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Research Article

Stock assessment of jumbo squid *Dosidicus gigas* in northwest Mexico

Ricardo Urías-Sotomayor[1], Gabriel Iván Rivera-Parra[2], Francisco Javier Martínez-Cordero[3] Nicolás Castañeda-Lomas[1], Raúl Pérez-González[1] & Guillermo Rodríguez-Domínguez[1]
[1]Facultad de Ciencias del Mar, Universidad Autónoma de Sinaloa, Mazatlán, Sinaloa, México
[2]Centro Regional de Investigación Pesquera, Instituto Nacional de Pesca, Mazatlán, Sinaloa, México
[3]Laboratorio de Economía Acuícola y Prospectiva, Centro de Investigación en Alimentación y Desarrollo A.C. Unidad Mazatlán, Mazatlán, Sinaloa, México
Corresponding author: Guillermo Rodríguez-Domínguez (guirodom@uas.edu.mx)

ABSTRACT. The population dynamics of jumbo squid *Dosidicus gigas* from northwest Mexico was evaluated for the period 1974-2012 using Schaefer's model, where model parameters were estimated with the catch maximum sustainable yield method (Catch-MSY) using two prior intrinsic population increase rate (*r*) range values (1.0 to 2.0 and 1.5 to 2.0). Estimated parameters with both prior *r* ranges were 1.23 and 1.68 yr^{-1} for *r* and 243,836 and 190,468 ton for carrying capacity (*k*), respectively. Corresponding management quantities were 75,147 and 80,098 ton for the maximum sustainable yield (MSY) and 121,918 and 95,234 ton for the biomass at MSY (B_{MSY}). Estimated jumbo squid biomass dropped below the B_{MSY} after 2003, and near to 0.2 *k* in 2012. The Schaefer's model showed that declines in estimated biomass were preceded by catches that exceeded the MSY. Strong El Niño-Southern Oscillation events can change the availability of jumbo squid in northwest Mexico through migratory processes and phenotype changes in maturation size, but stock biomass variability is most likely to be caused by fishing.

Keywords: *Dosidicus gigas*, jumbo squid, stock assessment, Catch-MSY, Schaefer's Model, Gulf of California.

INTRODUCTION

The jumbo squid *Dosidicus gigas* (D'Orbigny, 1835) is a cephalopod with a wide distribution in the eastern Pacific, from Alaska to Chile (Cosgrove, 2005; Wing, 2006; Zeidberg & Robison, 2007), where it is the basis of important fisheries (Csirke *et al*., 2015). Total landings of *D. gigas* amounted to 950,630 ton in 2012 with Peru, China, Chile and Mexico the largest producers (FAO, 2014). In Mexico, the *D. gigas* fishery has operated since 1974, with a maximum catch of 121,016 ton in 1997 and an average catch of 68,237 ton from 1995 to 2012 (CONAPESCA, 2012). After 2012 up to 2017 jumbo squid fishery collapsed and no catches have been obtained. Fishermen hope that jumbo squid fishery will recover as were observed in 1995 in the Gulf of California. The Mexican jumbo squid fleet consists of 222 ships (~24 m) and 1,828 small boats (~7 m, regionally known as pangas) with 7,724 fishermen (Diario Oficial de la Federación, 2014).

The Mexican management strategy is targeted to ensure the escapement of at least 40% of the adult biomass at the end of the fishing season (Nevárez-Martínez & Morales-Bojórquez, 1997; Nevárez-Martínez *et al*., 2000, 2006).

To evaluate potential squid populations yields, surplus production models, depletion methods, age-structured models, virtual population analysis, swept area methods, acoustic and size-structured models have been used (Sato & Hatanaka, 1983; Bravo de Laguna, 1989; Rosenberg *et al*., 1990; Goss *et al*., 1998; Starr & Thorne, 1998; Cadrin & Hatfield, 1999; Morales-Bojórquez *et al*., 2001; Rodhouse *et al*., 2014; Arkhipkin *et al*., 2015). Age-structured models are difficult to implement due to uncertainty in estimates of age because growth patterns and maturity processes of squids are highly variable and affected by environmental conditions and food availability (Rodhouse *et al*., 2014). Simple surplus production models have been successfully applied, despite their limitations (Sato & Hatanaka, 1983; Bravo de Laguna, 1989; Rodhouse *et al*., 2014). These models require annual catch series and effort. Martell & Froese (2013) developed a method named Catch-MSY for data-poor stocks based on catch

Corresponding editor: Antônio Olinto Ávila da Silva catch series, resilience assumptions and relative biomass in the first and final years of the catch series.

In this paper, Schaefer's model parameters (1954) are estimated for the *D. gigas* population in northwest Mexico using Martell & Froese's method (2013) with capture data from 1974 to 2012.

MATERIALS AND METHODS

The data comprise jumbo squid *Dosidicus gigas* catches recorded in northwest Mexico from 1974 to 2012. The Catch-MSY (Martell & Froese, 2013) was applied to these data to estimate Schaefer´s biomass model parameters (Schaefer, 1954) of the fishery. This method requires a catch time series Ct, initial (λ_{01}, λ_{02}) and final biomass (λ_1, λ_2) of the stock as a proportion of the carrying capacity (*k*) and a set value of *r* (the maximum rate of population increase) and *k* selected by a random process with a uniform distribution in a range for each parameter. Annual biomasses were estimated using Schaefer's model. Intervals of 0.5 to 0.9 for the initial relative biomass and of 0.01 to 0.4 for the depletion range (λ_1, λ_2) were chosen. In the Catch-MSY the outputs estimated values of *r* and *k* depend strongly on the lower prior limit of *r* chosen and especially the estimated *r* value is obtained near the lower limit, so to obtain estimates of *r* close to the range of r reported in the bibliography for *D. gigas* between 1.33 and 1.76 yr^{-1} (Arkhipkin *et al*., 2015; Csirke *et al*., 2015; Xu *et al*., 2015) two prior *r* ranges from 1 to 2 and 1.5 to 2 were chosen. Therefore, the values used in the model were randomly selected from these two intervals, considering a uniform distribution of ln (*r*) between these intervals. *k* values were chosen randomly in the same way as those of *r* considering a range between the maximum catch and 100 times the maximum catch. Subsequently, the initial biomass B_0 was estimated with:

$$B_0 = \lambda_0 \ k \exp(\gamma t)$$

where λ_0 is the assumed initial relative biomass and *k* is the parameter randomly chosen. The term exp(γt) was considered 1, assuming an observation error.

From the second year of the catch series, biomass was estimated with Schaefer´s model:

$$B_{t+1} = B_t + r \times B_t \times \left(1 - \frac{B_t}{k}\right) - C_t$$

where B_{t+1} and B_t are biomass to year t+1 and t, respectively, and C_t is caught in year t.

This process was reiterated 100,000 times for each increment of 0.05 of λ_{01} to reach λ_{02}, which also requires generating 100,000 pairs of values of *r* and *k* in each run. Each pair of *r* and *k* values generated is evaluated using a Bernoulli distribution as a likelihood function. If the estimated biomass collapses (considered as the extinction of the resource) or exceeds the *k* value before the last year of the analyzed series, it is assigned a value of 0, while if it is included within the range of final status assumed λ_1 to λ_2, it is assigned number 1. The *r* and *k* pairs that were evaluated as 1 were chosen as viable Schaefer´s model parameters, which are compatible with catches and prior assumptions. The above procedure was performed using a macro of Excel. From each *r* and *k* values accepted, the MSY and B_{MSY} were estimated as

$$MSY = \frac{r*k}{4}, \qquad B_{MSY} = \frac{k}{2}$$

RESULTS

From jumbo squid catches recorded during 39 years in northwest Mexico (1974-2012), two distinct periods of development are observed. The first ranges from 1974 to 1994, with a maximum catch of 23,577 ton in 1980; the second is from 1995 to 2012, with a maximum catch of 121,016 ton in 1997 (Fig. 1).

Outputs from the Catch-MSY applied to jumbo squid are shown in Table 1. When prior *r* values were set from 1.0 to 2.0, the mean values of the parameters and management quantities were r = 1.23 yr^{-1}, k = 243,836 ton, MSY = 75,147 ton and B_{MSY} = 121,918 ton.

When a prior value of *r* was set in the range of 1.5 to 2.0, the mean value of parameters and management quantities were: r = 1.68 yr^{-1}, k = 190,468 ton, MSY = 80,098 ton and B_{MSY} = 95,234 ton. The values of *k* and B_{MSY} estimated with prior *r* values between 1.0 and 2.0 were 22% higher than those estimated with prior *r* values between 1.5 and 2.0. All valid *r* and *k* values output from the Catch-MSY shown a negative relation but without variation in *k* for each value of *r* (Fig. 2).The expected relationship was a broader range of *k* at low values of *r* and more reduced to high values of *r*,

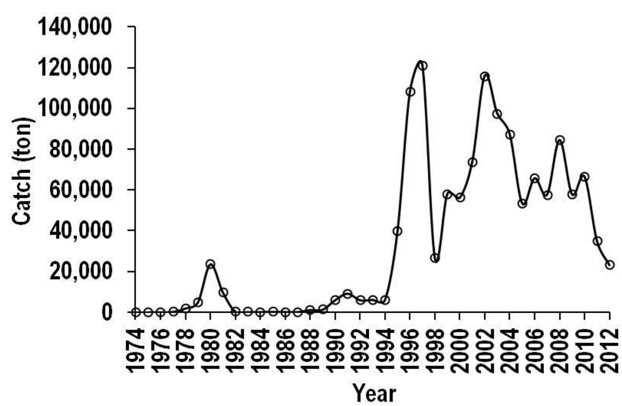

Figure 1. Catches of *Dosidicus gigas* in Mexico (1974-2012).

Table 1. Schaefer´s model (1954) estimated parameters, and management quantities (95% confidence interval), for *D. gigas*, with two prior *r* ranges.

Prior *r* ranges	*r*	*k*	MSY	B_{MSY}
1.0 to 2.0	1.23	243,836	75,147	121,918
	(0.88-1.72)	(186,785-318,314)	(70,185-80,460)	(93,392-159,157)
1.5 to 2.0	1.68	190,468	80,098	95,234
	(1.43-1.97)	(168,306-215,548)	(77,386-82,906)	(84,153-107,774)

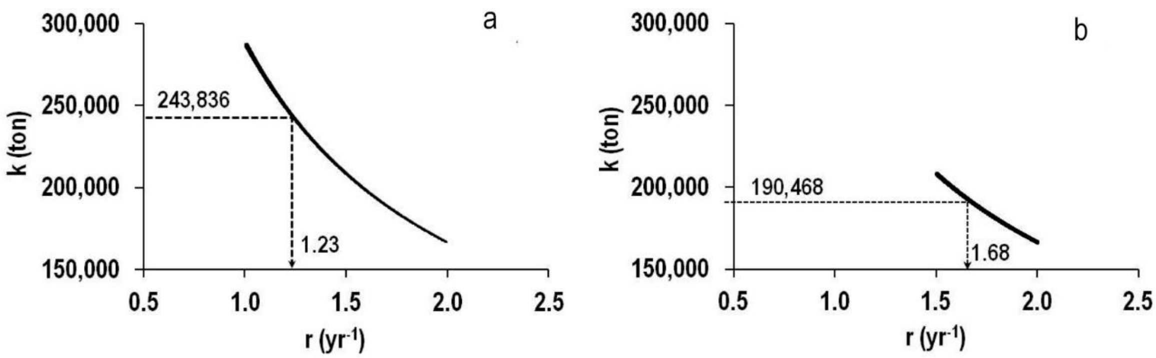

Figure 2. Valid *r*-*k* combinations outputs from Catch-MSY that are compatible with time series of jumbo squid catches using two prior ranges of *r* a) 1.0 to 2.0, and b) 1.5 to 2.0.

but surprisingly there is not much independent variation of the value of *r*, In fact the figure of the relationship between the viable *r* and *k* pairs estimated with a range of *r* prior from 1.5 to 2 is included in those obtained with a prior range of *r* from 1 to 2 and can be described with a power function as $k = 288046\ r^{0.796}$. Considering the extreme values of *r* reported in the bibliography for *D. gigas* (1.33, 1.76) this power function estimates a difference of MSY of only 4,500 ton (80814-76325) and 22,940 ton (114775-91834) in B_{MSY}.

The Schaefer's model (1954) when applied to the jumbo squid fishery in northwest Mexico, consistently explains the inter-annual fluctuations in commercial catches and stock biomass. It was shown that the strong decrease in the biomass between 1995 and 1998 was associated to the increased catches between 1995 and 2007, which far exceeded the MSY in the last two years (Fig. 3). Although between 1998 and 2002, the biomass to levels recovered to above the $B_{MSY,}$ catches from 2002 to 2004 exceeded the MSY again. After 2003, biomass began to decline steadily until 2012, when the level reached 0.2 *k* (Fig. 3).

DISCUSSION

Dosidicus gigas has biological qualities that make it a species with high resilience. These include high fertility (Nesis, 1970), maturity at a young age (Markaida, 2001) and a high intrinsic rate of population increase (Arkhipkin *et al.*, 2015; Csirke *et al.*, 2015). It is therefore considered a suitable candidate for the Catch-MSY to adjust the Schaefer's model from just capture data. Martell & Froese (2013) found that the MSY estimates obtained with this method are robust and consistent with estimates obtained with methods that demand more information and that this agreement increases for high resilience species. However, the Schaefer's model parameters (*r* and *k*) estimated by this method strongly depend on the lower prior limit of the *r*-value and therefore must be carefully established (Martell & Froese, 2013). In this work, prior *r* lower limits were set based on reported values for this species ranging from 1.33 to 1.76 (Arkhipkin *et al.*, 2015; Csirke *et al.*, 2015; Xu *et al.*, 2015). Thus, the estimated *r* values in this work (1.23 to 1.68 yr^{-1}) meet the Catch-MSY requirements, and the *r* y *k* estimates are considered robust.

A fully developed fishery is another requirement of the Catch-MSY because, in a developing fishery, or a fishery that has a continuous increase in catch, it will be more difficult to define the upper bound of k because the maximum potential has yet to be realized. Jumbo squid catches from 1974 to 2012 reveal that the jumbo squid fishery is fully developed, and productivity stock information is revealed from inter-annual catch variations.

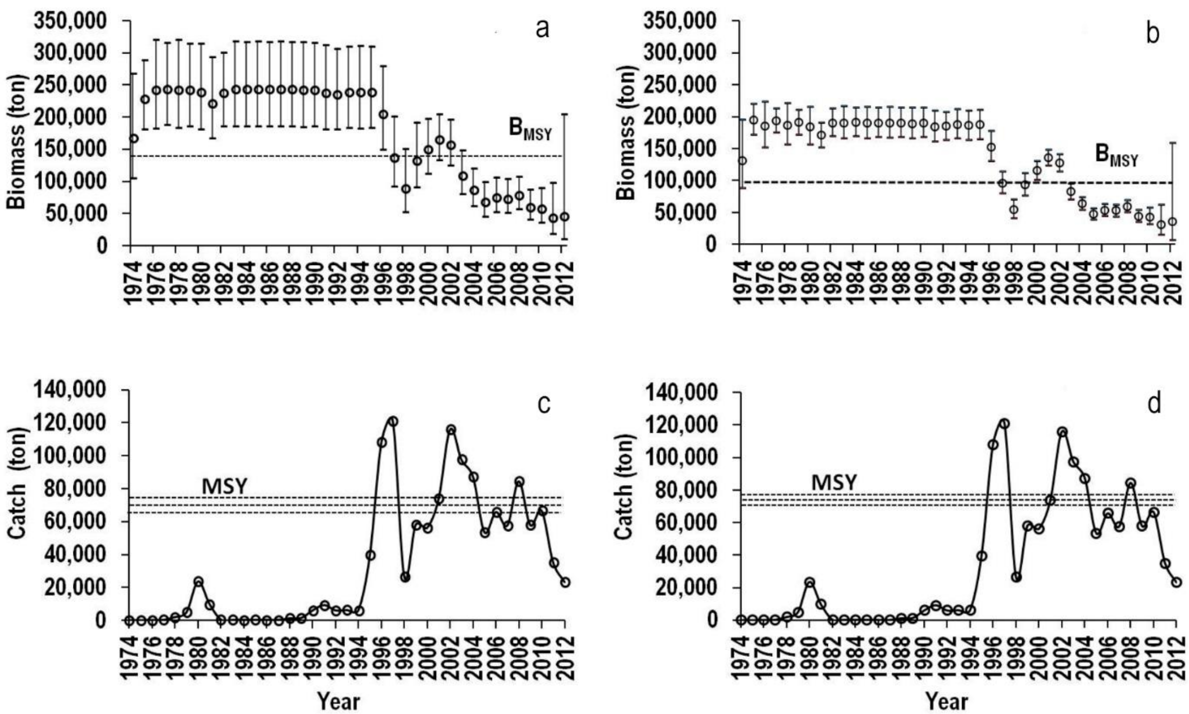

Figure 3. Inter-annual variation of estimated biomass (a and b) and catches (c and d) of jumbo squid in northwest Mexico using two prior ranges of *r* 1.0 to 2.0 (a and c) 1.5 to 2.0 (b and d). The B_{MSY} and MSY are shown with a dashed horizontal line as a reference.

Martell & Froese (2013) indicated that the *r* and *k* values compatible with catch data are inversely related with slope -1 on a logarithmic scale, but at the lower limit of *r* there is a wider range of possible *k* values. However, in this work, the *k* value range is very narrow for any *r* value, indicating a strong relationship between *r* and *k*.

High inter-annual variability of commercial catches of *D. gigas* in different areas of the eastern Pacific has been attributed to exogenous factors, mainly associated with El Niño and La Niña (Waluda *et al.*, 2006), without considering the dynamics of the resource. Organisms with a high intrinsic rate of population increase (*r*), such as the jumbo squid *D. gigas,* can show high inter-annual fluctuations in biomass as a result of population dynamics associated with density-dependent factors in addition to those due to environmental fluctuations (Haddon, 2011).

By 2012, the estimated jumbo squid biomass decreased below twenty percent of *k*, which could be the explanation for the catch collapse after 2012 and may have been a result of the depensatory effects at low levels of jumbo squid biomass and the deterioration of habitat quality in the Gulf of California from 2002 to 2012 (Robinson *et al*., 2014, 2016). However fishing also has played a role as after 2005, the stock biomass was already below the B_{MSY}, and catches in 2006, 2009 and 2010 exceeded the productivity of the stock, which explains the reduction in biomass and catches in 2011 and 2012. Catch falls observed in 1998 and 2003 are coincident with the strong El Niño 1997-1998 and moderate El Niño 2003-2004. However, to explain the observed catches, Schaefer's model estimates a biomass drop one year before these events, which is consequence also, of catches that exceeded the productivity of the stock in the periods 1995-1997 and in 2001-2003. Even the low catch of 2005 was preceded by three consecutive years of catches above the surplus yield which resulted in a drastic reduction of the biomass from 0.64 *k* in 2002 to 0.28 *k* in 2005. Robinson *et al*. (2016) explain drop of jumbo squid catches in the mid Gulf of California as consequence of winds speed decrease and chlorophyll-*a* concentrations, but both dropped drastically after strong El Niño 2009-2010, and biomass of jumbo squid stock started to decline from 2002 to 2012, a period with six years of catches exceeding surplus yield of jumbo squid stock. From above it is evident that fishing was an important factor in catch decline and the collapse of the fishery.

The MSY estimates obtained with this method are comparable to those obtained with more robust models although biomass is overestimated (Martell & Froese, 2013). Rodríguez-Domínguez *et al*. (2014) discussed that even with this biomass overestimation, Catch-MSY is useful to estimate biological reference points, such as B_{MSY}. When B_{MSY} is compared with current biomass, both are overestimated using Catch-MSY. These biases are deemed not important because what matters is their relative position. However, if Catch-MSY overestimates with 10% biomass, then biomass in 2012 would be even lower 0.2 k as predicted by Schaefer's model and this means a population even more susceptible to collapse.

Jumbo squid catches are concentrated in upwelling zones of high primary productivity and decreased chlorophyll-*a* often is related to commercial catch declines of this cephalopod (Robinson *et al*., 2013). This association assumes that a decrease in primary productivity may exert downstream impacts on higher trophic levels, affecting the availability of food for squid (Hoving *et al.*, 2013). However, during strong El Niño events in the Gulf of California, there have been increases in the abundance of secondary producers and even myctophids, which are the preferential food of jumbo squids (Jiménez-Pérez & Lara-Lara, 1988; Lavaniegos-Espejo *et al*., 1989; Valos-García *et al*., 2003; Sánchez-Velasco *et al*., 2004). The declining trends of jumbo squid catch and estimated biomass from 2002 to 2012 were coincident with an ascendant trend of small fish pelagic catches (CONAPESCA 2012), which are jumbo squid food species (Hoving *et al.*, 2013).

Jumbo squid population in the Gulf of California appears to respond to El Niño events with migrations and phenotypic plasticity. Squids move from their usual areas of high primary productivity to areas where tidal mixing dampens the effects of El Niño, and the phenotype of smaller mature individuals dominates the population, replacing the normally large-sized mature phenotype (Hoving *et al*., 2013). This behavior was observed during two strong El Niño events (1997-1998 and 2009-2010) in the Gulf of California, accompanied by a drastic decline in commercial catches, despite an increase in jumbo squid biomass, because the fishing gear used was not appropriate for catching small squid (Hoving *et al*., 2013). Variability in catchability rather than in biomass could be influencing the high inter-annual variability in commercial catches. Morales-Bojórquez *et al*. (2008) said that variability in the jumbo squid catch rate and therefore catchability could be explained by different aspects that involve the distribution and availability of the resource, possibly caused by ENSO affecting the California Current. Varying catchability (based on sea surface temperature) in the dynamic biomass model Arkhipkin *et al*. (2015) obtained a better fit for jumbo squid catch/effort data that assumed constant catchability.

Between the two strong El Niño events of 1997-1998 and 2009-2010, warm events occurred that were not classified as strong and jumbo squid remained in their usual areas and large-sized individuals dominated (Hoving *et al.*, 2013). However, in the same period, a drastic decline in biomass from 2002 to 2005 was observed as result of commercial catches exceeding the MSY. The hypothesis sustained here is that jumbo squid stock changes in availability due to migration from traditional fishing areas and the dominance of the small-sized mature phenotype during strong El Niño events is reflected in catch declines but has no impact on jumbo squid biomass. Biomass declines in the analyzed period were preceded by high commercial catches that exceeded the MSY. The population dynamics of *D. gigas* in northwest Mexico, as evaluated using Schaefer's model, explains the inter-annual catch variations and the collapse of the fishery at the end of the reporting period. The environment certainly has effects on the population dynamics of *D. gigas*, but their migratory behavior and phenotypic plasticity help avoid collapse at the population level, although catches could be adversely affected by catchability changes associated with the disappearance of the resource in traditional catch areas or the abundance of small sized-individuals not compatible with usually fishing gear used.

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