A REVIEW OF BIOLOGICAL REFERENCE POINTS AND MANAGEMENT OF THE CHILEAN JACK MACKEREL

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Introduction

The estimation procedure is normally based on the definition of an age-structured production model and biological parameters as natural mortality that provides considerable uncertainty (Sinclair, 1999). Thus, there are several key problems with management by reference points, particularly the often large uncertainty in actual stock size, and even larger uncertainty in unfished biomass.

While some (Hilborn, 2002) have argued we need to move away from reference points, they are, at present, a common feature of assessments and management tools and different regional management organizations are using biological reference points (García, 1995; Kohin et al. 2006, see Annex 1).

If the environment is strongly affecting survival of pre-recruits, one would not expect a strong relationship between stock size and recruitment. Thus, clearly there will not be a functional relationship between stock size and recruitment (Clark, 1993) or recruitment will have an autocorrelated error structure (Haltuch et al., 2008).

The estimation of biomass reference points needed to implement harvest control rules for fisheries e.g. average unfished spawning biomass *B*0, the biomass at which MSY is achieved *B*MSY, or current spawning biomass relative to *B*0 – stock depletion – is predicated on a stationary stock–recruitment relationship (Methot and Stewart, 2005; Haltuch et al., 2008). However, the fit of stock–recruitment models is often improved by including autocorrelated error structure, suggesting that it may be important to explicitly consider strongly autocorrelated recruitment success or more extreme shifts in the stock–recruitment relationship driven by changes in the environment when estimating biomass reference points (Brodziak et al., 2001; Ianelli, 2002).

Moreover, harvest policies which appear sustainable in the absence of autocorrelated recruitments can have difficulty maintaining target spawning biomass levels in the face of autocorrelated recruitment under commonly accepted fishing policies (Clark, 1993). It is therefore important to understand the properties of commonly used estimators for biomass reference points given autocorrelated recruitment or shifts in the stock–recruitment relationship (Haltuch et al., in press).

A review on the biological reference points estimates for the Chilean jack mackerel (*Trachurus murphyi*) based on an age-structured production model (Cubillos et al. 2002) and the harvest strategy applied in Chile is presented.

The harvest strategy and control rules

A harvest strategy should consider the management actions necessary to achieve defined biological and economic objectives that are identified for a given fishery.

To generate an adequated advice, harvest strategies must contain a process for monitoring of the fishery assessments of the biological and economic conditions of the fishery. A research program should be also developed according to a check list of knowledge on the biology and parameters estimated for the resource. Finally, control rules for the intensity of fishing activity according to the biological and economic conditions of the fishery (as defined by the assessment) should be applied.

Control rules are developed to maintain the fishery safe. To obtain effective and clear control rules, the objectives should be defined in function of quantifiable reference points. These reference points are used to guide management decisions, and these decisions should be pre-agreed actions linked directly to the biological and economic status of the fishery relative to the reference points.

Management and the Chilean Jack Mackerel Fishery

Chilean jack mackerel has supported a pelagic fishery allocated in Central Chile for more than 25 years, reaching a total hold capacity of more than 120.000 m^3 and annual catches of more than 3 million tons between years 1989 to 1997. Until 1991 the fishery was regulated only by a size limit tactic to avoid recruitment overfishing in an open access system, but in 1992 an access close was also introduced in the Chilean fishing law. At the same time, an international fleet, mainly composed by Russian trawlers that were operating for more than 10 years in oceanic waters, interrupted their operation. A fleet increase of 28.000 m^3 was authorized to develop activities from a new harbour, based on the expectations generated by the cessation of the international fleet and optimistic predictions established for the stock status and the biomass estimations. Since 1997, the strategy was to introduce control on the effort and to reduce the over capacity of the purse seine fleet up to 60.000 m^3. The simultaneous decrease in fish size and the abundance inicators were given overfishing signs to the authority, that in agreement with the fishery industry were establishing a reduction of the hold capacity, setting referential quotas and finally in 2001 establishing an allowable catch distributed by owner considering historical rights in the landings and the hold capacity by owner, the annual quotas were set between 1.0 to 1.6 million metric tons (Figure 1).

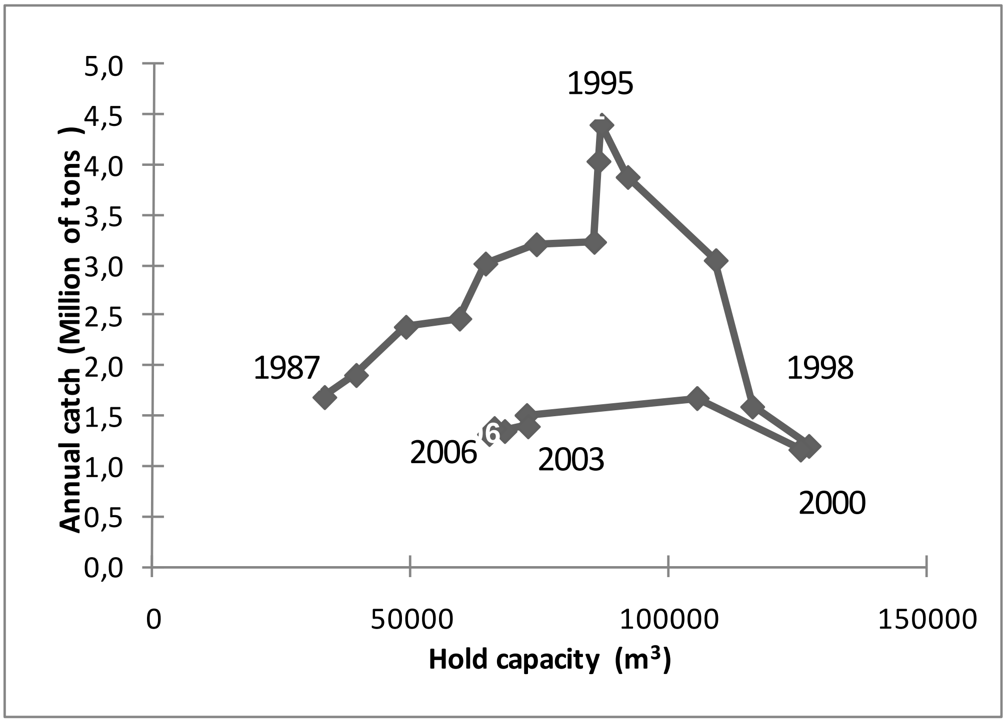


Figure 1. Annual catch and development of the Chilean jack mackerel fishery.

In year 2001, the Chilean Undersecretariat of Fisheries, after many technical discussions identified the following objectives of management, depending on the time scale:

In the medium term, the desirable conservation objective was to recover structure and biomass levels to assure the sustainability of the population. In this case, a significant number of escapements of recruits during the exploited phase were expected, to provide a strengthening of the year classes that were participating in the spawning fraction.

In the short term, with the aim to support the social and economic stage of the industry, the objective was to remove a level of catch in such a magnitude that does not affect the levels of spawning biomass.

The Chilean authority use a management strategy considering a target reference point based on a level of spawning biomass close to 40% of the virginal spawning biomass ($SSB_{40\%}$).

Estimating Biological Reference Points for the Chilean jack mackerel

Based on an analytical age-structured production model and management related quantities for the Chilean jack mackerel, Cubillos et al. (2002) were exploring different approaches to bridging the relationship between equilibrium surplus production and age-structured models of fisheries.

The approach consider the so called "age-structured production model" (ICES, 1997), which is a combination of yield per recruit (YPR) and spawning biomass per recruit (SPR) analysis with a suitable stock-recruitment relationship, to produce total equilibrium yield curves for a fishery (Shepherd, 1982). Usually, production modeling begins when a stock recruitment curve is fitted to the respective stock data, *i.e.* when a time series of recruitment and spawning biomass data is available for the stock under analysis. However, the traditional statistical analysis of stock-recruit data pairs can be confounded by environmental variation and measurement error for several fisheries, or time series of stock-recruit data pairs can be short and non informative about the stock-recruitment process. This is a real problem for many fisheries, particularly in data-limited situations of many stocks.

In the paper of Cubillos et al. (2002), stock-recruitment parameters were estimated from relationships based on an equilibrium, which are combinations between properties of the stock-recruitment models and the SPR-curve. In fact, the stock-recruitment models of Ricker and Beverton and Holt were re-parameterized in terms of equilibrium spawning stock biomass (S_0) and a factor, which permits to estimate the slope of the stock-recruitment relationship. We developed our analysis using fishery and life history parameters of the Chilean jack mackerel, *Trachurus murphyi* (Nichols). The objective was to analyse the equilibrium yield curve and to provide some additional reference points for fishery management, such as the maximum sustainable yield (MSY), fishing mortality rate at maximum sustainable yield (F_{MSY}), spawning biomass at MSY (S_{MSY}), 90%MSY, spawning biomass and fishing mortality at 90%MSY ($S_{90\%MSY}$ and $F_{90\%MSY}$, respectively) and Fcrash.

Yield and spawning biomass per recruit

Yield per recruit (YPR) and spawning biomass per recruit (SPR) were computed using the following age-structured models:

Assuming equilibrium, the abundance of a complete year-class of a stock is equal to the abundance of all year-classes in the stock In this way, the age-specific dynamics of the population at the deterministic equilibrium (per recruit) is governed by:

1)...
$$\begin{aligned} N_{ar} &= R = 1 \\ N_{a+1} &= N_a \, exp(-(v_a F + M)) \\ N_m &= N_{m-1} \, exp(-(v_a F + M))/(1 - exp(-(v_a F + M))) \end{aligned}$$

where N is the number of fish of age a , where "a" is defined between the age at recruitment (ar) and the maximum age (m) considered (take to be a plus-group), v_a is the age-specific selectivity function, F is the fishing mortality and M is the rate of natural mortality.

Yield to the fishery per recruit (YPR) was determined by:

2)...
$$YPR = \sum_{ar}^{m} w_{a+0,5} v_a F N_a \frac{(1 - exp(-(v_a F + M)))}{v_a F + M}$$

where $w_{a+0,5}$ is the mass of a fish of age a in the middle of a year, v_a, F, N and M were previously defined.

Spawning biomass per recruit (SPR) was estimated by:

3) $$SPR = \sum_{ar}^{m} w_a m_a N_a \, exp(-(v_a F + M)T_s)$$

where m_a is the maturity ogive, T_s is a factor denoting time of spawning, w, F, N and M were previously defined. In the case of the Chilean jack mackerel, T_s was considered in 0,75 (9 months), thus spawning biomass per recruit is quantified as the biomass surviving at 1° October.

Stock-recruitment relationships

Model of Ricker

Ricker established that recruitment is related to spawning stock biomass by the following model:

4)... $$R = \alpha S \, exp(-\beta S)$$

where R is the recruitment at age of recruitment (r), α is a coefficient related with the density-independent effects, β is a coefficient associated with the dependent effects of the density, and S is the spawning biomass at the time of spawning, *i.e.* October for the Chilean jack mackerel.

Parameters of Ricker's stock-recruitment model, were estimated by:

5)... $$\hat{\alpha} = \frac{exp(1)}{SPR_{max}}$$

where SPR_m has units of spawning biomass per recruit. The inverse of SPR_m represents the reason between the maximum recruitment (R_{max}) and the spawning biomass at the maximum recruitment (S_{Rmax}) in model of Ricker. SPR_{max} can be estimated through

6)... $$SPR_{max} = \tau \cdot SPR_{F=0}$$

where $SPR_{F=0}$ is the unexploited spawning stock biomass per recruit when fishing mortality is zero, while τ is a factor that could fluctuate between 0,2 and 0,5. Therefore, the main assumption of this method is that the inverse of the ratio R_{max}/S_{Rmax} (*i.e.* SPR_{max}) of the stock-recruitment model of Ricker can be estimated at levels between 0,2 to 0,5 times the unexploited spawning biomass per recruit (Cubillos, 1994). This range for τ can be recommended because usually a range between 20 and 50% of the unexploited level (referred as the %SPR) has been used to define targets for the rate of fishing mortality, particularly when a functional stock-recruitment curve is unknown for the stock under analysis (see Mace, 1994; Mace et al., 1993).

The relationship in Eq. (6) can be easily demonstrated and it is showed in Figure 2, where the inverse of the slopes that goes through the points (R_{max},S_{Rmax}) and (R_0,S_0) have units of spawning biomass per recruit. Therefore, combination of those slopes of the stock-recruitment curve with the spawning biomass per recruit data is equal to:

7)... $$SPR_m = \tau SPR_{F=0} = \left(\frac{R_{max}}{S_{Rmax}}\right)^{-1} = \tau\left(\frac{R_0}{S_0}\right)^{-1}$$

where R_0 is the recruitment at the equilibrium that corresponds to an absence of exploitation and forming part of the unexploited spawning stock biomass (S_0), i.e. at F=0. Eq. (4) was suggested by Cubillos (1994) by combining the mathematical definitions of the maximum recruitment:

8)... $$R_{max} = \alpha / \beta \, exp(1)$$

and the spawning stock biomass at maximum recruitment (S_{Rmax}):

9)... $$S_{Rmax} = 1/\beta$$

The parameter β of the stock-recruitment model of Ricker can be estimated by:

10)... $$\hat{\beta} = \frac{ln(\alpha \cdot SPR_{F=0})}{S_0}$$

where $SPR_{F=0}$, α and S_0 have been previously defined.

Model of Beverton and Holt

Beverton and Holt, propose the following model:

11)... $$R = \frac{S}{\alpha' + \beta' S}$$

where R is the recruitment (at age a_r), S is the spawning biomass at time of spawning, α' and β' are stock-recruitment relationship parameters (which should not be confounded with the Ricker stock-recruitment parameters).

The stock-recruitment model of Beverton and Holt was re-parameterized according to Francis (1992), where a factor called the "steepness" and symbolized by "h" was introduced. "Steepness" is defined as the fraction of virgin number of recruits expected when the spawner stock size is reduce to 20% of its unexploited (virgin) size (Francis, 1992). In this way, the parameters α' and β' can be estimated by:

12)... $$\hat{\alpha}' = \frac{(1-h)SPR_{F=0}}{4h}$$

and

13)... $$\hat{\beta}' = \frac{(5h-1)SPR_{F=0}}{4hS_0} = \frac{(5h-1)}{4hR_0}$$

Note that β' could be also estimated using Eq. (15) and solving for β' (see below).

Equilibrium yield curve

Once the parameters of the stock-recruitment models have been estimated, the equilibrium yield (Ye) and equilibrium spawning stock (Se) can be estimated. Such curves can be useful in understanding the likely spawning stock and yield associated with a given exploitation regime. The equilibrium spawning stock (Se) was obtained as a function of the fishing mortality rate by transforming the spawning biomass per recruit values by rearranging the stock recruit model, i.e.

14)... $$\hat{S}e = \frac{ln(\hat{\alpha}SPR)}{\hat{\beta}}$$

for the stock-recruitment model of Ricker, and

15)... $$\hat{S}e = \frac{(SPR - \hat{\alpha}')}{\hat{\beta}'}$$

in the case of the Beverton and Holt model.

Once equilibrium spawning biomass was estimated at each F value, recruitment was computed using the respective stock-recruitment models. Then equilibrium production curves can be obtained simply by multiplying the estimated recruitment ($\hat{R}$) value, by the appropriate yield per recruit value, i.e.

16)... $$\hat{Y}e = YPR \cdot \hat{R}$$

Clearly such method of estimating the equilibrium production curve involve the exercise of scientific judgement. This should be, however, considered an advantage, rather than a disadvantage, since in all moment the relationships between age-structured and stock-recruitment models are always considering an equilibrium, which is achieved in the long-term and by applying constant harvest rates.

Fishery and life history parameters of the Chilean jack mackerel

The fundamental input parameters, in terms of which all other parameters and quantities can be obtained, are: S_0, v_a, w_a, $w_{a+0,5}$, m_a, M, and h ('steepness') or τ. In the case of the Chilean jack mackerel, the parameters subject to large uncertainties are S_0, the factor τ or h, and the assumed age-specific selectivity pattern.

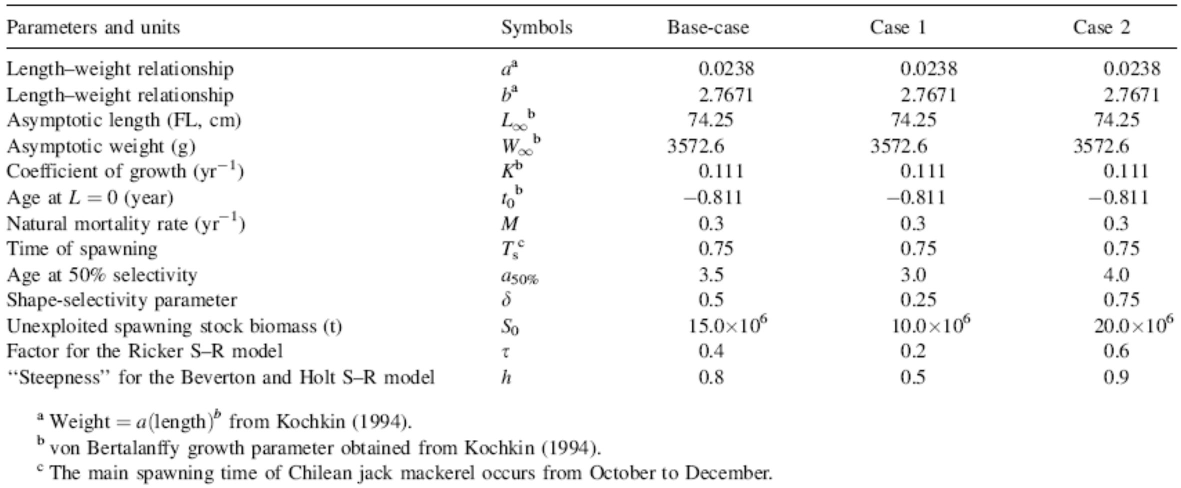
The selectivity-at-age (v_a) can be assumed to follow a logistic curve:

$$15)\ldots \qquad v_a = \left[1 + exp\{-(a - a_{50\%})/\delta\}\right]^{-1}$$

where $a_{50\%}$ is the age at 50% selectivity and δ is the width parameter. In the base-case specification of parameter values the age-at-50%-selectivity was based on visual examination of age composition, while the width parameter δ was assumed to be 0.5 years.

Life history parameters of the Chilean jack mackerel used in the analysis are showed in Table 1 and 2. The mass of a fish at age a, at begining or in middle of the year, were estimated using the length-at-age data predicted by the von Bertalanffy growth function and the relationship length-weight estimated by Kochkin (1994). Natural mortality rate and maturity-at-age are from Cubillos *et al.* (1998), which are parameters usually used in stock assessment by the Instituto de Investigación Pesquera of Talcahuano (Chile). We carry out the analysis according to three options for the parameters of the selectivity ($a_{50\%}$ and δ), the unexploited spawning stock biomass (S_0), and the factors τ and h that allow to estimate the parameters of the stock-recruitment parameters.

Table 1. Chilean jack mackerel. Life history parameters used in the analytical age-structured production model.



Parameters and units	Symbols	Base-case	Case 1	Case 2
Length–weight relationship	a^a	0.0238	0.0238	0.0238
Length–weight relationship	b^a	2.7671	2.7671	2.7671
Asymptotic length (FL, cm)	$L_\infty{}^b$	74.25	74.25	74.25
Asymptotic weight (g)	$W_\infty{}^b$	3572.6	3572.6	3572.6
Coefficient of growth (yr^{-1})	K^b	0.111	0.111	0.111
Age at $L = 0$ (year)	$t_0{}^b$	−0.811	−0.811	−0.811
Natural mortality rate (yr^{-1})	M	0.3	0.3	0.3
Time of spawning	T_s^c	0.75	0.75	0.75
Age at 50% selectivity	$a_{50\%}$	3.5	3.0	4.0
Shape-selectivity parameter	δ	0.5	0.25	0.75
Unexploited spawning stock biomass (t)	S_0	15.0×10^6	10.0×10^6	20.0×10^6
Factor for the Ricker S–R model	τ	0.4	0.2	0.6
"Steepness" for the Beverton and Holt S–R model	h	0.8	0.5	0.9

[a] Weight $= a(\text{length})^b$ from Kochkin (1994).
[b] von Bertalanffy growth parameter obtained from Kochkin (1994).
[c] The main spawning time of Chilean jack mackerel occurs from October to December.

Table 2. Chilean jack mackerel. Length (L), weight (w) and maturity ogive at age (a).

Age, a (years)	L_a (cm)	w_a (kg)	$L_{a+0.5}$ (cm)	$w_{a+0.5}$ (kg)	m_a
2	19.9	0.094	22.8	0.137	0.21
3	25.6	0.188	28.2	0.246	0.54
4	30.7	0.311	33.1	0.381	0.84
5	35.3	0.456	37.4	0.536	0.96
6	39.4	0.618	41.3	0.703	0.99
7	43.1	0.791	44.7	0.879	1.00
8	46.3	0.969	47.8	1.058	1.00
9	49.3	1.148	50.6	1.237	1.00
10+	57.0	1.733	57.9	1.810	1.00

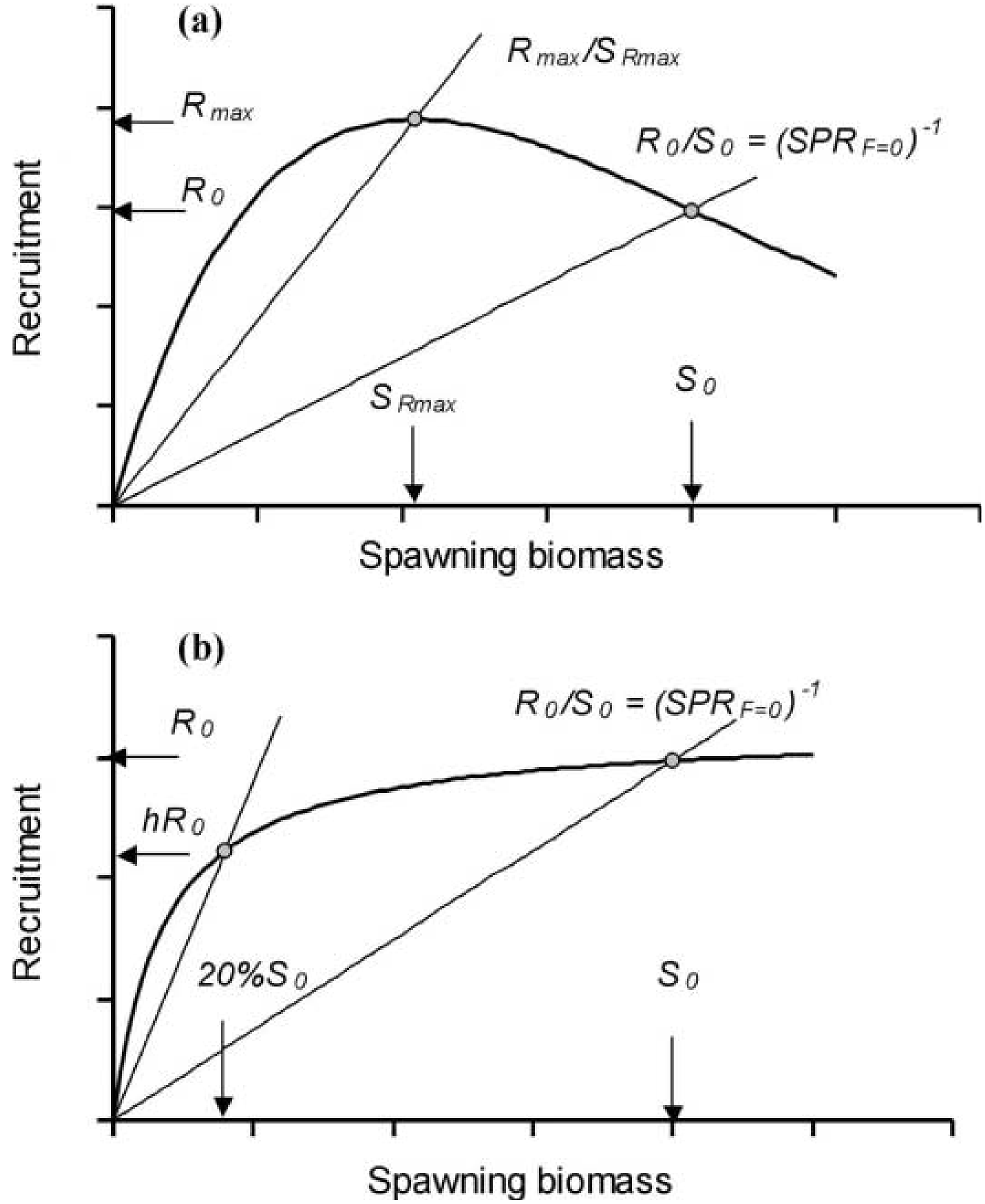


Figure 2. Relevant points that are used to estimate Biological Reference Points considering the stock –recruitment models of a) Ricker and b) Beverton and Holt.

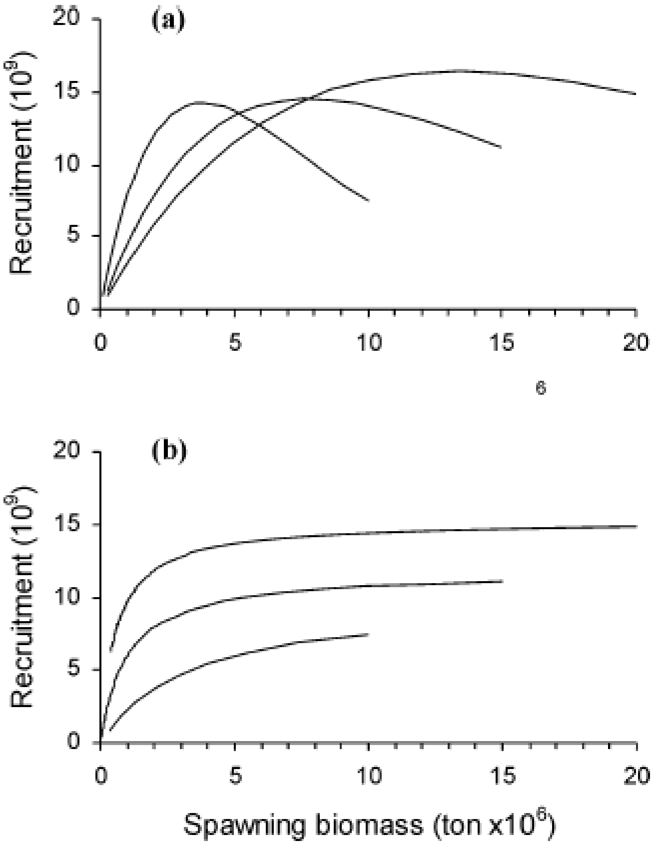


Figure 3. Stock-recruitment relationships of a) Ricker and b) Beverton and Holt considering a base model and 2 cases according with the parameters described in Table 1.

Resultant equilibrium yield curves can be observed in Figures 4 and 5. The parameters and biological reference points estimates are summarized in Tables 3 and 4.

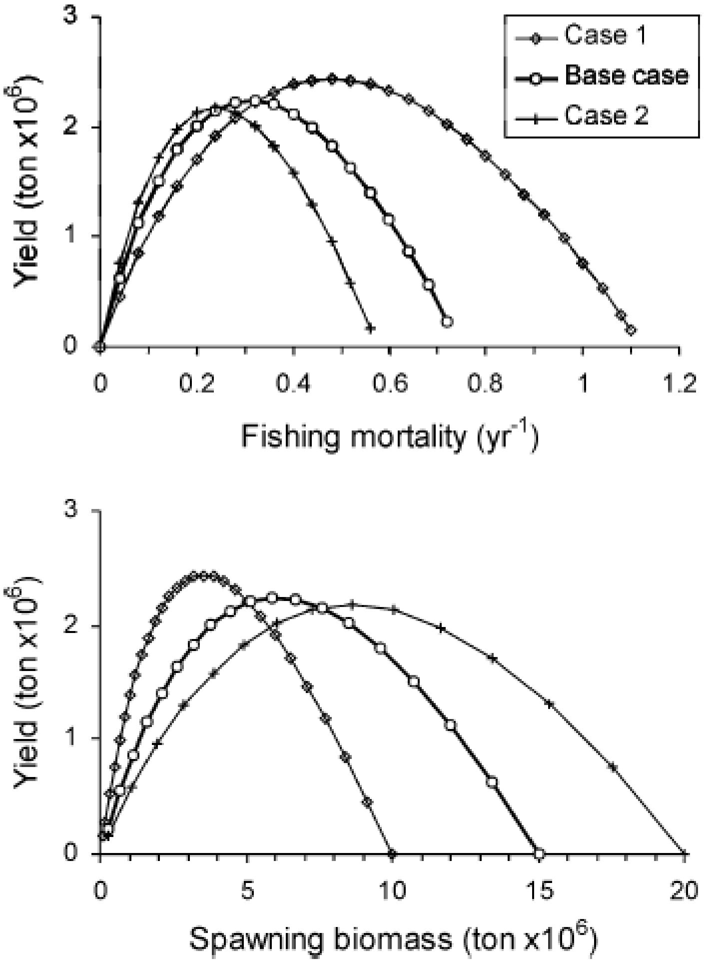


Figure 4. Equilibrium yield curves as a function of the a) Fishing mortality rate and b) Spawning stock biomass, considering a base model and 2 cases according with the parameters described in Table 1 (Stock-recruitment relationships of Ricker).

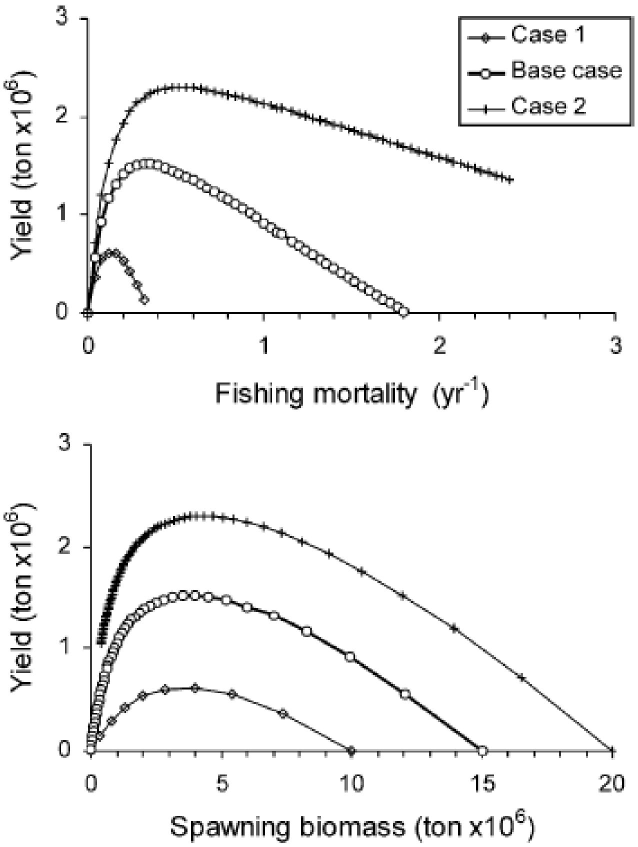


Figure 5. Equilibrium yield curves as a function of the a) Fishing mortality rate and b) Spawning stock biomass, considering a base model and 2 cases according with the parameters described in Table 1 (Stock-recruitment relationships of Beverton and Holt).

Table 3. Biological reference points derived from 3 different equilibrium yield curves.

Parameters	Base-case	Case 1	Case 2
(a) Ricker S–R model			
MSY/S_0	0.150	0.244	0.109
$0.9MSY/S_0$	0.135	0.219	0.098
S_{MSY}/S_0	0.404	0.354	0.431
$0.9S_{MSY}/S_0$	0.566	0.513	0.593
F_{crash}/F_{MSY}	2.393	2.344	2.393
$F_{0.9MSY}/F_{MSY}$	0.647	0.650	0.647
F_{MSY}/M	1.038	1.599	0.800
(b) Beverton and Holt S–R model			
MSY/S_0	0.102	0.062	0.115
$0.9MSY/S_0$	0.092	0.055	0.104
S_{MSY}/S_0	0.256	0.363	0.217
$0.9S_{MSY}/S_0$	0.433	0.532	0.400
F_{crash}/F_{MSY}	5.441	2.680	9.423
$F_{0.9MSY}/F_{MSY}$	0.539	0.627	0.470
F_{MSY}/M	1.109	0.440	1.744

Table 4. S-R relationship and biological reference points for the base-case model (varying S_0, τ and h).

	Ricker S–R model, τ			Beverton and Holt S–R model, h		
	0.2	0.4	0.6	0.5	0.8	0.9
MSY/S_0	0.247	0.150	0.107	0.063	0.102	0.115
$0.9MSY/S_0$	0.223	0.135	0.097	0.057	0.092	0.103
S_{MSY}/S_0	0.357	0.404	0.428	0.365	0.256	0.209
$0.9S_{MSY}/S_0$	0.517	0.566	0.591	0.534	0.433	0.391
F_{crash}/F_{MSY}	2.642	2.393	2.270	2.835	5.441	9.287
$F_{0.9MSY}/F_{MSY}$	0.623	0.647	0.658	0.620	0.539	0.487
F_{MSY}/M	1.929	1.038	0.707	0.491	1.109	1.523

Estimation of Biological Reference Points in a variable environment

Chilean jack mackerel is recognized as a termofilic species (Sharp et al., 2008) and there is evidence of autocorrelation in the recruitment series. There is also evidence of a relationship between sea temperature during the spawning season and recruitment; and changes in the position of the 16 ° C at the mean spawning season in November are related with recruitment (Figure 6).

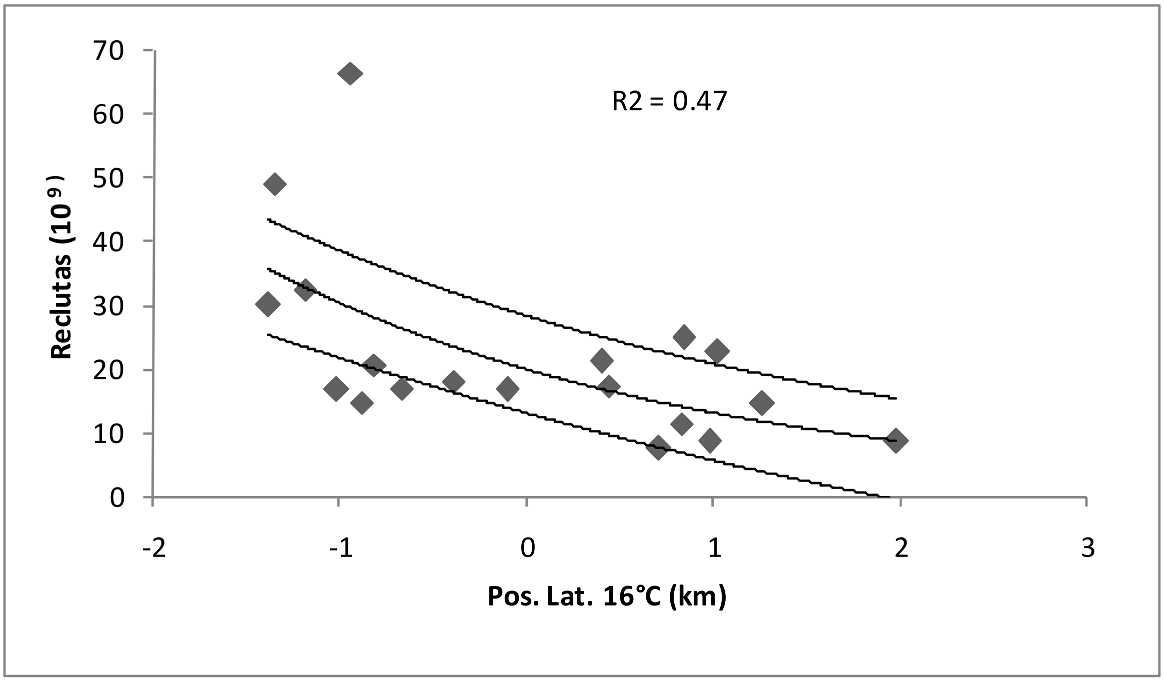


Figure 6. Relationship between the latitudinal position of the 16°C isotherm and recruitment.

Special consideration should be addressed when there is some evidence of average changes in productivity over time (due, for example, to regime shifts). This implies the need to (1) calculate average recruitments over the full range of environmental variability, under the assumption of a stationary stock–recruitment relationship; or (2) identify regime shifts in a timely fashion so that recruitment can be averaged during periods of sustained ecosystem shifts (e.g. Hollowed et al. 2001; Dorn et al., 2006). In the second case, we have to estimate the stock–recruitment relationship outside the stock assessment model, and calculate B0 on the basis of average recruitment over a pre-defined period of time.

The effects of some of the key factors, such as recruitment variability and stock-recruitment steepness, which might determine the performance of alternative estimators of these reference points, should be explored (see Haltuch et al., in press). A moderately long-lived species with highly variable recruitment, allows the effects of biological parameters such as longevity, growth and maturity rates, recruitment variability, stock productivity, and age-based selectivity on estimator performance to be evaluated.

A simulation framework is needed to explore a variety of factors which may affect the ability of age-structured stock assessment methods to estimate biomass reference points given a variable environment.

Conclusions

1. The simulation framework and the methodology presented here can be used to stablish a protocol for the estimation procedure of biological reference points.
2. Is important that in the jack mackerel sub-group of the RFMO, scientists agree in the biological and life history parameters to be used for the estimation of biological reference points and a range of values should be identified.
3. The impact of the environmental changes and their effects over recruitment success and biological parameters of the life history in Chilean jack mackerel should be considered in the procedure.

References

Brodziak, J.K.T., Overholtz, W.J., Rago, P.J., 2001. Does spawning stock affect recruitment of New England groundfish? Can. J. Fish. Aquat. Sci. 58, 306–318.

Clark,W.G., 1993. The effect of recruitment variability on the choice of a target level of spawning biomass per recruit. In: Kruse, G., Eggers, D.M., Marasco, R.J., Pautzke, C., Quinn II, T.J. (Eds.), Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Alaska Sea Grant College Program Report No. 93-02. University of Alaska, Fairbanks, pp. 233–246.

Cubillos, L., Hernández, A., Sepúlveda, A. and Arcos, D. 2002. Equilibrium yield-curve analysis through an analytic age-structured production model: A sensitivity study for the Chilean jack mackerel fishery. Fish. Res. 54: 395-407.

Dorn,M.W.,Aydin, K., Barbeaux, S., Guttormsen, M., Megrey, B., Spalinger, K., Wilkins, M., 2006. Chapter 1: Assessment of Walleye Pollock in the Gulf of Alaska. In: 2006 North Pacific Marine Fishery Council Gulf of Alaska Stock Assessment and Fishery Evaluation Reports for 2007. North Pacific FisheryManagement Council, 605W. 4th Avenue, Suite 306, Anchorage, Alaska, 99501, USA, pp. 39–146.

Francis, R. I. C. C. 1992. Use of risk analysis to assess fishery management strategies: a case of study using orange roughy (Hoplostethus atlanticus) on the Chatman Rise, New Zealand. Can. J. Fish. Aquat. Sci. 49, 922-930.

Haltuch, M.A., Punt, A.E., Dorn, M.W., 2008. Evaluating alternative estimators of fishery management reference points. Fish. Res. 94, 290–303.

Haltuch, M.A., A. E. Punt and M. W. Dorn. in press. Evaluating the estimation of fishery management reference points in a variable environment. Fish. Res. (2009), 15 pp.

Hilborn, R. 2002. The dark side of reference points. Bull. Mar. Sci. 10: 403-408.

Hilborn, R. 2003. The state of the art in stock assessment: where we are and where we are going. Sci. Mar. 67 (Suppl. 1): 15-20.

Hollowed, A.B., Hare, S.R., Wooster, W.S., 2001. Pacific basin climate variability and patterns of northeast Pacific marine fish production. Prog. Oceanogr. 49 (1–4), 257–282.

Ianelli, J.N., 2002. Simulation analyses testing the robustness of productivity determinations from west coast Pacific Ocean perch stock assessment data. N. Am. J. Fish. Manage. 22, 301–310.

Kohin, S., Conser, R., Sakagawa, G. 2006. Biological reference points for use by ISC. ISC/06/PLENARY/15

Maunder, M.N., Watters, G.M., 2003. A general framework for integrating environmental time series into stock assessment models: model description, simulation testing, and example. Fish. Bull. 101 (1), 89–99.

Sharp, G., Klyashtorin, L., Lyubushin, A. 2008. Cambio cíclico del clima producción de las principales especies comerciales.

Sinclair, M. 1999. Biological reference points relevant to a precautionary approach to fisheries management: An example for southern Gulf of St. Lawrence cod. NAFO Sci. Coun. Studies 32: 25-35.

Annex 1. List of target and limit reference points

(according to Kohin et al. 2006)

Target reference points

Target reference points are benchmarks intended to achieve management objectives, and represent desirable outcomes to be attained (e.g., optimum yield). They should not be exceeded on average, or more than 50% of the time.

Examples of target reference points are:

MSY	maximum sustainable yield
F_{MSY}	fishing mortality rate associated with maximum sustainable yield
B_{MSY}	stock biomass associated with maximum sustainable yield
SSB_{MSY}	spawning stock biomass associated with maximum sustainable yield
$F_{0.1}$ F_{MSY}	proxy reference point defined by a line having a slope 0.1 times that of the yield per recruit (Y/R) curve near the origin (yields near maximum Y/R with significantly less effort than needed to achieve maximum Y/R)
$B_{0.1}$	associated stock biomass
$SSB_{0.1}$	associated spawning stock biomass
$F_{30\%}$	fishing mortality rate producing 30% of the maximum spawning potential in the absence of fishing
$B_{30\%}$	associated stock biomass
$SSB_{30\%}$	associated spawning stock biomass
$F_{40\%}$	fishing mortality rate producing 40% of the maximum spawning potential in the absence of fishing
$B_{40\%}$	associated stock biomass
$SSB_{40\%}$	associated spawning stock biomass

Limit reference points

Limit reference points are benchmarks intended to constrain harvests so that the stock remains within safe biological limits. The probability of exceeding limit reference points should be low, i.e. close to zero. When a limit reference point is exceeded, it triggers significant limitations on the fishery in order to rebuild the stock.

Examples of limit reference points are:

$F_{20\%}$	fishing mortality rate producing 20% of the maximum spawning potential in the absence of fishing
$SSB_{20\%}$	associated spawning stock biomass
F_{MAX}	fishing mortality rate that yields maximum yield per recruit
SSB_{MAX}	associated spawning stock biomass
$F_{\text{SSB-Min}}$	fishing mortality rate that prevents the SSB from declining below the minimum observed SSB
SSB_{Min}	associated spawning stock biomass
$F_{\text{SSB-10th}}$	fishing mortality rate that prevents the SSB from declining below the 10th percentile of observed SSB
SSB_{10th}	associated spawning stock biomass
$F_{\text{SSB-25th}}$	fishing mortality rate that prevents the SSB from declining below the 25th percentile of observed SSB
SSB_{25th}	associated spawning stock biomass

Table 1. Summary of limit, threshold and target reference points as defined by U.S. advisory documents and legislation, and international management institutions. Initial definition of limit, threshold and target reference points are by Garcia (1995).

	Rosenberg *et al.*, 1996	**National SAW SC/NSG, 1998**	**Revised MFCMA**	**ICES**	**NAFO**	**NASCO**	**ICCAT**
Term: Limit	Absolute threshold	Threshold	Limit	Limit: B_{lim}, F_{lim}	Limit: B_{lim}, F_{lim}	Conservation limit	Overfishing BRPs
Term: Threshold	Precautionary threshold	Precautionary target		Precautionary value: B_{pa}, F_{pa}	Buffer: B_{buf}, F_{buf}		
Term: Target	Target	Target	Target	Target: B_{target}, F_{target}	Target: B_{tr}, F_{tr}	Management target	
BRP: *F* Limit	F where E(R)=0.5 $E(R_{max})$	F = Min(F_{MSY}, or proxies $F_{\%SPR}$, $F_{0.1}$, F=M)= MFMT	F_{MSY}	$F_{lim}=F_{crash}$, F_{loss} or F_{med} (left limb)	$F_{lim}=F_{MSY}$, F_{max}, F_{med} or $F_{30\%SPR}$	Escapement producing B_{MSY}	$F = F_{MSY}$, $F_{0.1}$ or F_{max}
BRP: *F* Threshold		F = 0.75 MFMT		$F_{pa} = F_{lim}e^{-2s}$ or F_{lpg} or F_{med}	$F_{buf} = F_{lim}e^{-2s}$, M, or $F_{MSY}/2$		
BRP: *F* Target		$F_{OY} < F_{MSY}$	$F_{OY} < F_{MSY}$				
BRP: SSB Limit	SSB where E(R)=0.5 $E(R_{max})$	B = Max($B_{MSY}/2$, B to B_{MSY} in 10 years) = MSST	B_{MSY} (for rebuilding)	$B_{lim} = B_{loss}$ or MBAL	$B_{lim} = B_{loss}$, MBAL, or $0.2*B_{max}$ (survey)	Escapement producing B_{MSY}	$B = B_{MSY}$
BRP: SSB Threshold				$B_{pa} = B_{loss}$ or $B_{lim}e^{-2s}$	$B_{buf} = B_{lim}e^{-2s}$, $2/3B_{MSY}$, or $0.5*B_{max}$ (survey)		
BRP: SSB Target		B_{OY}	B_{OY}		B_{MSY}		