Stock assessment of the flying jumbo squid in Ecuadorian waters with generalised depletion models: a proof of concept note

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Abstract

The flying jumbo squid fishery is one of the largest fisheries of the world and the largest invertebrate fishery. In the region of the South-East Pacific Ocean (SEP) it is fished in four sub-regions: Ecuadorian, Peruvian and Chilean exclusive economic zones (EEZ), and international waters off those EEZs. In this meeting of OROP-PS, the CALAMASUR group is proposing a regional stock assessment model that includes flows among these sub-regions (Wiff and Roa-Ureta, 2021). Therefore the question arises: is there any evidence for flows of the stock among sub-regions? In this note I explored this issue by modelling Ecuadorian catch, effort and mean weight data taken during 2018 using intra-annual generalized depletion models (Roa-Ureta, 2012). The model runs on weekly time steps and the presence of pulses of abundance that enter the Ecuadorian sub-region is tested by fitting models with 1, 2, 3 and 4 pulses of abundance. Under the hypothesis that there are incoming pulses of abundance, the best model should have more than one pulse of abundance, while under the alternative hypothesis of no flows from outside the Ecuadorian sub-region, the best model should have just one pulse of abundance, the pulse corresponding to the annual recruitment of squids that grow to the size captured and retained by the fishing gears. We show here that the best model for the Ecuadorian weekly catch, effort and mean weight data is a model with three pulses of abundance, thus supporting the hypothesis in the conceptual proposal of Wiff and Roa-Ureta (2021).

Keywords: stock assessment; generalized 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 (Fig. 1). In 2014 Ecuadorian artisanal fleets joined the exploitation of this large stock with significant catches, reaching a maximum in 2018, with over 30 thousand tonnes.

In 2018, the Instituto Público de Investigación de Acuicultura y Pesca (IPIAP) of Ecuador carried out an extensive sampling program of the catch of the jumbo squid stock by an artisanal fleet using a variety of fishing gears but mainly jigging. This program covered 2162 fishing trips over the whole year, and they accounted for 6% of the total Ecuadorian catch of the jumbo squid that year. In this note I use these catch and fishing effort data from 2018, along with mean weight data taken in separate sampling effort, to fit an intra-annual generalised depletion model (Roa-Ureta, 2012). This idea follows the advice of an international team of experts that reviewed the state of of stock assessment modelling of cephalopod fisheries (Arkhipkin et al., 2021). The model will not evaluate absolute stock abundance because not all the catch and fishing effort are included in the data. Nevertheless, the model will be used to test the hypothesis of the existence of multiple inputs of abundance to the Ecuadorian sub-region.

In a separate note (Wiff and Roa-Ureta, 2021) we are proposing a regional stock assessment model based on multi-annual generalised depletion models (Roa-Ureta, 2015; Roa-Ureta et al., 2019) with flows of stock among all sub-regions in the wider South-East Pacific Ocean. Under the proposed region-wide stock assessment model, there are several inputs and outputs of stock abundance due these flows among sub-regions. Therefore, the present note is a proof of concept for the viability of the regional stock assessment proposal in Wiff and Roa-Ureta (2021).

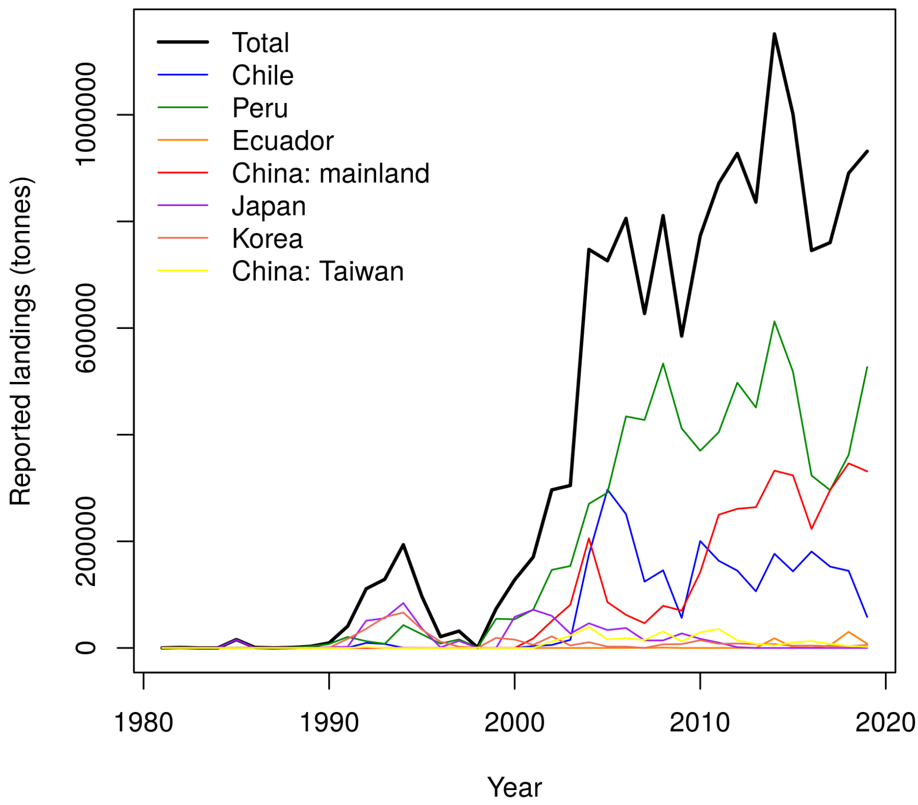

Figure 1: Historical landing records of the flying jumbo squid in FAO database (FAO, 2021) in the South-Eastern Pacific Ocean.

2 Ecuadorian Data

The sampling program conducted by IPIAP in 2018 recorded the catch and several other identification and classification measures per fishing trip with dates of sailing and arrival to port of 2162 fishing trips. No specific measure of fishing effort (such as number of time spent fishing) was recorded. I turned these granular data into a weekly aggregation of catch by all boats sampled during any given week. To match that catch, as a result, with a suitable measure of fishing effort, as one of the causes of the catch, I counted the number of fishing trips per week.

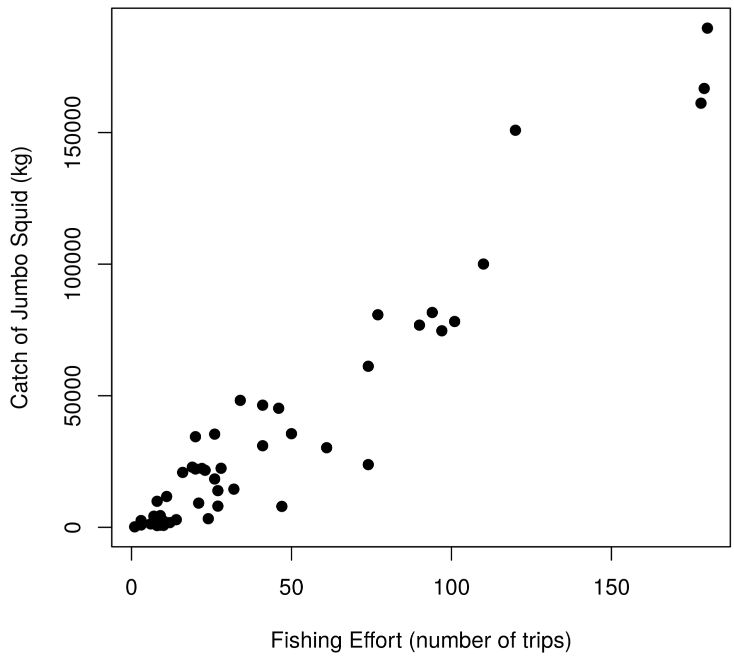

Figure 2: Fishing effort and catch relationship in the sample of fishing trips of the Ecuadorian jumbo squid fishery conducted by IPIAP.

Fig. 2 shows the resulting connection between fishing effort and catch. There is a very strong connection between the chosen measure of fishing effort and the resulting catch for the sample of fishing trips in IPIAP's database. This was to be expected given the large fraction (6%) of the total Ecuadorian catch that was covered by this sample of fishing trips.

An additional database compiled and curated by IPIAP included 6798 individual squids sampled from the commercial catch during the period 2013 to 2020. This database contained data on mantle weight with the month of the sample being recorded. I used R package MMWRweek (Niemi, 2020) to assign week of the year to the monthly mantle weight data at a randomly selected day within the month. This allowed matching the fishing effort and catch data with the mean weight data at the cost of introducing some timing noise. Further random noise was added to this weekly mantle weight data by sampling from truncated normal distributions using R package Runuran (Leylold and Hormann, 2020) and the mean mantle weight data and its standard deviation. In this manner the mantle weight data matched to fishing effort and catch data added sampling variation in the biological sampling to the model. The resulting mean mantle weight vector for the model as well as the original data are shown in Fig. 3.

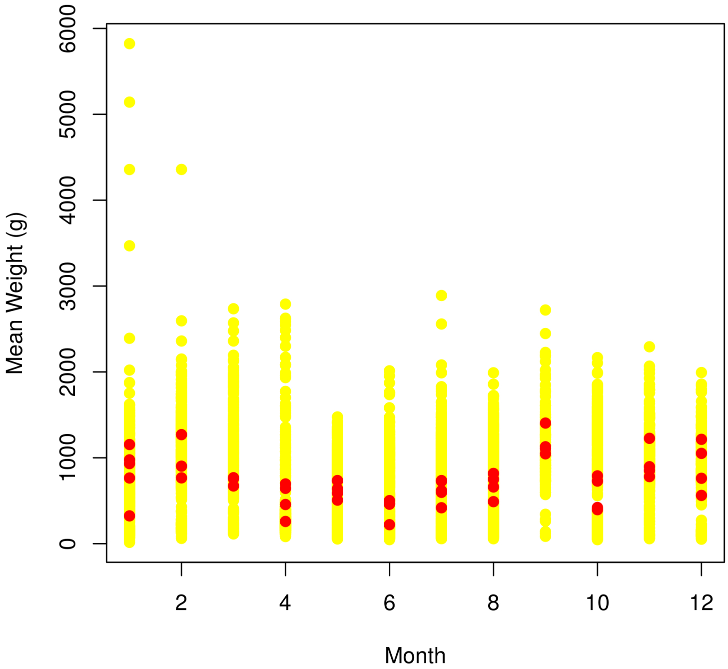

Figure 3: Mean monthly weight of jumbo squid in IPIAP's database (yellow dots) and the re-sampled mean weight per week to use in the model (red dots).

3 Intra-Annual Generalised Depletion Model

Generalised depletion models are depletion models for open populations with nonlinear dynamics. Intra-annual versions work with rapid time step data and are fitted to one season of fishing (Roa-Ureta, 2012; Roa-Ureta et al., 2015, 2021). In this application, the general form of the model is

$$
\begin{aligned}
C_t &= kE_t^{\alpha} N_t^{\beta} \\
C_t &= kE_t^{\alpha} e^{M/2} \left(N_0 e^{-Mt} - e^{M/2} \left[\sum_{i=1}^{i=t-1} C_i e^{-M(t-i-1)} \right] + \sum_{j=1}^{J} I_j P_j e^{-M(t-\tau_j)} \right)^{\beta} \qquad (1)
\end{aligned}
$$

where t is a week of the year, C is the expected catch under the model, k is the scaling, a proportionality constant which is comparable to catchability (although more general, see Roa-Ureta (2012)) having units of effort^{-1} $\times$ abundance^{-1}, E is the fishing effort E modulated by the effort-response parameter α, N is stock abundance modulated by the abundance-response parameter β, M is the weekly natural mortality rate, N_0 is initial abundance, I_j is an indicator variables taking values of 0 before an exogenous pulse of abundance enters the vulnerable stock, and 1 afterwards, J is the total number of abundance pulses, P_j is the magnitude of pulse of abundance j, and tau_j is the week at which pulse of abundance j happens along the season. I fitted models of this kind with J taking values of 1, 2, 3 and 4, thus describing hypotheses with different numbers of in-season exogenous pulses of abundance.

The model in Eq. 1, in its four variants ($J = 1, 2, 3, 4$) is the process model, the postulated mechanism linking the true catch C_t to fishing effort and abundance, which is assumed to be fairly complete and exact, with negligible process error. The true catch time series however, is not observed. Instead, a random time series $\chi_{f,t}$ is observed and its expected value is $C_{f,t}$. Thus the catch time series is a random variable and the stock assessment model is completed with a statistical model where $\chi_{f,t}$ has a probability distribution, a specific parametric distribution. In this proposal, two distributions were implemented for each fleet, normal and lognormal, corresponding with additive or multiplicative hypotheses for the observations of catch. In implementing the normal and lognormal distributions for the fleet's catch data, I fitted models with the exact normal and exact lognormal distributions and adjusted profile approximations, where the dispersion parameters are eliminated from the inference. These approximations are as follows,

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

where l_p is the negative log-likelihood function, $\boldsymbol{\theta}$ is the vector of 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 weeks. 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 free parameters vector is $\boldsymbol{\theta} = (N_0, M, k, \alpha, \beta, \{P\})$. The model was fit using R package CatDyn (Roa-Ureta, 2018).

4 Results

None of the intra-annual generalised depletion models with two in-season exogenous inputs of abundance yielded successful numerical convergence results. Furthermore, all model variants fitted to the lognormal distribution (both the exact version and the adjusted profile approximation) yielded poor numerical results, with large absolute values of numerical gradients and/or pathological Hessian matrix, or did not converge at all. Thus model selection is restricted to variants with 1, 3 or 4 exogenous in-season pulses of abundance and the exact and adjusted profile approximation to the normal likelihood.

Table 1: Akaike information criterion (AIC) for the selection of the best working model in Eq. 1 in four version, with 1, 3 or 4 in-season exogenous pulses of abundance.

Variant	**Likelihood**	**AIC**	**Best model**
1	A.P. normal	524	
3	A.P. normal	492	1
4	A.P. normal	494	
1	Exact normal	494	
3	Exact normal	460	1
4	Exact normal	462	

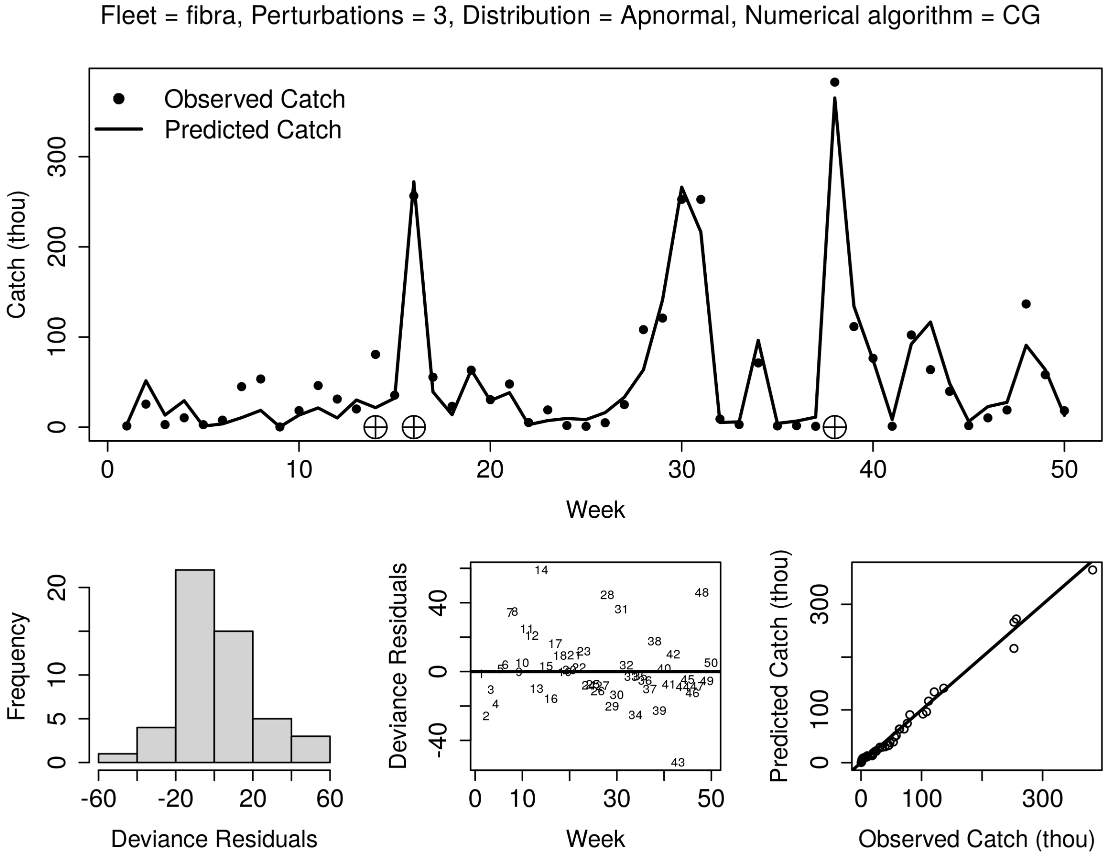

Figure 4: Top panel: fit of the intra-annual generalised depletion model to the catch and fishing effort data of the Ecuadorian sampled fleet during 2018 (target symbols indicate weeks at which the inputs of abundance happened). Bottom left panel: histogram of residuals. Bottom mid panel: cloud of residuals. Bottom right panel: quantile-quantile plot.

Under both versions of the normal likelihood, the Akaike Information Criterion identifies the model with three pulses of abundance as the best working model (Table 1). To select between these two variants, we note that the mean coefficient of variation of parameters estimated under the adjusted profile normal variant was 79.5% while the same average for the model variant fitted with the exact normal likelihood was 119.5%. Therefore, on account of better precision of estimates, the 3-inputs of abundance model fitted with the adjusted profile normal approximation to the likelihood was retained as the best working model.

The fit of this model to the data is shown in Fig. 4. The top panel shows model predicted catch and observed catch in numbers of squids. Bottom panels are diagnostics plots to check the quality of the fit from several measures from the distribution of residuals. It is noted that in addition to having model predictions that closely follow the data, diagnostic residual analysis indicate a good fit of the model to the data, with symmetric residuals histogram, a shapeless cloud of residuals, and very good connection between quantiles of the observed and predicted random variable.

Another useful diagnostics plot is the histogram of correlation coefficients between parameter estimates. A good model must have those correlation coefficients well-centred around zero, meaning that all parameters make unique and necessary contributions to the fit of the data. Although this histogram for the selected model (Fig. 5) is quite broad, it is concentrated around 0. It could be noted as well that other model variants had worse or similar histogram of correlations. Thus this additional diagnostic examination further supports the result that the model with three exogenous in-season pulses of abundance and the adjusted profile normal distribution for the data is the best working model.

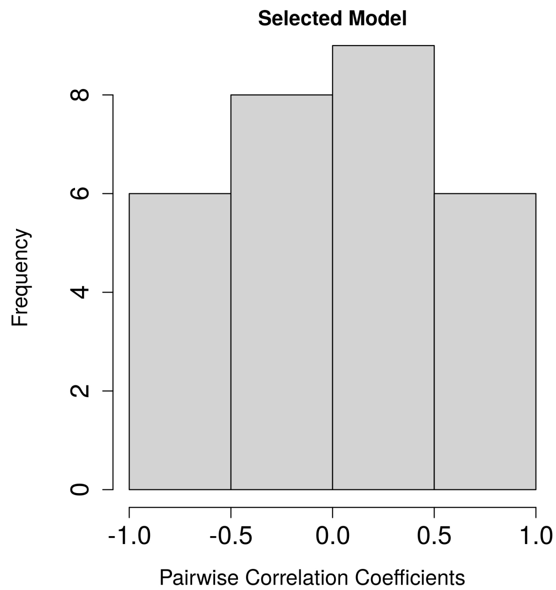

Figure 5: Histogram of correlation coefficients between parameter estimates of the best generalised depletion model for the catch and fishing effort data of the Ecuadorian sampled fleet during 2018.

5 Discussion

Under the hypothesis that the inputs of jumbo squid abundance to the vulnerable stock during the 2018 season in Ecuadorian waters happen only because of somatic growth, i.e. squids becoming large enough to be vulnerable to the various gears employed to fish them, we would expect a single pulse of abundance in a generalised depletion model. This would be the annual pulse of recruitment to the fishery. This is not what we have obtained. We have found that the best model includes three pulses of abundance. Moreover, two of those pulses of abundance happened in April, and the third one happened in September, which is very far apart along the season. When examining the variation in monthly weight (Fig. 3 we find that in April the mean weight is one of the lowest along the year while in September the opposite is true. Therefore, those two pulses of abundance in April probably are the annual recruitment due to growth while the pulse in September is more likely the result of immigration.

6 Conclusions

- A database of fishing effort and catch at rapid time steps plus mean weight data allows assessment of the jumbo squid fishery in the South-East Pacific with generalised depletion models.
- Intra-annual generalised depletion modelling with Ecuadorian data from one year supports the regional stock assessment model proposal by Wiff and Roa-Ureta (2021) in the sense that it provides evidence in favour of the existence of flows among sub-regions in the wider regional context.
- Generalised depletion models are appropriate to assess the jumbo squid fishery in the South-East Pacific.

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