Research Article

Chilean fishing law, maximum sustainable yield and the stock-recruitment relationship

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ABSTRACT. During 2013, the Chilean fishing law was amended to incorporate, among other changes, the maximum sustainable yield (MSY) as target reference point for managing fishery resources. This mandate triggered the estimation of MSY-based reference points (RPs) in each fishery subject to catch limits in Chile. Recent investigations indicate that production models provide MSY-based RPs, which are predicted only by using the steepness of the stock-recruitment relationship (*h*). In this paper, we compare predicted MSY-based RPs using production models with estimates from an age-structured per-recruit model for eleven demersal stocks harvested in Chile. The MSY-based RPs assessed were: 1) The ratio between the biomass leading to MSY to the unfished biomass $\left(\frac{B_{msy}}{B_0}\right)$; 2) the ratio between the fishing mortality that gives the MSY and natural mortality $\left(\frac{F_{msy}}{M}\right)$; and 3) the ratio of spawning biomass per recruit (*SR*) when the population is fished at F_{msy} to the spawning biomass per recruit of an unfished population $\left(\frac{SR(F_{msy})}{SR_0} = SPR_{msy}\right)$. The production model provides $\frac{B_{msy}}{B_0}$ and SPR_{msy} that well predicted estimates from the age-structured models in most of the species analyzed. However, $\frac{F_{msy}}{M}$ was overestimated by the production model in most of the stocks. We discuss the dependence of *h* with the MSY-based RPs in light of the Chilean fishing law. This paper reveals the complexity of implementing the Chilean Fishing Law into real situations and the uncertainty surrounding the estimation of *h* and, by extension, MSY and MSY-based RPs.

Keywords: MSY, steepness, stock-recruitment function, fisheries management, demersal fish stocks, Chilean fisheries.

Ley de pesca chilena, rendimiento máximo sostenible y la relación stock-recluta

RESUMEN. Durante 2013 la ley de pesca chilena fue modificada para incorporar, entre otros cambios, el rendimiento máximo sostenible (RMS) como punto biológico de referencia objetivo para el manejo de recursos pesqueros. Este mandato ha requerido la estimación de puntos de referencias (PRs) basados en RMS para cada pesquería manejada con cuotas de pesca en Chile. Investigaciones recientes indican que los modelos de producción proveen PRs basados en RMS, los cuales son predichos usando solo el parámetro de "steepness" de la relación stock-recluta (*h*). Se compara los PRs basados en RMS predichos usando los modelos de producción con aquellos estimados desde un modelo edad-estructurado para once especies de peces demersales explotados en Chile. Los PRs basados en RMS evaluados fueron: 1) la razón entre la biomasa desovante que conduce al RMS y la biomasa virginal $\left(\frac{B_{msy}}{B_0}\right)$, 2) la razón entre la mortalidad por pesca que hace llegar la población al RMS con respecto a la mortalidad natural $\left(\frac{F_{msy}}{M}\right)$ y 3) la razón entre la biomasa desovante por recluta (*SR*) cuando la población es explotada al F_{msy} con respecto a la biomasa desovante por recluta virginal $\left(\frac{SR(F_{msy})}{SR_0} = SPR_{msy}\right)$. Modelos de producción para $\frac{B_{msy}}{B_0}$ y SPR_{msy} predicen adecuadamente aquellos estimados provenientes del

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modelo edad-estructurado. Por otra parte, $\frac{F_{msy}}{M}$ fue sobreestimado por los modelos de producción en la mayoría de los stocks analizados. Se discute la dependencia directa que tiene h con los PRs basados en RMS a la luz de la ley de pesca chilena. Este artículo muestra la complejidad que presenta la implementación de la ley chilena de pesca a situaciones reales y la incertidumbre asociada a la estimación de h y por consiguiente, al RMS y a los PRs basados en RMS.

Palabras clave: RMS, escarpamiento, función stock-recluta, manejo pesquero, stock de peces demersales, pesquerías chilenas.

INTRODUCTION

Chile lands around 2.5 million ton of fish every year, the eighth largest catch of any country in the world (FAO, 2014). Fishing activity became important in the early 1920s when mostly European investors developed the small pelagic fishery in the northern zone, and afterwards, during the 1940s, the demersal fishery in the central and southern zones of Chile. Despite this relatively long history of fishing exploitation, only in the preceding three decades fishing monitoring, stock assessment and fishery management became well-established programs. Fishing monitoring program collects information regarding operational and biological attributes of the main target species, while stock assessment in Chile is based on integrate models that combine all available information to produce estimates of abundance and exploitation status. Fishery management takes the advice from stock assessment to propose an annual total allowed catch (TAC) of each stock, usually based on biological reference points (RPs) and the associated risk of incompliance with management objectives. Since 1991, fisheries management in Chile has been framed by "the General Law of Fishing and Aquaculture" including a system for quota allocation based on individual transferable quotas (ITQs) from 2001 to 2012. This system, however, lacked a specific procedure to establish a TAC using RPs. This often resulted in managers setting TACs along political and/or social criteria, instead of emphasizing the associated risk of not fulfilling the conservation objective associated to the RPs (Leal *et al*., 2010). Such bad and incorrect management practice contributed to the current overfishing and depletion of most Chilean fisheries managed by TAC (SUBPESCA, 2013). During December 2012, several amendments to the general fishing law were introduced. One of the most important amendments is concerned with the ownership of the fishing licenses in those fisheries subjected to TAC. In this case, ITQs were adjudicated to a small group of industrial fishermen for 20 years with prorogation. Legislators also wanted to make sustainability the core of the new legal framework and indicated that management must explicitly consider the guidelines of the precautionary and ecosystem approaches. In this framework, the maximum sustainable yield (MSY) became the cornerstone by playing two main roles: it is a target RP for fishing management, and it also defines the threshold upon which the remaining surplus quota may be auctioned, allowing new actors into the fishery market. The latter was one of the most controversial issues in the legislative discussion during 2012. Several members of parliament and fisheries scientists exposed the shortcomings of a focus on MSY. Nevertheless, expert opinion had little impact on the final changes introduced to the general fishing law. The mandate of using MSY in the new fishing law was introduced to align fishery management, imposing greater specificity and less flexibility in the way TACs are set every year. During 2013, these modifications to the general fishing law came into effect, which has triggered a demand for estimating MSY-based RPs in each fishery resource managed by TAC.

Since the popularization of the concept of MSY by Schaefer (1954), fisheries science has seen a controversial debate about the usefulness (or lack thereof) of MSY in managing fisheries (*e.g*., Larkin, 1977; Mace, 2001; Punt & Smith, 2001). During the last few years, several studies have noticed that MSY estimates and MSY-based RPs are deeply connected to one single parameter: the steepness of the stock-recruitment relationship (see Brooks *et al*., 2010; Mangel *et al*., 2010; Hart, 2013). Steepness (h) is a common measurement of stock resilience and is defined as the recruitment produced by a spawning biomass at 20% of unfished spawning biomass, relative to the recruitment produced by unfished spawning biomass (Mace & Doonan, 1988). Steepness is firmly rooted in evolutionary ecology (Enberg *et al*., 2012) and it integrates several different aspects of the reproductive biology of fish stocks (Mangel *et al*., 2010). RPs are based on the reproductive biology of fishes and thus MSY and MSY-based RPs have a strong connection with steepness. Williams (2002) and Punt *et al*. (2005) showed that MSY and MSY-based RPs can be accurately predicted using only steepness. Recently, Mangel *et al*. (2013) derived an analytical function connecting MSY-based RPs and steepness using a production model. In such cases, MSY-based RPs are the only function of the steepness and other life history parameters have no influence. On the hand, complex age-structured models produced MSY-based RPs

merging several biological and fishery aspects to compute MSY-based RPs. Thus, evaluation on MSY-based RPs estimates using production and age-structured models became relevant. This comparison will shed light on the influence steepness has on the estimates MSY-based RPs when using a complex age-structured model. In this paper, we compare estimates of MSY-based RPs from production models which only depend on steepness, with age-structured models for eleven fish demersal species harvested in Chile.

MATERIALS AND METHODS

Although, the most commonly used stock-recruitment functions (SRF) can be parameterized in terms of steepness (Hillary *et al.*, 2012), we use the Beverton-Holt SRF (Beverton & Holt, 1957) because of its wide use in the demersal stocks in Chile. The Beverton-Holt SRF (BH-SRF) parameterized in terms of steepness (h) is as follows:

$$R_{t+\Delta} = \frac{0.8\, R_0\, h\, S_t}{0.2 S_0(1-h)+S_t(h-0.2)}, \qquad (1)$$

where R is the recruitment produced by the spawning biomass, S, after Δ time (t). Likewise, S_0 and R_0 are the unfished levels for spawning biomass and recruitment, respectively. Steepness is a dimensionless parameter that takes values in the range [0.2-1] and defines the shape of the BH-SRF (see Fig. 1). Thus, h is useful in comparing resilience across fish populations. Stocks with low values of steepness have low recruitment compensation, and therefore the rebuilding of those stocks after overfishing will take longer and TAC should be kept small (Mace & Doonan, 1988).

Here, we are interested in three MSY-based RPs proposed in Mangel *et al.* (2013). They are the ratio between the biomass leading to MSY and the unfished biomass $\left(\frac{B_{msy}}{B_0}\right)$, the ratio between the fishing mortality that gives the MSY and natural mortality $\left(\frac{F_{msy}}{M}\right)$ and the ratio of spawning biomass per recruit (SR) when the population is fished at F_{msy} to the spawning biomass per recruit (SR) of an unfished population, $\frac{SR(F_{msy})}{SR_0} = SPR_{msy}$. According to Mangel *et al.* (2013) these MSY-based RPs derived from a production model can be computed as follows, using only steepness:

$$\frac{B_{msy}}{B_0} = \frac{\sqrt{\frac{4h}{1-h}}-1}{\frac{4h}{1-h}-1}, \qquad (2)$$

$$\frac{F_{msy}}{M} = \sqrt{\frac{4h}{1-h}} - 1, \qquad (3)$$
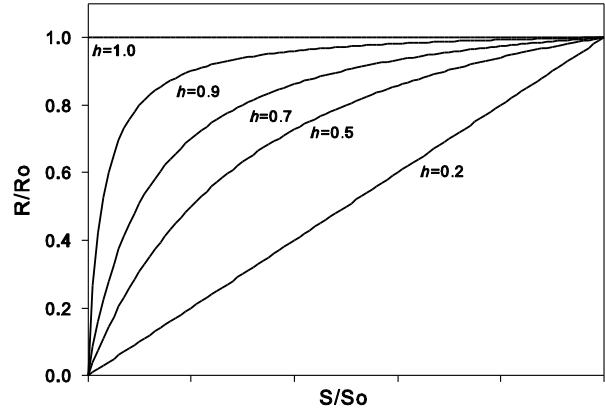
Figure 1. Characterization of Beverton-Holt stock recruitment relationship, using different steepness values.

$$\frac{SR(F_{msy})}{SR_0} = SPR_{msy} = \sqrt{\frac{1-h}{4h}}. \qquad (4)$$

For reasons of brevity, estimates from Eq. (2) to (4) will be called hereafter "production model". When assuming BH-SRF and the population dynamic is modeled using a production model, these three MSY-based RP are deterministic functions depending only on the steepness parameter. Mangel *et al.* (2013) also explored the connection between MSY-based RPs using an age-structured model, although no analytical solution is found in such cases. In age-structured models, life history parameters and fishing selectivity will have some influence in determining the MSY-based RPs. However, as discussed in Mangel *et al.* (2013), even in those cases estimates of MSY-based RPs from highly sophisticated age-structured models can be closely approximated using only the deterministic models in Eq. (2) to (4). Therefore, our goal in this paper was to compare the prediction of MSY-based RPs from a production model described by Mangel *et al.* (2013), with estimates from the age-structured models described below and implemented for eleven demersal stocks managed by TAC in Chile.

An age-structured per recruit model was implemented, using life history and fishing selectivity parameters reported in DER (2012) (Table 1) to estimate $\frac{B_{msy}}{B_0}$, $\frac{F_{msy}}{M}$ and SPR_{msy} in the following demersal stocks managed by TAC in Chile: 1) Patagonian toothfish (*Dissostichus eleginoides*); 2) yellow-nose skate (*Zearaja chilensis*); 3) alfonsino (*Beryx splendens*); 4) orange roughy (*Hoplostethus atlanticus*); 5) cardinalfish (*Epigonus crassicaudus*); 6) Chilean hake (*Merluccius gayi gayi*); 7) southern blue whiting (*Micromesistius australis*); 8) pink cusk-eel (*Genypterus blacodes*), northern stock; 9) pink cusk-eel, southern stock; 10) southern hake (*Merluccius australis*),

Table 1. Life history and fishery parameters used to implement the age-structured per recruit model in each demersal stock assessed. Growth parameters are asymptotic length (l_∞), intrinsic growth rate (K) and age at length zero (a_0). Max. Age, represents the lifespan in years and logistic model for maturity ogive is described by the slope and shape parameters (l_{50} and Δl_{50}). The length at weight relationship (L-W) is represented by two parameters (φ and b) and τ_{50} is the length at 50% of selectivity.

	Growth				Maturity		Mortality	L-W		Selectivity
	l_∞ (cm)	K (year^{-1})	a_0 (year)	Max Age (A)	l_{50} (cm)	Δl_{50} (cm)	M (year^{-1})	φ (g*cm^{-1})	b	τ_{50} (cm)
Patagonian toothfish	176.2	0.06	-1.65	36	85.2	14.0	0.15	4.9E-03	3.17	86.53
Yellownose skate	128.3	0.11	-0.51	34	103.9	11.1	0.12	2.6E-03	3.22	73.83
Alfonsino	63.69	0.09	-2.57	19	33.1	1.9	0.28	2.4E-02	2.89	36.66
Orange roughy	52.13	0.03	-1.72	90	38.0	2.2	0.05	8.8E-02	2.65	39.90
Cardinalfish	35.25	0.08	-3.39	42	23.2	4.0	0.08	2.0E-02	2.90	23.65
Chilean hake	80.40	0.14	0.92	12	38.5	5.1	0.30	1.3E-02	2.83	25.01
Southern blue whiting	59.64	0.16	-2.51	24	38.2	2.6	0.20	8.3E-04	3.50	49.57
Pink cusk-eel (north)	117.40	0.19	-0.84	14	82.2	2.0	0.27	2.5E-03	3.15	89.60
Pink cusk-eel (south)	123.45	0.15	-1.78	14	82.2	2.0	0.23	2.3E-03	3.16	84.79
Southern hake	115.00	0.12	-1.60	24	72.0	15.0	0.21	2.4E-03	3.25	84.65
Patagonian grenadier	105.50	0.17	-0.81	14	54.0	28.0	0.35	3.4E-03	2.96	54.23

and 11) Patagonian grenadier (*Macruronus mage-llanicus*). These stocks were selected because they are the most important demersal species harvested in Chile in terms of total catch and economic importance (Payá *et al.,* 2014). Pelagic stocks were not considered here for the following reason. Small pelagic fish in Chile have a particular biology including fast growing species making difficult a straightforward comparison of results with demersal species. Although comparison of *h* between pelagic and demersal species is interesting, is beyond the scope of this paper.

The relative size for each stock, as well as the yield curve under variable fishing mortality levels, was modeled using an age-structured production model that incorporates the BH-SRF and the most feasible life-history parameters. The survival per recruit for unfished (n_a) and fished (N_a) populations are defined as:

$$n_a = \begin{cases} 1, & a = 1 \\ n_{a-1}e^{-M}, & a > 1 \\ \frac{n_{a-1}e^{-M}}{1-e^{-M}}, & a = A \end{cases} \quad (5)$$

$$N_a = \begin{cases} 1, & a = 1 \\ N_{a-1}e^{-M-f_e\tau_{a-1}}, & a > 1 \\ \frac{N_{a-1}e^{-M-f_e\tau_{a-1}}}{1-e^{-M-f_e\tau_{a-1}}}, & a = A \end{cases} \quad (6)$$

where M is the instantaneous natural mortality rate assumed age-invariant, f_e is the equilibrium fishing mortality rate, and τ_a is the fishing selectivity at age a. Table (1) contains the data used to implement the age-structured model.

Individual length at age (l_a) was modeled using the von Bertalanffy growth function $l_a = l_\infty\left(1 - e^{-k(a-a_0)}\right)$

where l_∞ is the asymptotic length, k is the growth parameter and a_0 is the theoretical age at length zero. The weight at age (w_a) was computed using the allometric function $w_a = \varphi(l_a)^b$, were φ and b are parameters. Selectivity (τ_l) and maturity (m_l) at length (l) were modeled independently using a logistic function such as $\{\tau_l, m_l\} = \left[1 + 19^{(l50-l)/\Delta l_{50}}\right]^{-1}$, which was parametrized in terms of length at 50% ($l50$) and the length range between 0.5 and 0.95 probability (Δl_{50}). Selectivity and maturity at age (τ_a, m_a) were computed using a deterministic conversion between lengths and age. The calculation was conducted using the inverse von Bertalanffy growth function.

The spawning biomass per recruit in unfished (n) and fished (N) populations is given by

$$spr_n = \sum_{a=1}^{\infty} n_a w_a m_a, \quad spr_N = \sum_{a=1}^{\infty} N_a w_a m_a, \quad (7)$$

and the vulnerable biomass per recruit is expressed as a function of τ_a using:

$$bpr_n = \sum_{a=1}^{\infty} n_a w_a \tau_a, \quad bpr_N = \sum_{a=1}^{\infty} N_a w_a \tau_a. \quad (8)$$

Equilibrium recruitment (R_e) was modelled using the Beverton-Holt stock-recruitment function of equation (1),

$$R_e = \frac{\alpha S_e}{1+\beta S_e} = \frac{\alpha R_e spr_N}{1+\beta R_e spr_N}, \quad (9)$$

where $S_e = R_e spr_N$ represents the equilibrium spawning biomass, $\alpha = \frac{4h}{(1-h)spr_n}$ is the maximum juvenile survival rate, and $\beta = \frac{5h-1}{(1-h)R_0 spr_n}$ represents the density-dependent term defined as the compensation rate of juvenile survival (Myers *et al.*, 1999). Replacing the expressions α, β and S_e into equation (9) and solving

for R_e, the equilibrium recruitment (R_e) for a given fishing mortality rate (f_e), is given by:

$$R_e = R_0 \frac{4h-(1-h)\Theta}{5h-1}, \qquad (10)$$

where $\Theta = spr_n/spr_N$, is the ratio of spawners per recruit, and $R_0 = B_0/spr_n$ represents the unfished recruitment as function of unfished spawning biomass (B_0).

MSY-based RPs from Eq. (2) to (4) can be obtained from maximum equilibrium yield Y_e for a plausible range of steady-state fishing mortality rate f_e. Under specific steady-state recruitment, the equili-brium yield is given by,

$$Y_e = f_e\,R_e\,\sum_{a=1}^{\infty} \frac{N_a w_a \tau_a}{Z_a}(1 - e^{-Z_a}), \quad (11)$$

where the total mortality at age Z_a was computed as $Z_a = M + f_e\tau_a$. To calculate MSY-based RPs from associated life-history parameters, the most common approach is to plot Y_e versus F_e and find the fishing mortality value that maximizes Y_e. Using a sequence of 10,000 equally spaced points falling in a range between 0 to 2 values of F_e, the maximum equilibrium yield was identified and subsequently mapped onto the F_e range. Relative differences between production and age-structured models were computed across the range of h but only formally compared in each species at $h = 0.7$ (see Table 2). We choose this value of h for comparing methods, because its represent a standard or "average" stock recruitment relationship in demersal fish stocks.

RESULTS

Differences between production model and age-structured estimates increases with steepness in all the MSY-based RPs evaluated (Figs. 2-4). Estimates of SPR_{msy} presented the smallest differences between production model and age-structured estimates across h, while $\frac{F_{msy}}{M}$ shows the largest differences between estimates. Predictions from the production model for $\frac{B_{msy}}{B_0}$ and SPR_{msy} are smaller than those estimates of the age-structured model across the range of h analyzed. On the other hand, production model predictions for $\frac{F_{msy}}{M}$ produced larger values than those predicted by the age-structured models, except alfonsino and pink cusk-eel (southern stock) where the production model produced smaller estimates (Figs. 2-4).

The relative difference between production and age-structured model predictions at $h = 0.7$, can be found in Table 2. Cardinalfish and Chilean hake showed the biggest differences between estimates for $\frac{B_{msy}}{B_0}$ while Patagonian toothfish and yellownose skate showed smaller ones. When we analyzed $\frac{F_{msy}}{M}$ at $h = 0.7$, most of the stocks show large differences between production and age-structured estimators. Only in the cases of orange roughy and cardinalfish, differences between estimates of $\frac{F_{msy}}{M}$ are negligible. In general, estimates of SPR_{msy} from production model produces the best prediction for the age-structured estimates especially for Patagonian toothfish and yellownose skate, while the biggest differences between estimates were found in alfonsino and Chilean hake.

DISCUSSION

Equations (2) to (4) were analytically derived from a production model. Thus, models based on these equations will only approximate those estimates from an age-structured model as shown in our results. MSY-based RPs from age-structured models are determined mostly by the value of h, but also by the life history parameters and fishing selectivity. Here, SPR_{msy} estimated from the age-structured model were accu-rately predicted by the production models, in most of the stocks analyzed and across the range of steepness. This means that this RP is mostly determined with information on h alone. For the selected demersal fish stocks in Chile, production models produced the best predictions in SPR_{msy} and the worst in $\frac{F_{msy}}{M}$. This is in line with the theory in Mangel *et al.* (2013) in which SPR_{msy} is independent of the life history parameters or selectivity function and is strongly determined by h. The same authors added that $\frac{F_{msy}}{M}$ is highly influenced by h, but also by the fishing selectivity. MSY-based RPs estimated here for the demersal stocks in Chile confirm the theory in Mangel *et al.* (2013) in which $\frac{B_{msy}}{B_0}$ and SPR_{msy} are predicted almost exclusively using h, whereas for $\frac{F_{msy}}{M}$ the selectivity pattern became also important. In this context, $\frac{F_{msy}}{M}$ is the only RP assessed here that may incorporate fishing dynamics on the demersal stocks in Chile and the parameters defining the selectivity function in each stock may explain the reported differences between the production model predictions and those from the age-structured model.

In all demersal stocks managed with TAC in Chile, a common practice is to fix M and h in the stock assessment and the shape of the SRF is selected before-hand. M values are estimated using empirical models

Table 2. Estimates of MSY-based reference points from production and age-structured model (Age-S) predicted at $h = 0.7$ across species analyzed. DEV is the relative difference (in percentage) between production and age-structured model estimates. B_{msy}/B_0 is the ratio between the biomass leading to MSY to the unfished biomass. $Fmsy/M$ is the ratio between the fishing mortality that gives the MSY and natural mortality. $SPRmsy$ is the ratio of spawning biomass per recruit (SR) when the population is fished at F_{msy} to the spawning biomass per recruit of an unfished population.

|	B_{msy}/B_0		F_{msy}/M		SPR_{msy}	
Production ($h = 0.7$)	0.247		2.055		0.327	
	Age-S	DEV %	Age-S	DEV %	Age-S	DEV %
Patagonian toothfish	0.273	10.7	0.880	-57.2	0.351	7.2
Yellownose skate	0.262	6.3	0.900	-56.2	0.341	4.2
Alfonsino	0.347	51.7	9.389	356.9	0.441	34.8
Orange roughy	0.288	16.8	2.040	-0.7	0.364	11.3
Cardinalfish	0.346	40.3	1.900	-7.5	0.416	27.1
Chilean hake	0.357	44.9	0.773	-64.3	0.426	30.2
Southern blue whiting	0.317	28.5	1.815	-11.7	0.390	19.1
Pink cusk-eel (north)	0.289	17.3	1.641	-20.2	0.365	11.6
Pink cusk-eel (south)	0.322	30.7	3.022	47.0	0.395	20.6
Southern hake	0.314	27.5	1.581	-23.1	0.388	18.5
Patagonian grenadier	0.306	24.0	0.966	-53.0	0.380	16.1

from meta-analysis, while h values usually lack a clear rationale and no further considerations (*e.g.*, sensitivity analysis) are given to this parameter. As we discussed above, BH-SRF is commonly used in Chilean fisheries, although, in some cases, such as Chilean hake and Patagonian grenadier, the Ricker-SRF has also been implemented. Fixing M, h and pre-determining the shape of the SRF will certainly either fix MSY-based RPs when using a production model or highly influence them when using an age-structured model. For the latter case, fixing h, M and the shape of the SRF will only guarantee that observed data used in the stock assessment will have at best little influence on the estimates of MSY-based RPs of stock analyzed, as shown above.

Following Mangel *et al.* (2013), there are two main avenues we could follow in order to surpass these shortcomings. First, we could explicitly incorporate an extra parameter in the SRF, such as the compensation parameter used in the general SRF proposed by Shepherd (1982). This will allow enough flexibility for another parameter to be estimated directly from the data (Martell *et al.*, 2008), then avoiding the specification of SRF beforehand. A good example of how to compare steepness parameters across SRFs is found in Hillary *et al.* (2012). A second approach is to avoid the assumption of fixed h. We are aware that the problems associated with fixing h in the stock assessment are not exclusive to Chilean fisheries. Fishery management systems based on MSY, like those in the USA, are also facing this problem. Although in the USA for some

data-rich fisheries, h is estimated within the stock assessment model, still an important proportion of their stock assessments consider a fix value of h. Yet, when h is fixed in those assessments, a clear and explicit rationale is given for this parameter, and it is usually approximated by using the meta-analysis described in Rose *et al.* (2001) and Dorn (2002). In addition, a sensitivity analysis of h is commonly conducted in those stocks.

In the demersal stocks managed by TAC in Chile, fishing monitoring and stock assessment have comparable standards to those implemented in developed countries (Payá *et al.*, 2014). Fishing monitoring is a lengthy process and well established. Stock assessments use sophisticated models with an appropriate treatment of uncertainty in the state variables (*e.g.*, spawning biomass). In addition, the assessments are regularly scrutinized through an international peer-review process. This means that, if we are following the same MSY-based RPs route as the USA, we should also follow a similar procedure in dealing with h. This means, we should estimate h as best as possible in those fisheries with adequate information. In other cases, an approximation for h is desirable when meaningful estimates are impossible to obtain. Although this may seem simple, h is one of the most difficult parameters to estimate within the stock assessment models, even in data-rich stocks. This is because the usual lack of information in the stock-recruitment relationship and the confounding effect between h with other life history parameters (*e.g.*, M). However, h can be estimated in

Figure 2. Estimates of $\frac{B_{msy}}{B_0}$, across steepness from production (grey lines) and age-structured models (black lines).
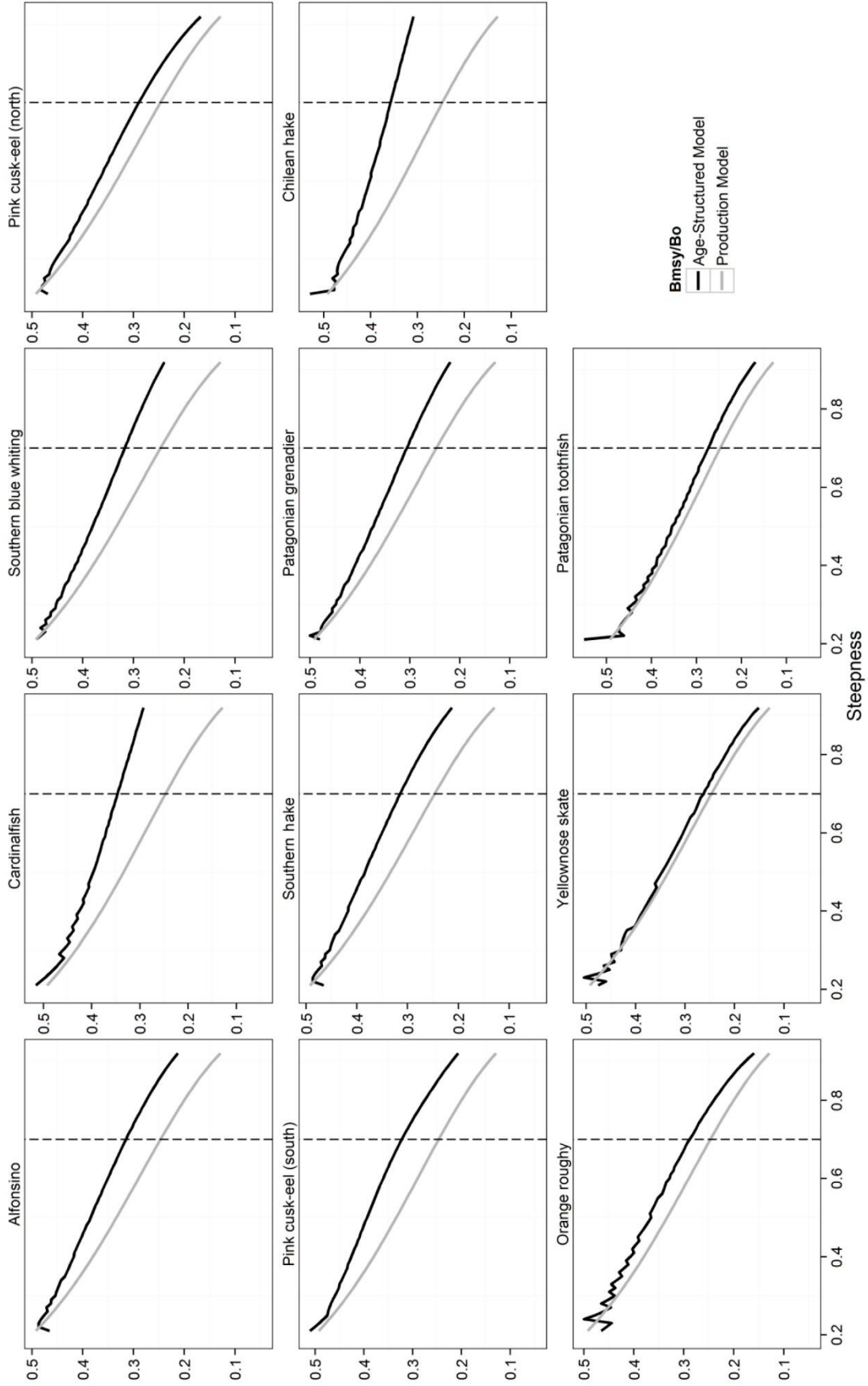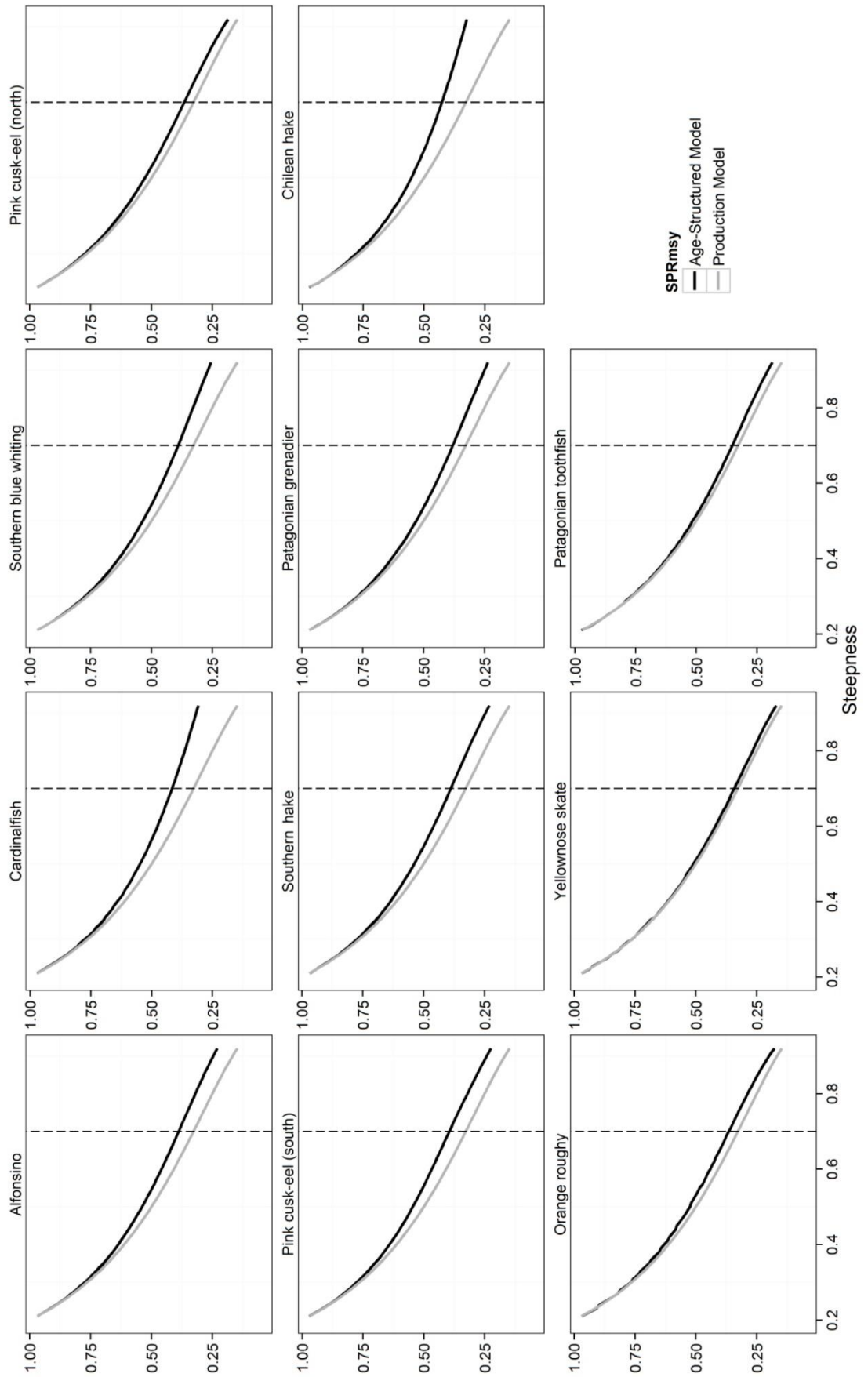
Figure 3. Estimates of $\frac{F_{msy}}{M}$ across steepness from production (grey lines) and age-structured models (black lines).
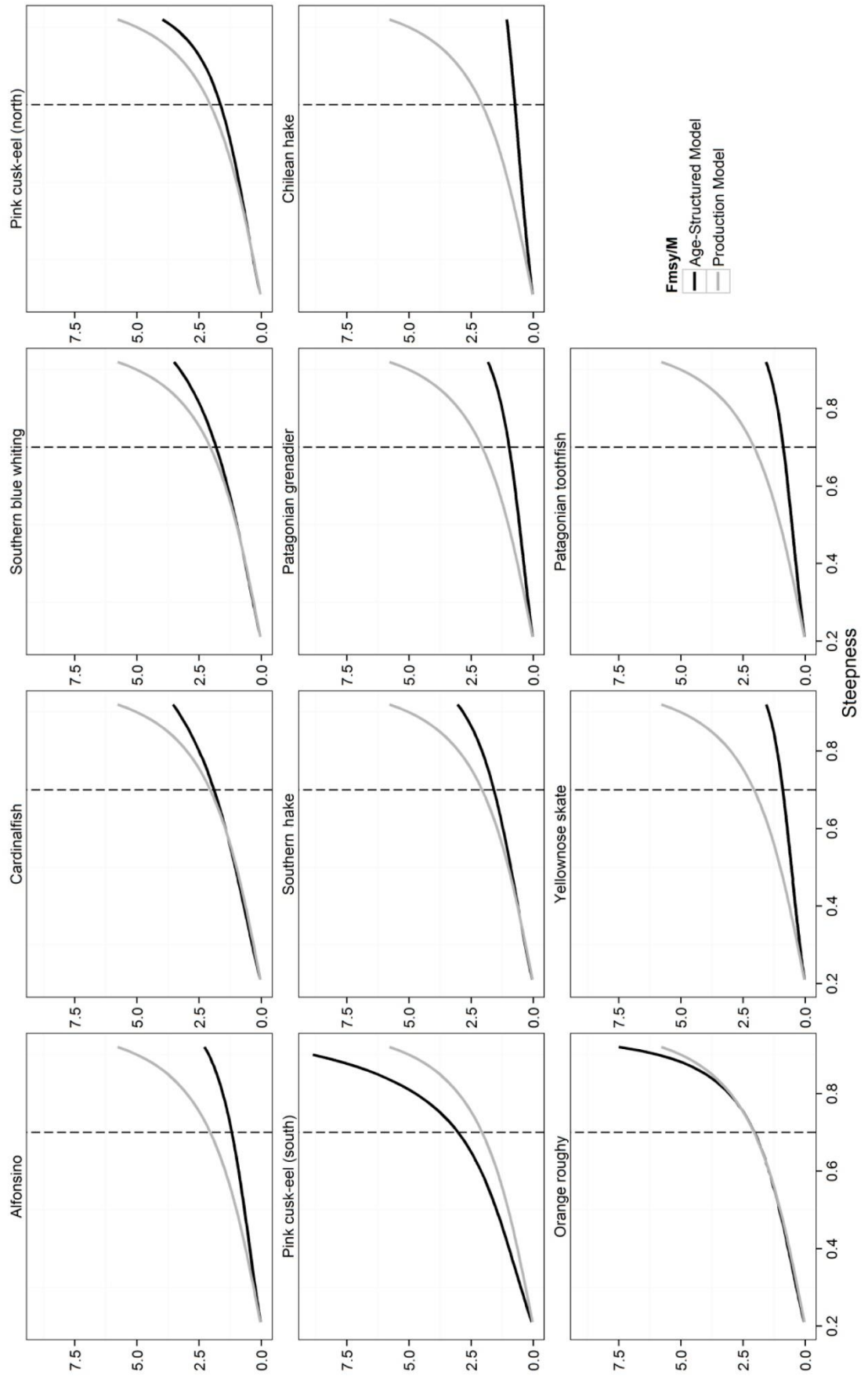
Figure 4. Estimates of SPR_{msy} across steepness from production (grey lines) and age-structured models (black lines).

stocks where a good contrast between high and low spawning abundance is available (Lee *et al.*, 2012).

Meta-analysis is a useful tool for proposing informative priors of *h* (Shertzer & Conn, 2012). Meta-analysis has been widely applied in fisheries science to approximate parameters that in other cases are difficult to obtain (Minte-Vera *et al.*, 2005). The use of meta-analysis rests upon the assumption that certain parameters such as *h*, can be interchangeable between stocks with similar life history attributes. Mixed effect models, such as in Myers *et al.* (2002) and hierarchical Bayesian analysis described in Dorn (2002), are promising methods for estimating priors of *h* for fish stocks in Chile. The main drawback of such meta-analysis methods is that available estimates of *h* coming almost exclusively from highly valuable species inhabiting the northern hemisphere (see compilation of species in Shertzer & Conn, 2012). This may challenge the use of meta-analysis for *h* in Chilean fisheries and thus careful selection of available data for estimating *h* is recommended. In applying such meta-analysis, special attention needs to be paid to the double use of data explained in Minte-Vera *et al.* (2005) and the manner to select the group of species to be included in the analysis (Myers *et al.*, 2002). In addition to the meta-analysis, Mangel *et al.* (2013) indicated that possible values for *h* should be constrained with the used value of *M* and observed mean age *T* using the following expression $\frac{exp(TM)}{M} \approx \frac{4h}{1-h}$. This approximation will be useful in delimiting a solution for *h* to have, at least, consistency with *M* and *T* used in the stock assessment. The procedure described using meta-analysis and constraining of *h* values can be useful in the context of proposing priors for estimating *h* and to approximate this parameter in those cases where it cannot be estimated within the stock assessment model.

In Chile, stocks with extensive data available such as southern hake, Chilean hake and Patagonian grenadier are good candidates to attempt an estimation of *h* within the stock assessment model. This could be done without using extra funding or human resources. For the rest of the species listed above, we may not be able to get meaningful estimates of *h* in the short-term. For those cases, the approximation using meta-analysis described above can be implemented, although we recognize that in extreme cases it will be impossible to have an approximation for *h*. The endemic and/or unique biology of some fish species fished in Chile, such as orange roughy, alfonsino, Patagonian toothfish and cardinalfish, violate the assumption of interchangeability of *h* between stocks on which meta-analysis rests. In such species, additional alternatives to approximate *h* need to be explored. In the meantime, fishery management need to be fully aware of the limitations of MSY-based RPs in each stock managed with TAC in Chile. We recommend to develop workable protocols to deal with those stocks in which meaningful estimates of *h* are difficult (if not impossible) to obtain with the current level of knowledge. Fully considering the uncertainty in mana-gement actions is also desirable in the light of the precautionary approach in FAO guidelines. The Chilean MSY-based management system in which *h* and *M* are fixed, gives a false sense of certainty about the specific productivity at which each stock can be harvested. This is a very undesirable situation because incorrect assumptions about *h* will lead to inaccurate estimates of MSY-based RPs. When fixing *h* in the stock assessment, the rest of the data contributes little to the estimation of MSY-based RPs, and thus alternatives to estimate or approximate *h* in Chilean stocks need to be explored.

During 2014, the Instituto de Fomento Pesquero (IFOP) conducted a project on biological reference points in Chilean fisheries subjected to annual quotas (for further details see Payá *et al.*, 2014). The project included extensive work to first classify stocks in tiers (groups) according to quantity and quality of the data available (poor, medium and rich data), and then selecting the best method to estimate MSY-based RPs in each tier. Most of the stocks illustrated here, except common hake, were classified in such tier in which proxy quantities are used as reference points. This means that these stocks contain enough information to conduct an age-structured stock assessment, but none of them has reliable information to estimate *h* within the stock assessment model (except common hake). Extensive simulation analyses were carried out to assess the robustness of such proxy measurements of MSY-based RPs. Proxies seem an appropriate way to deal with in these fisheries, although they need to be interpreted cautiously. The proxies implicitly assume a value of steepness that may either under- or overestimate the stock-specific productivity, which could distort the population status and total allowable catch estimates. We do not offer a solution for this problem; rather we emphasize the high dependence of MSY-based RPs and steepness on most of selected Chilean stocks. Thus, results obtained here should be seen as complementary to the simulations analyses presented in Payá *et al.* (2014).

Our analysis reveals the complexity of imple-menting the Chilean Fishing and Aquaculture Law into real situations where data are incomplete and/or absent. We also show that even in data rich fisheries, the uncertainty surrounding the estimation of *h* and, by extension, MSY and MSY-based RPs indicates that MSY should have been considered as limit rather than objective RP. The above is the recommendation of the

international and Chilean fishery science community. Insisting in using MSY as target RP is clearly against the precautionary and ecosystem approaches that should guide the decision making process, and does not secure sustainability and conservation. In addition to our advice on how to deal with h values in Chilean fisheries, we posit that more research is needed to include a full ecosystem approach into the RPs, since the current efforts are based only in the traditional single-species approach. For example, fisheries of low trophic levels should be managed as to fulfil the requirements of other fishing resources located in higher trophic levels as well as other predators such mammals and birds.

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