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Regional Stock Assessment of Flying Jumbo Squid in the South-Eastern Pacific – A Conceptual Proposal

CALAMASUR

Regional stock assessment of the flying jumbo squid in the South-Eastern Pacific: a conceptual proposal

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Abstract

The flying jumbo squid fishery is the largest invertebrate fishery in the world and one of the largest of the world even when including finfish fisheries. In the South East Pacific Ocean (SEP) it is fished in four regions: Ecuadorian, Peruvian and Chilean exclusive economic zones (EEZ), and international waters off those EEZs. In international waters, the main operators currently are China (mainland and Taiwan) and South Korea, and a Japanese fleet with substantial catches also operated until 2012. In recent years, efforts have been made toward sharing and standardising databases among countries fishing jumbo squid in the SEP. However, a common regional framework for stock assessment on the SEP is still lacking. Knowledge of abundance and productive capacity of Jumbo squid will allow moving forward to a regional management of the stock aiming at sustainability. A recent review of stock assessment for cephalopod fisheries argued that the best approach to assess cephalopod stocks involves innovative depletion models. In this note, we propose such a model to be applied at the SEP regional level building upon recent progress with a family of stock assessment methods called generalised depletion models. The proposal aims at building an elementary regional database of fisheries data to apply the model, as a first step in the direction of a regional stock assessment and management.

Keywords: stock assessment; generalised depletion models; flying jumbo squid; South-East

Pacific

1 Introduction

The flying jumbo squid fishery extends over the whole Eastern Pacific Ocean yielding the largest volume of landings of any invertebrate fishery worldwide, reaching over a million tonnes in recent years (Robinson et al., 2016). According to FAO records (FAO, 2021), in the South Eastern Pacific Ocean (SEP) the fishery started to develop and grow in the early 90s, with the activities of Japanese and Korean fleets in international waters off the jurisdiction of Ecuador, Peru and Chile, and Peruvian fleets in Peru's Exclusive Economic Zone (EEZ) (Fig. 1). Starting in the 2000s, Chilean and Chinese fleets joined the exploitation in Chilean EEZ and international waters, respectively, and in 2014 Ecuadorian fleets became active in the fishery with landings in the low thousands (Fig. 1).

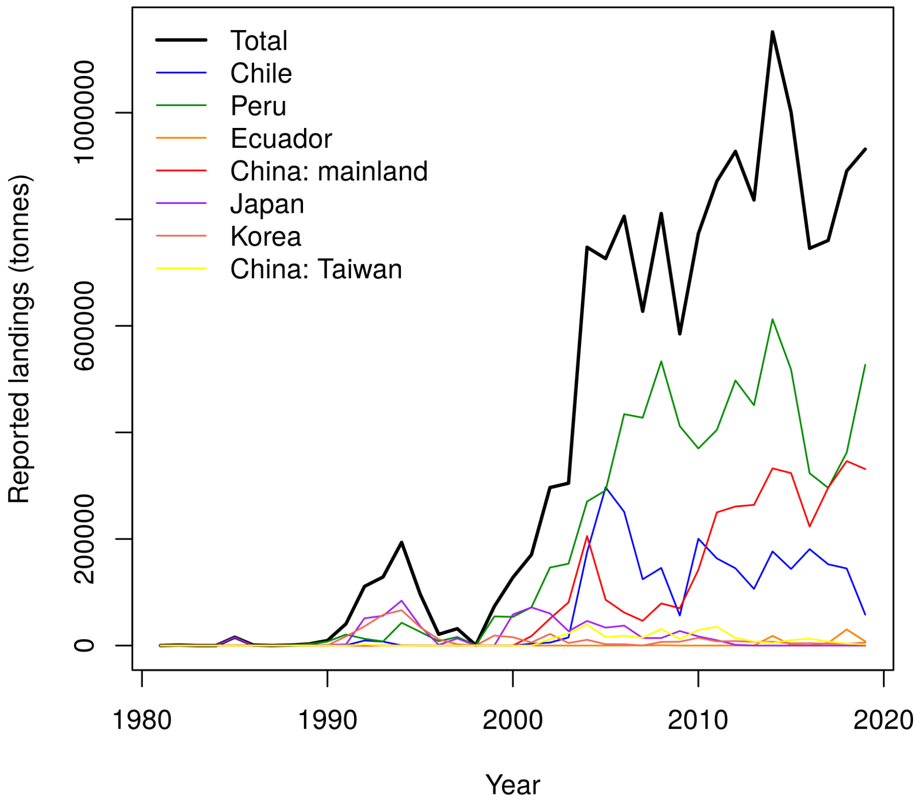

Figure 1: Historical landing records of the flying jumbo squid in FAO database (FAO, 2021) in the South-Eastern Pacific Ocean.

A special issue of Fisheries Research (Rodhouse et al., 2016) compiled important biological research including feeding (Rosas-Luis and Chompoy-Salazar, 2016), predators (Rosas-Luis et al., 2016), reproduction (Hernández-Muñoz et al., 2016), and the connection between volume of catches and environmental conditions (Paulino et al., 2016; Robinson et al., 2016). In recent years, discussions regarding method to assess jumbo squid and efforts toward sharing and standardising databases have been made among countries fishing jumbo squid in the SEP (SPRFMO, 2019, 2020). In spite of these efforts, there is still need of an integrated system of observation, modelling and management to secure the continued viability of the fishery (Rodhouse et al., 2016). Currently, there is much interest in generating scientific knowledge leading to an assessment of the abundance and productive capacity of the stock in the SEP region as a whole. This knowledge would be useful to take coordinated and agreed upon management actions aimed at the sustainable exploitation of the stock by the various fleets and countries involved.

Life history and population dynamic of cephalopods differ for many harvested fish populations which imposes challenges for assessing and manage their populations. Cephalopods are commonly characterised by very fast growth rates, short life span, high fecundity, continuous spawning during a given season and they show highly phenotypic plasticity as a result of changes in environmental conditions (Arkhipkin et al., 2021). In addition most of cephalopods are semelparous (Hoving et al., 2015), an individual undergoes only a single reproductive cycle after which it dies. Some cepalopods like jumbo squid exhibited high migratory behaviour (Nesis, 1983; Ibáñez and Cubillos , 2007) and age is difficult to asses given the formation of daily increments in hard structures such statolihts. For an assessment viewpoint, in semelparous and fast-growing animals, the estimation of natural mortality became extremely challenging. On the other hand, the time consuming-nature of reading daily increments in cephalopods hard structures make age-based models impractical to be used in the context of stock assessments. These characteristics preclude the application of routine age and cohort-based stock assessment methods usually applied in teleost fishes. In this context, Arkhipkin et al. (2021) conducted a recent review of cephalopods stock assessment and management and recommended the use of depletion models running at rapid time steps. Such family of stock assessment models can handle rapid life history with short life span in which age and natural mortality are not requires to be estimated beforehand. Depletion models are also less data demanding because they do not require intensive biological sampling or fishery independent data. Roa-Ureta et al. (2021) propose a depletion model for non-closed populations which are particularly useful in the context of flying jumbo squid given trans zonal and long migratory behaviour describe for this species.

The purpose of this conceptual paper, presented to the 2021 SC SPRFMO Metting, is to propose the construction of a simple and viable regional database to serve as input information for a stock assessment model that would evaluate movements (flows) among sub-regions in the wider SEP region, annual recruitment pulses to each sub-region, average natural mortality rate over the whole region, fishing mortality rates exerted by the various fleets in each sub-region, and total abundance of the stock in the region. The model to be proposed is a new type of generalised depletion model (Roa-Ureta, 2012, 2015; Roa-Ureta et al., 2015, 2019, 2020, 2021) especially modified and adapted to the evaluation of flows among sub-regions. Results of the model will be further exploited to fit a population dynamics model of the general surplus production kind (Roa-Ureta et al., 2019) and a spawners-recruitment model (Roa-Ureta et al., 2021), this latter application depending on the availability of additional biological knowledge or data concerning the maturity ogive.

2 Regional Database

To apply the depletion model described in the next section, the database that needs to be compiled and curated by Ecuadorian, Peruvian, Chilean, Chinese and Korean fleets, and the Japanese fleet that operated until 2012, consists of complete monthly landings (assumed very close to catches) and fishing effort, plus samples of mean weight in the landings. For purposes of exposition, we are going to assume that the data cover the period of January 2001 to December 2020, because a long time series is more informative, although it should be stressed at this point that the application of the model does not depend on the length of the time series. Note that a general and common template for collecting data in the context of depletion models have been already discussed in the SPRFMO (SPRFMO, 2020).

We are also going to assume a single fleet per country though the mode may accommodate any number of fleets with the subsequent increase in the numerical burden for maximization of the likelihood function. A graphical representation is shown in Fig. 2. In this figure, olive cells ideally are complete, meaning that there could be no gaps (i.e. months with fishing but without recorded data) and the full amount of catch and effort by the fleet has been recorded. On the other hand, yellow cells could have gaps and be based on samples, meaning that the mean weight of squids in the catch was computed by averaging over random samples. In the case of the Japanese fleet all the cells after December 2012 (or an earlier month in that year) will be filled with zeros.

One important consideration is that each fleet may report the fishing effort in different units. For instance one fleet may report fishing effort in coarse units such as number of boats or number of fishing trips per month, while another fleet may report fishing effort in more granular units such number of fishing hauls or even hours of fishing per month. As will be shown below, each fleet has its own parameters related to its operations so it is not necessary that all fleets report their fishing effort in the same units. Nevertheless, for every fleet the unit of fishing effort must the same along the entire time series.

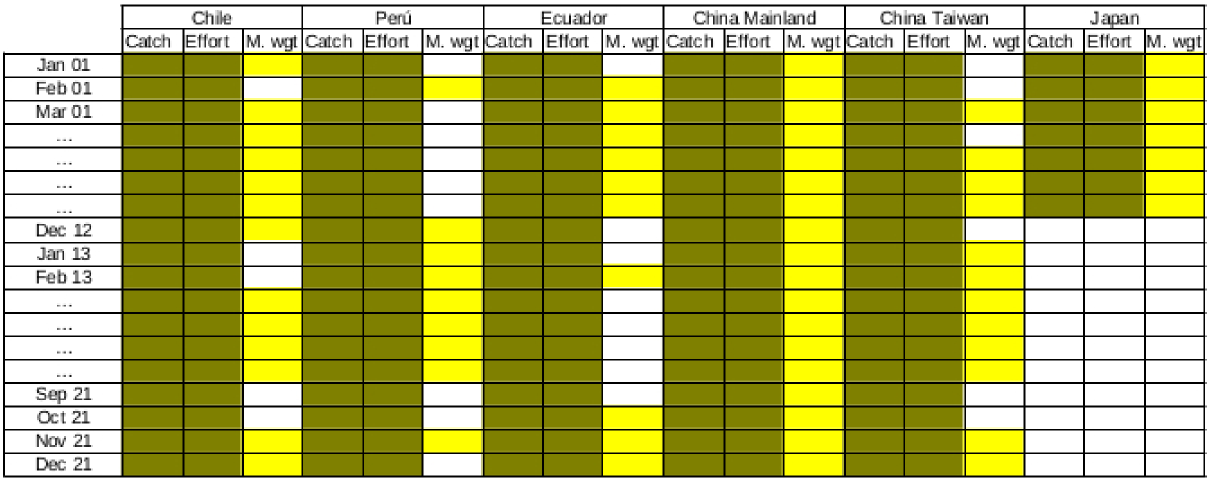

Figure 2: Pictorial representation of the regional database to be compiled and curated to apply the depletion model.

Another important aspect of fitting this type of models is that, although ideally all the catch and all the fishing effort per time step are reported, the existence of a few gaps in the time series of a given fleet may be overcome by using statistical imputation techniques but for this to be acceptable, without seriously compromising the reliability of results, these gaps need to be few and spread over the whole time series.

3 Generalised Depletion Model with Flows Among Sub-regions

3.1 General model

Generalised depletion models are depletion models for open populations with nonlinear dynamics. Regarding the open population aspect, traditional depletion models do not admit inputs of abundance during the fishing and that is the reason they could not be used for multi-annual assessments, since in that case one obvious factor, the annual pulse of recruitment, could not be included in the assessment. Therefore, depletion models were often connected to assessing stocks with intra-annual data, for one season of fishing separately. Generalised depletion models allow any number of exogenous inputs of abundance during the fishing, so they are apt for multi-annual assessments with monthly data (Roa-Ureta, 2015). Regarding the nonlinear dynamics aspect, traditional depletion models assumed a linear relationship between catch as the result, and fishing effort and stock abundance as the causes of the catch. Therefore, it is common with these traditional depletion models to use the catch per unit of effort on the l.h.s of the equation and the abundance dynamics in the r.h.s. of the equation. Generalised depletion models allow for nonlinear dynamics for the effect of fishing effort and stock abundance on catch, and therefore fishing effort is not used as a standardising quantity but as a predictor on the r.h.s. of the equation. Perhaps more importantly, generalised depletion models allow for a nonlinear effect of stock abundance on the resulting catch, which allows considering phenomena such as hyper-stability (Roa-Ureta, 2012).

With those introductory remarks, and assuming a database of 20 years (2001 to 2020) and six fleets, we can now define precisely the model that we propose to assess the jumbo squid stock in the SEP. So let C be the expected total (across all fleets) catch under the model and let t be a month in the time series. Let $E_{t,f}$ be the total fishing effort of fleet f in month t. Then the model states that

$$
\begin{aligned}
C_t &= \sum_{f=1}^{f=6} C_{f,t} \\
&= k_1 E_{1,t}^{\alpha_1} N_t^{\beta_1} + k_2 E_{2,t}^{\alpha_2} N_t^{\beta_2} + k_3 E_{3,t}^{\alpha_3} N_t^{\beta_2} + k_4 E_{4,t}^{\alpha_4} N_t^{\beta_4} + k_5 E_{5,t}^{\alpha_5} N_t^{\beta_5} + k_6 E_{6,t}^{\alpha_6} N_t^{\beta_6} \\
C_t = k_1 E_{1,t}^{\alpha_1} e^{M/2} &\left(N_0 e^{-Mt} - e^{M/2} \left[\sum_{i=1}^{i=t-1} C_{1,i} e^{-M(t-i-1)} \right] + \sum_{j=1}^{j=20} I_{1,j} R_{1,j} e^{-M(t-\tau_{1,j})} \pm f(\Phi_1) \right)^{\beta_1} + \\
k_2 E_{2,t}^{\alpha_2} e^{M/2} &\left(N_0 e^{-Mt} - e^{M/2} \left[\sum_{i=1}^{i=t-1} C_{2,i} e^{-M(t-i-1)} \right] + \sum_{j=1}^{j=20} I_{2,j} R_{2,j} e^{-M(t-\tau_{2,j})} \pm f(\Phi_2) \right)^{\beta_2} + \\
k_3 E_{3,t}^{\alpha_3} e^{M/2} &\left(N_0 e^{-Mt} - e^{M/2} \left[\sum_{i=1}^{i=t-1} C_{3,i} e^{-M(t-i-1)} \right] + \sum_{j=1}^{j=20} I_{3,j} R_{3,j} e^{-M(t-\tau_{3,j})} \pm f(\Phi_3) \right)^{\beta_3} + \\
k_4 E_{4,t}^{\alpha_4} e^{M/2} &\left(N_0 e^{-Mt} - e^{M/2} \left[\sum_{i=1}^{i=t-1} C_{4,i} e^{-M(t-i-1)} \right] + \sum_{j=1}^{j=20} I_{4,j} R_{4,j} e^{-M(t-\tau_{4,j})} \pm f(\Phi_4) \right)^{\beta_4} + \\
k_5 E_{5,t}^{\alpha_5} e^{M/2} &\left(N_0 e^{-Mt} - e^{M/2} \left[\sum_{i=1}^{i=t-1} C_{5,i} e^{-M(t-i-1)} \right] + \sum_{j=1}^{j=20} I_{5,j} R_{5,j} e^{-M(t-\tau_{5,j})} \pm f(\Phi_5) \right)^{\beta_5} + \\
k_6 E_{6,t}^{\alpha_6} e^{M/2} &\left(N_0 e^{-Mt} - e^{M/2} \left[\sum_{i=1}^{i=t-1} C_{6,i} e^{-M(t-i-1)} \right] + \sum_{j=1}^{j=20} I_{6,j} R_{6,j} e^{-M(t-\tau_{6,j})} \pm f(\Phi_6) \right)^{\beta_6}
\end{aligned}
\tag{1}
$$

The monthly catch of each fleet is determined by a proportionality constant, the scaling (k), which is comparable to catchability (although more general, see Roa-Ureta (2012)) having units of effort^{-1} $\times$ abundance^{-1}, times the fishing effort E modulated by the effort-response parameter α, times stock abundance N modulated by the abundance-response parameter β. Thus, the monthly catch of each fleet is the result of two causes, effort and abundance, with effort being an observed cause and abundance being a latent cause. In the third line of Eq. 1, latent abundance available to each fleet is made explicit and expanded with Pope's equation (second sum inside parentheses) and the input of abundance (third sum inside parentheses) corresponding to the annual recruitment (R) to the fleet as a part of the total recruitment ($R = R_1 + R_2 + R_3 + R_4 + R_5 + R_6$) in year j ($j = 1, ..., 20$, 2001 to 2020) minus or plus a function of immigration and emigration pulse among sub-regions, to be explained below. Parameters N_0 and M are the initial abundance (January 2001) and the average (across the whole period) monthly natural mortality rate, respectively, and these two parameters are common to all fleets because they are characteristics of the stock, independent of fishing operations. The variable I_j is an indicator that takes the value of 0 before the input of recruitment and 1 afterwards. Finally, parameters τ_j are the months in which recruitment happens in year j, which can be different for each fleet.

The model has a total of 120 recruitment parameters (20 years $\times$ 6 fleets), plus N_0 and M, plus six k, α and β parameters, giving a total of 140 free differentiable parameters, before counting immigration and emigration pulses. To tackle this multidimensional optimization problem there would be 1440 pairs of observations of catch and effort (20 years $\times$ 12 months $\times$ 6 fleets). This total data count does not count the months when the fishing is not happening in some fleets because of seasonality of operations.

The model in Eq. 1 is the process model, the postulated mechanism linking the true catch C_t to effort and abundance, which is assumed to be fairly complete and exact, with negligible process error. The true catch time series however, are not observed. Instead, random time series $\chi_{f,t}$ are observed and its expected value is $C_{f,t}$. Thus the catch time series are random variables and the stock assessment model is completed with a statistical model where $\chi_{f,t}$ has a probability density, a specific parametric distribution. In this proposal, two distributions will be implemented for each fleet, normal and lognormal, corresponding with additive or multiplicative hypotheses for the observations of catch. Each fleet's catch data may have any of the two distribution, giving rise to $2^6 = 64$ combinations for distributional hypothesis of the total catch distribution. In implementing the normal and lognormal distributions for the fleet's catch data, adjusted profile approximations will be coded to eliminate the dispersion parameters, leading to the following approximate likelihood functions for the data,

$$l_p(\boldsymbol{\theta}; \{\chi_t, E_t\}) = \begin{cases} \frac{T-2}{2} log\left(\sum_{i=1}^{T} (\chi_t - C_t)^2\right) & Normal \\ \frac{T-2}{2} log\left(\sum_{i=1}^{T} (log(\chi_t) - log(C_t))^2\right) & Lognormal \end{cases} \tag{2}$$

where l_p is the negative log-likelihood function, $\boldsymbol{\theta}$ is the vector of 140+ parameters, $\{\chi_t, E_t\}$ are the catch and effort data, C_t is the predicted catch according to the model in Eq. 1, and T is the total number of months ($T = 240$ with 20 years of data). These negative log-likelihood functions are minimised numerically as a function of $\boldsymbol{\theta}$ to estimate maximum likelihood parameter values and their covariance matrix. The $140+\times 140+$ covariance matrix contains the asymptotic standard errors of parameter estimates along

its main diagonal and the covariances/correlations in the off diagonal triangles.
In addition to the 140+ differentiable parameters, the model has 20 years $\times$ 6 fleets $= 140\ \tau$ parameters corresponding to the month of recruitment to each fleet in each year, and these τ parameters are non-differentiable. They can be estimated by maximum likelihood by fitting models with alternative τ for each fleet and year combination and selecting the fit that maximises the likelihood. In this proposal the τ parameters will be initially evaluated using the non-parametric catch spike statistics (Roa-Ureta, 2015). After examination of optimization results with this initial timing hypothesis, further hypotheses will be evaluated by changing some of the months of recruitment for some of the fleets. The final best model will be selected as the one with the lowest Akaike Information Criterion (AIC) as well as better numerical, biological realism and statistical quality criteria.

3.2 Flows among sub-regions

There are several authors that have hypothesised that groups of jumbo squid that differs in life history traits such as maturity and size should represent genetically discrete units, and thus should be treated as isolated stocks for managing purposes (see revision in Ibáñez et al. (2015)). However, many molecular studies have demonstrated that specimens of different sizes in different areas of the South Pacific are genetically identical (Sandoval-Castellanos et al., 2009; Wang et al., 2021). Variations found in life history traits seem to be caused by the large phenotypic flexibility of this species (Hoving et al., 2013). The lack of genetic differences and the migratory behaviour of jumbo squids support the hypothesis that this species composes only one large interconnected stock in the South east Pacific.
There are few hypotheses regarding flows and interconnections among sub-regions along the exclusive economic zones (EEZs) and open international seas in the South East Pacific. However, one of the most accepted hypotheses indicates flows in the north-south axis along the cost of Ecuador, Peru and Chile and also a reproductive migration of individuals off shore from Chile and Peru (Ibáñez et al., 2015). We Followed this hypothesis as first approach to modelling the jumbo squid stock in the South east Pacific. An idealised representation of hypothesis is shown in Figure 3.

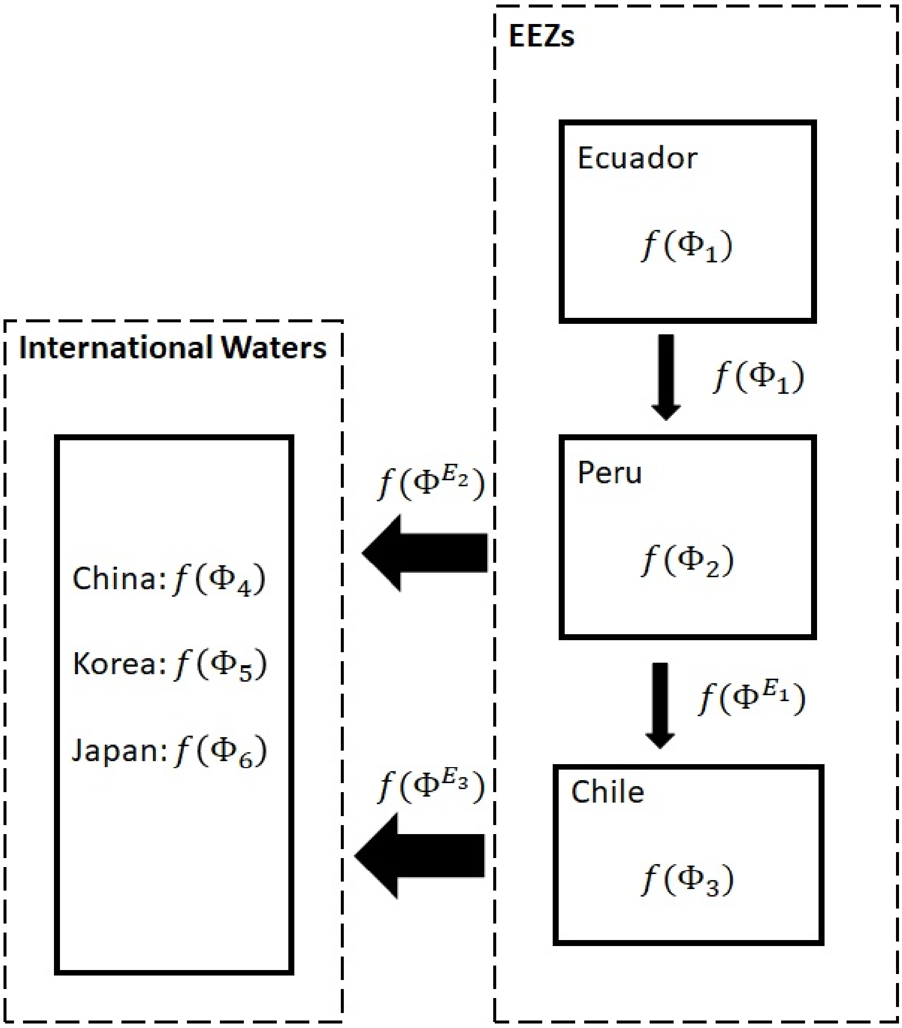

Figure 3: Idealised representation of stock flows across sub-regions in an arbitrary υ month. $f(\Phi)$ represents the immigration/emigration flows on each sub-region/fleets

The $f(\Phi_f)$ terms in Eq. 1 account for the possibility that part of the stock moves from one sub-region to another sub-region at specific months during the period covered by time series of data. To simplify the exposition, consider the idealised situation represented in Fig. 3. On an arbitrary month υ, there are minor pulses from Ecuador to Peruvian EEZs and also from Peru to Chilean EEZ. In the same month (υ), larger pulses happen from the Peruvian EEZs and from Chilean EEZs to international waters offshore. The catch and effort data, when of sufficient quality, may contain information on immigration and emigration that allow estimation of the magnitude of those pulses as demonstrated in Roa-Ureta et al. (2021).

Let enumerate the fleets in eq. 1, as Ecuador (1), Peru (2), Chile (3), China (4), Korea (5) and Japan (6), then, the modelled flows on each sub-region/fleets are as follows:

Ecuador:

$$f(\Phi_1) = -\Upsilon\left[\sum_{j=1}^{j=20}\Phi_{1,j}e^{-M(t-\upsilon)}\right] \tag{3}$$

where Υ is an indicator variable that takes the value of 1 in the month υ where flows among fleets occurs, and takes a value of 0 otherwise. Note the simplified assumption that all flows among sub-regions occur at the same month (υ).

The Peruvian sub-region included the most complex case in which an immigration input is received from Ecuador, but this sub-region also generates emigrations for Chile EEZ (which magnitude is refers as $\Phi_j^{E_1}$) and to international waters ($\Phi_j^{E_2}$) as follows,

Peru:

$$\begin{aligned} f(\Phi_2) &= \Upsilon\left[\sum_{j=1}^{j=20}\Phi_{1,j}e^{-M(t-\upsilon)} - \sum_{j=1}^{j=20}\Phi_j^{E_1}e^{-M(t-\upsilon)} - \sum_{j=1}^{j=20}\Phi_j^{E_2}e^{-M(t-\upsilon)}\right] \\ &= \Upsilon\left[\sum_{j=1}^{j=20}(\Phi_{1,j} - \Phi_j^{E_1} - \Phi_j^{E_2})e^{-M(t-\upsilon)}\right] \\ &= \Upsilon\left[\sum_{j=1}^{j=20}(\Phi_{2,j})e^{-M(t-\upsilon)}\right] \end{aligned} \tag{4}$$

where ($\Phi_{2,j} = \Phi_{1,j} - \Phi_j^{E_1} - \Phi_j^{E_2}$) represents the net flux from the EEZ Peruvian sub-region in the year j. Note the sign of parameter $\Phi_{f,j}$ is indicating the importance of either immigration or emigration on each particular sub-region and year.

Note that Peruvian vessels had fished for Jumbo squid in international waters (SC7-Doc33, 2019). However, on this first modelling approach, we considered these catches negligible in comparison with Peru's catches on its EEZ. Nevertheless, the proposed modelling framework can be easily adapted to include any other fleet in international waters if adequate data are available.

Likewise, in the case of the Chilean sub-region, we consider an immigration from Peru ($\Phi_j^{E_1}$) and an emigration to international waters defined as ($\Phi_j^{E_3}$). Then, the flow model for Chile can be described as,

Chile:

$$f(\Phi_3) = \Upsilon\left[\sum_{j=1}^{j=20}\Phi_j^{E_1}e^{-M(t-v)} - \sum_{j=1}^{j=20}\Phi_j^{E_3}e^{-M(t-v)}\right]$$
$$= \Upsilon\left[\sum_{j=1}^{j=20}(\Phi_j^{E_1} - \Phi_j^{E_3})e^{-M(t-v)}\right] \quad (5)$$
$$= \Upsilon\left[\sum_{j=1}^{j=20}(\Phi_{3,j})e^{-M(t-v)}\right]$$

In the case of the International sub-region, we consider an immigration from Peru ($\Phi_j^{E_2}$) and another from Chile ($\Phi_j^{E_3}$). However, these immigration pulses are shared among the three international fleets. In general terms, the Peruvian immigration to international waters can be divided among the Chinese (4), Korean (5) and Japanese (6) fleets as follows: $\Phi_j^{E_2} = \Phi_{4,jj}^{E_2} + \Phi_{5,jj}^{E_2} + \Phi_{6,jj}^{E_2}$. Likewise, the Chilean immigration to international waters can be divided among fleets as, $\Phi_j^{E_3} = \Phi_{4,jj}^{E_3} + \Phi_{5,jj}^{E_3} + \Phi_{6,jj}^{E_3}$. Note from data alone, it is impossible to know which amount of immigration is fished by which international fleet (e.g $\Phi_{f,jj}^{E_2}$, $\Phi_{f,jj}^{E_3}$). However, it is possible to know from data the net flux from each international fleet in the same manner as we did in the other sub-regions above:
China:

$$f(\Phi_4) = \Upsilon\left[\sum_{j=1}^{j=20}\Phi_{4,j}^{E_2}e^{-M(t-v)} - \sum_{j=1}^{j=20}\Phi_{4,j}^{E_3}e^{-M(t-v)}\right]$$
$$= \Upsilon\left[\sum_{j=1}^{j=20}\Phi_{4,j}e^{-M(t-v)}\right] \quad (6)$$

Korea:

$$f(\Phi_5) = \Upsilon\left[\sum_{j=1}^{j=20}\Phi_{5,j}^{E_2}e^{-M(t-v)} - \sum_{j=1}^{j=20}\Phi_{5,j}^{E_3}e^{-M(t-v)}\right]$$
$$= \Upsilon\left[\sum_{j=1}^{j=20}\Phi_{5,j}e^{-M(t-v)}\right] \quad (7)$$

and Japan:

$$f(\Phi_6) = \Upsilon \left[\sum_{j=1}^{j=12} \Phi_{6,j}^{E_2} e^{-M(t-v)} - \sum_{j=1}^{j=12} \Phi_{6,j}^{E_3} e^{-M(t-v)} \right] = \Upsilon \left[\sum_{j=1}^{j=12} \Phi_{6,j} e^{-M(t-v)} \right] \quad (8)$$

where $\Phi_{4,j}$, $\Phi_{5,j}$ and $\Phi_{6,j}$, are the net immigration fluxes on the year j by China, Korea and Japan, respectively.

In practice, only the larger emigration/immigration pulses would be estimated reliably enough from the model and the data. With further reference to eq. (1), on an arbitrary month all sub-regions receive an input of abundance corresponding to annual recruitment, i.e. squids that grow to become vulnerable to the fishing gear, and there are no emigration/immigration pulses, thus in a month like this Eq. 1 would have the Φ_f terms evaluating to zero by virtue of indicator variable Υ.

4 General Surplus Production Model for the Region

The depletion model above allows direct estimation of 140 parameters but it also permits posterior calculation of derived parameters and predictions such as monthly fishing mortality by fleet (from Baranov catch equation), regional abundance and regional biomass per month in absolute terms. The latter two predictions are estimated with standard errors using the Delta method. By selecting one of the monthly regional biomass estimates per year (preferably the biomass in the month that on average across the years, produces the estimate with the lowest standard error) and by appending the regional total catch for the years before the time series covered with the depletion model, it is possible to estimate a general surplus production model of the Pella-Tomlinson type. In our approach this is done with a non-Bayesian hierarchical inference method based on hybrid likelihood functions (Roa-Ureta et al., 2015). The Pella-Tomlinson model is

$$B_y = B_{y-1} + rB_{y-1} \left(1 - \left(\frac{B_{y-1}}{K} \right)^{p-1} \right) - C_{y-1}, p > 1, y_1 \leq y \leq y_{end} \quad (9)$$

where r is the intrinsic population growth rate, p is the symmetry of the production function, K is the carrying capacity, B_y is the biomass estimated in the depletion model, and C_{y-1} is the total annual catch during the previous fishing season.

The annual biomass and its standard deviation from fitting the depletion model and the annual biomass predicted by the Pella-Tomlinson model are linked through a hybrid (marginal-estimated) likelihood function,

$$\ell_{HL}(\boldsymbol{\theta}_{PT}|\{\hat{B}_y\}) \propto -\frac{1}{2}\sum_{y_1}^{y_{end}}\left(log(2\pi S^2_{\hat{B}_y}) + \frac{(\hat{B}_y - B_y)^2}{S^2_{\hat{B}_y}}\right) \tag{10}$$

where $\boldsymbol{\theta} = \{B_{y0}, K, r, p\}$ is the vector of parameters of the Pella-Tomlinson model in Eq. 9 plus one additional parameter for biomass in the year prior to the first year in the time series, 2000, $S^2_{\hat{B}_y}$ are the distinct numerical estimates of standard deviations of each annual biomass estimate from the fitted depletion model (replacing the unknown distinct true standard deviations), $\hat{B}_y$ are the likelihood estimates of annual biomass from the fitted depletion model, and B_y are the true annual biomass according to Eq. 9.
With reference to $\boldsymbol{\theta}$, models could be fit where B_{y0} is a distinct parameter or where it is set to be equal to K. In the second option it is assumed that the stock was at the carrying capacity when the annual time series (that goes much more back in time than the depletion model time series) started. Thus the first option is a fit a 4-parameters model while the second option is a fit of 3-parameters model. The second option is useful because convergence of the fit may not need to be burdened with four parameters to estimate and also because the true biomass at the start of the annual time series, B_{y0}, is the least important parameter for management of the stock at the current time. To determine which of the two options is better for the biomass observations it is possible to use the model with the lowest AIC.
From the fit of Pella-Tomlinson model, we compute several biological reference points depending on the prevailing dynamics of the stock. Those reference points were the MSY,

$$MSY = rK(p-1)p^{-p/(p-1)} \tag{11}$$

the biomass at the MSY,

$$B_{MSY} = Kp^{1/(1-p)} \tag{12}$$

and the latent productivity,

$$\dot{P} = \gamma MSY\frac{B_y}{K}\left(1 - \left(\frac{B_y}{K}\right)^{p-1}\right), \gamma = \frac{p^{p/(p-1}}{p-1} \tag{13}$$

For all those biological reference points, standard errors are computed using the delta method.
With reference to the latent productivity (Quinn and Deriso, 1990), this is a biological reference point analogous to the MSY, but while the MSY is a constant, the latent productivity varies with the biomass of the stock. Thus the latent productivity is more

relevant for stocks that tend to fluctuate because of environmental forces or because of their intrinsic population dynamics. For instance, in Roa-Ureta et al. (2015) we found that the stock under study was fluctuating because of a high value of the intrinsic population growth rate, r. In another case (Roa-Ureta et al., 2021) we found that the stock was undergoing cyclic fluctuations due to an unstable equilibrium point in the spawners-recruitment relationship. Thus the MSY was not applicable in those cases and it was actually an excessive harvest rate.

5 Final Remarks

- Data regarding monthly catches and average individually weight on each sub-region and fishing fleet will be needed on a first modelling approach. Future and more intensive biological sampling (e.g maturity) will allow coupling a depletion model with productivity derive from a stock-recruitment relationship.

- Model specification for flows can be adjusted to different competing hypotheses regarding immigration/emigration among sub-regions. These hypotheses can be evaluated in the context of model selection.

- The proposed modelling framework is flexible enough to capture the main features of the jumbo squid such as fast growth rate, inter-connectivity within the stock among several sub-regions and fleets with different units for effort.

- Collaboration among different countries in the SPRFMO will be crucial for the implementation of the proposed modelling framework. Main aspects of such collaboration should be based on data curation and data sharing in common templates, agreements regarding extension of the data used and the selection on the main migratory (flows) hypotheses to be tested.

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References

Arkhipkin, A.I., Hendrickson, L.C., Payá, I., Pierce, G.J., Roa-Ureta, R.H., Robin, J-P., Winter, A. 2021. Stock assessment and management of cephalopods: advances and challenges for short-lived fishery resources. ICES Journal of Marine Science 78, 714–730.

Berger, T., Sibeni, F., Calderini, F. 2021. FishStatJ, a tool for fishery statistics analysis, release 4.01.5. FAO, Fisheries Division, Rome.
Congcong Wang, Gang Li, Hao Xu

Hernández-Muñoz, A.T., Rodríguez-Jaramillo, C., Mejía-Rebollo, A., Salinas-Zavala, C.A. 2016. Reproductive strategy in jumbo squid *Dosidicus gigas* (D'Orbigny, 1835): A new perspective. Fisheries Research 173, 159–168.

Hoving, H.J.T., Gilly, W.F., Markaida, U., Benoit-Bird, K.J., -Brown, Z.W., Daniel, P., Field, J.C., Parassenti, L., Liu, B., Campos, B. 2013. Extreme plasticity in life-history strategy allows a migratory predator (jumbo squid) to cope with a changing climate. Global change biology 19, 2089–2103.

Hoving, H.J.T., Laptikhovsky, V.V., Robison, B.H. 2015. Vampire squid reproductive strategy is unique among coleoid cephalopods. Current Biology, 25(8), R322–R323.

Ibáñez, C.M., Cubillos, L.A. 2007. Seasonal variation in the length structure and reproductive condition of the jumbo squid *Dosidicus gigas* (d'Orbigny, 1835) off central-south Chile. Scientia Marina, 71(1), 123–128.

Ibáñez, C.M., Sepúlveda, R.D., Ulloa, P., Keyl, F., Pardo Gandarillas, M.C., 2015. The biology and ecology of the jumbo squid *Dosidicus gigas* (Cephalopoda) in Chilean waters: a review. Latin American Journal of Aquatic Research, 43, 402–414.

Nesis, K.N. 1983. *Dosidicus gigas* In: P.R. Boyle (ed.). Cephalopod life cycles, Vol. 1. Species accounts. Academic Press, London, pp. 216–231.

Robinson, C.J., Gómez-Gutiérrez, J., Markaida, U., Gilly, W.F. 2016. Prolonged decline of jumbo squid (*Dosidicus gigas*) landings in the Gulf of California is associated with chronically low wind stress and decreased chlorophyll a after El Niño 2009–2010. Fisheries Research 173, 128–138.

Rodhouse, P.J.K., Yamashiro, C., Arguelles, J. 2016. Introduction. Jumbo squid in the eastern Pacific Ocean: A quarter century of challenges and change. Fisheries Research 173, 109–102.

Rosas-Luis, R., Chompoy-Salazar, L. 2016. Description of food sources used by jumbo squid *Dosidicus gigas* (D'Orbigny, 1835) in Ecuadorian waters during 2014. Fisheries Research 173, 139–144.

Rosas-Luis, R., Loor-Andrade, P., Carrera-Fernández, M., Pincay-Espinoza, J.E., Vinces-Ortega, C., Chompoy-Salazar, L. 2016. Cephalopod species in the diet of large pelagic fish (sharks and billfishes) in Ecuadorian waters. Fisheries Research 173, 159–168.

Paulino, C., Segura, M., Chacón, G. 2016. Spatial variability of jumbo flying squid (*Dosidicus gigas*) fishery related to remotely sensed SST and chlorophyll-a concentration (2004-2012). Fisheries Research 173, 122–127.

Roa-Ureta, R.H. 2012. Modeling In-Season Pulses of Recruitment and Hyperstability-Hyperdepletion in the *Loligo gahi* Fishery of the Falkland Islands with Generalized Depletion Models. ICES Journal of Marine Science 69, 1403–1415.

Roa-Ureta, R.H., 2015. Stock assessment of the Spanish mackerel (*Scomberomorus commerson*) in Saudi waters of the Arabian Gulf with generalized depletion models under data-limited conditions. Fisheries Research 171, 68–77.

Roa-Ureta, R.H., Molinet, C., Bahamonde, N., Araya, P. 2015. Hierarchical statistical framework to combine generalized depletion models and biomass dynamic models in the stock assessment of the Chilean sea urchin (*Loxechinus albus*) fishery. Fisheries Research 171, 59–67.

Roa-Ureta, R.H., Santos, M.N., Leitão, F. 2019. Modelling long-term fisheries data to resolve the attraction versus production dilemma of artificial reefs. Ecological Modelling 407, 108727.

Roa-Ureta, R.H., Henríquez, J., Molinet, C. 2020. Achieving sustainable exploitation through co-management in three Chilean small-scale fisheries. Fisheries Research 230, 105674.

Roa-Ureta, R.H., Fernández-Rueda, M.P., Acuña, J.L., Rivera, A., González-Gil, R., García-Flórez, L. 2021. Estimation of the spawning stock and recruitment relationship of *Octopus vulgaris* in Asturias (Bay of Biscay) with generalized depletion models: implications for the applicability of MSY. ICES Journal of Marine Science. pdf.

Sandoval-Castellanos, E., Uribe-Alcocer, M. and Díaz-Jaimes, P. 2009. Lack of genetic differentiation among size groups of jumbo squid (Dosidicus gigas). Ciencias marinas, 35(4), 419–428.

SC7-Doc33. 2019. Peru'sAnnual report(SPRFMO Area). 7th MEETING OF THE SCIENTIFIC COMMITTEE, La havana, Cuba.

SPRFMO. 2019. SPRFMO SC 2nd Squid Workshop Report. 20 p. Wellington, New Zealand 2019.

SPRFMO. 2020. 8th Scientific Committee meeting report. 76 p. Wellington, New Zealand 2020.

Quinn, T.J., Deriso, R. 1990. Quantitative Fish Dynamics. Oxford University Press, NY.

Wang, C., Li, G., Xu, H. 2021. China genetics study of Jumbo flying squid, methods and results. South Pacific Regional Fisheries Management Organization. Technical Report, 10 p.