealed that surf clam recruitment does not occur annually, or even periodically, with a separation of 3 or more years between high recruitment episodes. The landing records from other areas where surf clam populations were depleted in previous decades show that exploitation could be unsustainable when the harvest rate intensity is not controlled. This behavior is typical in the exploitation of surf clam *M. donacium* along the Chilean coast (e.g., Aburto and Stotz, 2013), as well as for other surf clam species (Weinberg, 1999; Laudien et al., 2003; Fiori and Morsán, 2004; Ripley and Caswell, 2006; Herrmann et al., 2011).

The underlying problem is that, in practice, little is known about the intensity and success of recruitment in harvested marine populations, which can be attributed to biases introduced by the extractive activity itself (e.g., Punt and Cope, 2019). Sampling from the commercial catch is usually carried out on landings, which leaves out juvenile fractions. In the case of benthic species harvested from AMEBRs (Chile), population surveys usually consider the fraction that can be detected visually by scientific divers. Although this procedure includes individuals under commercial size, it is likely to leave out newly settled individuals, which are not always visible due to small size, pigmentation, or behavior. Thus, the quantification of newly established fractions in populations of commercial species usually is fraught with uncertainty and should be approached through indirect methods. For management areas where biomass and length-composition have been recorded annually over a long-enough period, it is advisable to implement an integrated stock-assessment model (Smith et al., 2009; Punt et al., 2011). Subsequently, biological reference points should be established as a means to assess the population's status, and to set a TAC based on population projections. Thereafter, the AMEBR's management procedure must be changed to keep the exploitation of benthic species within biologically safe margins.

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