

Applying economic guidelines to manage the Red Octopus (*Octopus maya*) fishery in the Yucatán Peninsula via harvest control rules

Jesús Jurado-Molina^{1*}, Jessica Johana García-Meléndez²

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CORRESPONDING AUTHOR

* E-mail: jjurado@uw.edu

¹ Independent consultant, Mexico City, Mexico.

² Academia Químico-Biológicas y de la Salud, División Preparatoria, Universidad La Salle, 57205 Cuidad Nezahualcóyotl, Estado de México, Mexico.

ABSTRACT. We present a biomass-dynamic bioeconomic model that integrates economic aspects and guidelines for the management of the Red Octopus (*Octopus maya*) fishery, propose economic reference points, and incorporate economic considerations into harvest control rules (HCRs). This framework allows for the consequences of alternative management actions to be evaluated within a probabilistic context. To develop the biomass-dynamic bioeconomic model, we employed a framework based on the Gordon-Schaefer model (Gordon 1954) without assuming equilibrium (constant stock size). Instead of fishing effort, the proposed model includes the annual cost per ton and is formulated in terms of biomass. We also established economic reference points, including a limit point based on bioeconomic equilibrium and a target point based on net profit at maximum sustainable yield (Π_{MSY}). These reference points were incorporated into the HCRs, along with management actions that are triggered when the fishery approaches each threshold. A Kobe plot indicated that overfishing occurred between 2009 and 2012 and confirmed that the *O. maya* stock was overfished in 2013. Accordingly, the HCRs recommend reducing fishing mortality. The model projections suggested that harvesting at 90% of the fishing mortality at maximum sustainable yield (F_{MSY}) would allow biomass to recover to that at maximum sustainable yield (B_{MSY}) in the medium term. The median of the posterior distribution of the bioeconomic model for net profit in 2018 was estimated at MX\$428.8 million. The probability of the net profit being zero at a harvest rate of $0.9F_{MSY}$ was zero. Additionally, the probability that net profit was below Π_{MSY} in 2018 was 0.61.

Key words: Bayesian methods, biological reference points, biomass-dynamic bioeconomic model, economic equilibrium, harvest control rules, net profit, maximum sustainable yield, Red Octopus, Mayan Octopus, *Octopus maya*, Gordon-Schaefer model.

INTRODUCTION

One of the main components of fisheries management is the harvest strategy, which integrates monitoring, stock assessments, and harvest control rules (HCRs) (MSC 2016). Monitoring focuses on gathering data on fish stocks, fishing operations, and environmental conditions. In some cases, managers apply this information within passive management frameworks to establish seasonal closures or minimum size limits. In other cases, abundance data and single-species models are used to perform quantitative stock assessments. Among the elements of a harvest strategy, monitoring and stock assessments are the most widely implemented globally.

A third component, HCRs, introduces notable complexity to fisheries management.

Harvest control rules are operational and include pre-agreed rules or actions for managing responses to changes in stock status indicators for defined reference points. Thus, HCRs are a set of if-then rules specifying the circumstances leading to management responses (MSC 2016). Although some fisheries employ advanced management frameworks that incorporate HCRs, these rules are not explicitly presented in an if-then format within fisheries management plans or stock assessment reports (Barbeaux et al. 2023, Bryan 2023, Johnson et al. 2023). Other fisheries either omit HCRs from their strategies altogether or demonstrate a limited understanding of their

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intended function (DOF 2018, 2022a, 2022b). While many fisheries implement elements of a harvest strategy, such as monitoring, stock assessments, or HCRs, these components are not always fully or correctly implemented.

Some fisheries have made notable progress toward establishing ecosystem-based management frameworks (Barbeaux et al. 2023, Bryan 2023, Ianelli et al. 2023). However, these frameworks remain difficult to implement in many contexts due to high costs, limited data availability, and a shortage of qualified personnel. On the other hand, the integration of economic perspectives into fisheries management remains rare. To our knowledge, explicit economic analyses are not systematically incorporated into management decisions, even in highly developed fisheries (Barbeaux et al. 2023, Ianelli et al. 2023). This omission is notable, given that fisheries operate as economic enterprises and could benefit from economic optimization.

One possible reason why economic aspects are often excluded from fisheries management is the continued reliance on equilibrium models that assume constant stock size to estimate economic indicators for decision-making. Several fisheries do not maintain reliable records of fishing effort; thus, managers cannot apply the equilibrium methodology. This methodology does not provide direct uncertainty estimates for indicators or reference points. An approach proposed by Jurado-Molina et al. (2021) could partially solve this problem. However, it is desirable to integrate economic aspects within a framework that uses maximum likelihood estimation (MLE) and Bayesian methods. The question is how to incorporate MLE and Bayesian methods in bioeconomic models. What kind of data do we need? How can we build economic indicators and reference points? How can we modify HCRs to incorporate them into a management strategy?

To answer these questions, we extend the work of Jurado-Molina et al. (2021) to develop a biomass-dynamic bioeconomic model. We also propose economic reference points for HCRs to enhance a harvest strategy that uses economic aspects for decision-making. This approach enables fishery managers to evaluate alternative management actions within a probabilistic framework, directly supporting decisions that balance resource sustainability with the economic viability of a fishery.

We selected the Red Octopus (*Octopus maya*) fishery in the Yucatán Peninsula, Mexico, to evaluate our proposed model. *Octopus maya* is endemic to the Yucatán Peninsula, exhibits rapid growth, and possesses a short life cycle with a maximum age of 18 months (Hernández-Sánchez and De Jesús-Navarrete 2010). The *O. maya* fishery in the Yucatán Peninsula is the largest octopus fishery on the American continent, and detailed information on the biology, management, and bioeconomics of this fishing resource has been published (Solís and Chávez 1985; DOF 1994, 2014, 2016, 2019; Hernández-Sánchez and De Jesús-Navarrete 2010; Jurado-Molina 2010; Gómez 2016; Jurado-Molina et al. 2021).

MATERIALS AND METHODS

We developed a biomass-dynamic bioeconomic model to conduct stock assessments and generate projections under the proposed HCRs that was specifically designed for *O. maya* management. These rules serve as a decision-making framework that provides management guidance to adjust fishing mortality and relevant economic variables based on stock status and net profit predictions derived from assessments and short-term simulations.

The Schaefer (1954) biomass-dynamic model given in Eq. (1), which provides a parsimonious and widely applied framework for management-oriented analyses, was used to construct the biomass-dynamic bioeconomic model proposed in this study:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t, \quad (1)$$

where B_t is the biomass in year t , r is the intrinsic growth rate, K is the carrying capacity, and C_t is the annual catch. Model fitting assumed observation error in log-normally distributed annual abundance index predictions ($I_{obs,t}$) (Hilborn and Mangel 1997):

$$LL = \ln(\sigma) + \frac{\ln(2\pi)}{2} + \frac{[\ln(I_{pred,t}) - \ln(I_{obs,t})]^2}{2\sigma^2}, \quad (2)$$

where LL is the negative log-likelihood, σ is the standard error of the abundance index, and $I_{pred,t}$ is the predicted abundance index. The total negative log-likelihood is the sum of the n components. The absolute abundance index ($I_{obs,t}$) was obtained during the middle of the year (INAPESCA 2012); therefore, we obtained the predicted abundance index ($I_{pred,t}$) as follows:

$$I_{pred,t} = \hat{q} \frac{B_t + B_{t+1}}{2}, \quad (3)$$

where \hat{q} is the estimated catchability. The data used to fit the model included annual landings from 1998 to 2013 (INAPESCA 2013, 2014; DOF 2014). During this period, landings ranged from a minimum of 7,206 t in 2005 to a maximum of 20,138 t in 2006. Approximately 50% of the annual landings exceeded maximum sustainable yield (MSY), with most of these occurrences concentrated in the latter years of the time series (Fig. 1). According to Jurado-Molina (2010), landings represented between 30% and 76% of the estimated biomass. We also used the abundance index reported by the Mexican Institute for Sustainable Fisheries and Aquaculture Research (IMIPAS, for its Spanish acronym; formerly the National Institute of Fisheries [INP] and the National Institute of Fisheries and Aquaculture [INAPESCA]) for 2002–2007 (INP 2002, 2003, 2004, 2005, 2006, 2007), 2008 (INAPESCA 2008), and 2011–2014 (INAPESCA 2011, 2012, 2013, 2014). Optimization was conducted with the ‘optim()’ function in R v. 4.4.1 (R Core Team 2024).

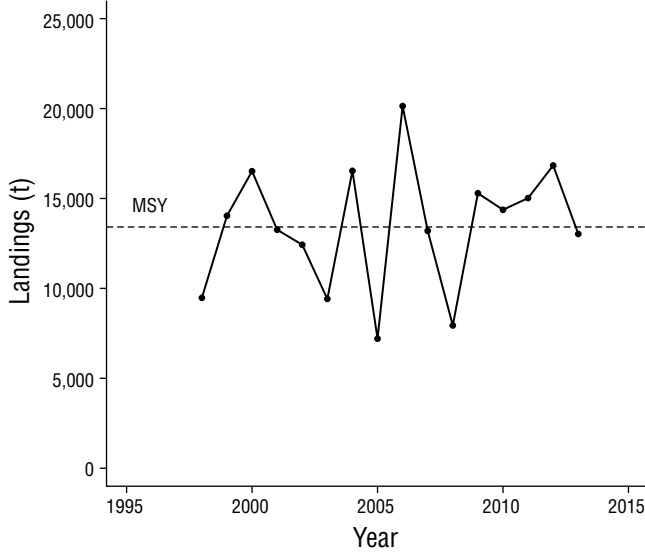


Figure 1. Annual variation in Red Octopus (*Octopus maya*) landings in the Yucatán Peninsula from 1998 to 2013. Maximum sustainable yield (MSY) is shown.

Using the Schaefer (1954) model, we calculated MSY, fishing mortality at MSY (F_{MSY}), and biomass at MSY (B_{MSY}) with Eq. (4), (5), and (6), respectively:

$$MSY = \frac{rK}{4}, \quad (4)$$

$$F_{MSY} = \frac{r}{2}, \text{ and} \quad (5)$$

$$B_{MSY} = \frac{K}{2}. \quad (6)$$

Using the estimated parameters and reference point derived from the Schaefer (1954) model, we constructed a Kobe plot to evaluate the stock status of *O. maya* in the final year of the assessment period. Stock status was evaluated in terms of relative biomass and fishing mortality ($\frac{B}{B_{MSY}}, \frac{F}{F_{MSY}}$). Based on this evaluation, the total allowable catch (TAC) for 2014 was calculated as follows:

$$TAC = JF_{MSY}B_{2013}, \quad (7)$$

where J is a multiplier ($J=0.9$), and B_{2013} is the biomass in 2013.

In the second step, we used the Gordon-Schaefer model (Gordon 1954) to develop a biomass-dynamic bioeconomic model. We modeled *O. maya* population dynamics with Eq. (1). The Gordon-Schaefer model (Gordon 1954) states that net profit depends on the difference between total income (TI) and total cost (TC). We used the same assumption in the proposed biomass-dynamic bioeconomic model that considered net profit (Π) defined as:

$$\Pi = TI - TC. \quad (8)$$

In the Gordon-Schaefer model (Gordon 1954), which assumes equilibrium (i.e., constant stock size), total sustainable income (TSI) depends on fishing effort (f):

$$TSI = C_{eq}P^* = qfK\left(1 - \frac{qf}{r}\right)P^*, \quad (9)$$

where C_{eq} is the equilibrium catch from the Schaefer (1954) model, P^* is the retail price per ton, q is fishery catchability, and f is the fishing effort measured as the number of fishing boats. As we did not assume equilibrium, the new biomass-dynamic bioeconomic model did not include total sustainable income but rather TI , defined as follows:

$$TI = C_tP^* = hB_tP^*, \quad (10)$$

where C_t is the annual catch, P^* is the retail price per ton, h is the harvest rate, and B_t is the biomass estimated with the Schaefer (1954) model. In the Gordon-Schaefer model (Gordon 1954), TC is defined as:

$$TC = C_{ship}f, \quad (11)$$

where C_{ship} is the cost per boat per season. Thus, in the Gordon-Schaefer model (Gordon 1954), Π depends on the fishing effort:

$$\Pi = qfK\left(1 - \frac{qf}{r}\right)P^* - C_{ship}f. \quad (12)$$

For the proposed biomass-dynamic bioeconomic model, TC was defined as:

$$TC = C_tC^* = hB_tC^*, \quad (13)$$

where C^* is the annual cost per ton. Thus, in the proposed biomass-dynamic bioeconomic model, Π depends on annual catch rather than fishing effort:

$$\Pi = C_tP^* - C_tC^* = hB_tP^* - hB_tC^* = hB_t(P^* - C^*). \quad (14)$$

As shown, this approach does not require an assumption of equilibrium (constant stock size). The key of the proposed biomass-dynamic bioeconomic model is calculating the annual cost per ton, which we obtained from anonymous, 20-question surveys. We used the survey data to calculate the average total cost per season (19.5 weeks), tons fished per season, annual cost per ton, sale price per ton, and standard errors of the last 2 variables. The proposed biomass-dynamic bioeconomic model relies on the Schaefer (1954) model and Eq. (1), (10), (13), and (14), as well as landings data (catch), the absolute index of abundance, the annual cost per ton, and the sale price per ton.

We used Bayesian methods based on Markov chain Monte Carlo and sampling-importance-resampling algorithms (Van Dijk et al. 1987, Rubin 1988, McAllister et al. 1994, McAllister and Ianelli 1997), assuming a uniform distribution for the K

and r parameters. We estimated the marginal posterior distribution, $Pr\{H_i|data\}$, for parameters and performance indicators following the methods of Hilborn and Mangel (1997):

$$Pr\{H_i|data\} = \frac{L\{data|H_i\}Prior\{H_i\}}{\sum_j L\{data|H_j\}Prior\{H_j\}}, \quad (15)$$

where L is the data likelihood given the hypothesis, and $Prior$ is the prior probability distribution of each hypothesis (parameter values) summarizing previous knowledge. Due to the lack of prior information on r and K for *O. maya*, we used non-informative uniform distributions for those parameters. We assumed $r \sim U(0.5, 1.7)$, $K \sim U(20,000, 90,000)$, $q \sim U(0.30, 1.3)$, and a fixed σ value (0.028); these distributions considered *O. maya* biological characteristics and previous research data (Jurado-Molina et al. 2021).

To assess stock status and implement HCRs, we used the proposed biomass-dynamic bioeconomic model to predict biomass, catch, and Π in the short term (2018) and medium term (2023). Based on the results from the stock assessment, we selected a smaller harvest rate ($0.9F_{MSY}$) instead of F_{MSY} in the projections. We also assumed a normal distribution for P^* and C^* , with the average and standard deviation calculated from the economic data obtained from interviews. We used random values from the K , r , q , P^* , and C^* distributions in the Schaefer (1954) model and Eq. (2), (3), (8), (10), (13), (14), and (15) to approximate the posterior distribution for r , q , K , and performance indicators. Posterior probability distributions were approximated in R v.4.4.1. A total of 90 million runs with a burn-in of 100,000 parameter vectors were conducted.

We proposed HCRs with a new economic component, and defined them as follows. The target reference point was B_{MSY} , which is the long-term average biomass if fishing at a constant fishing mortality rate that is equal to F_{MSY} (Wallace and Fletcher 2000). We proposed 20% of K as the limit reference point at which the fishery halts operations. We introduced a triggering reference point of 40% of K , where fishing mortality is reduced to avoid overfishing. We also defined a potential economic target reference point, the net profit at MSY, as follows:

$$\Pi_{MSY} = MSY(P^* - C^*) = \frac{rK}{4}(P^* - C^*). \quad (16)$$

Finally, we defined the economic equilibrium point (i.e., total income is equal to total cost) as a triggering reference point at which managers should take action to improve profit. The indicators were B_{2013} , biomass, catch, and Π in the short term (2018) and medium term (2023). We defined the HCRs as follows: (1) if the probability of biomass being less than 20% of K is $\geq 50\%$, then the fishery halts operations; (2) if the probability of biomass being less than B_{MSY} is $\geq 50\%$, then a program should be initiated to reduce fishing mortality; (3) if the probability of biomass being less than 40% of K is $\geq 50\%$, then a program should be initiated to reduce fishing mortality;

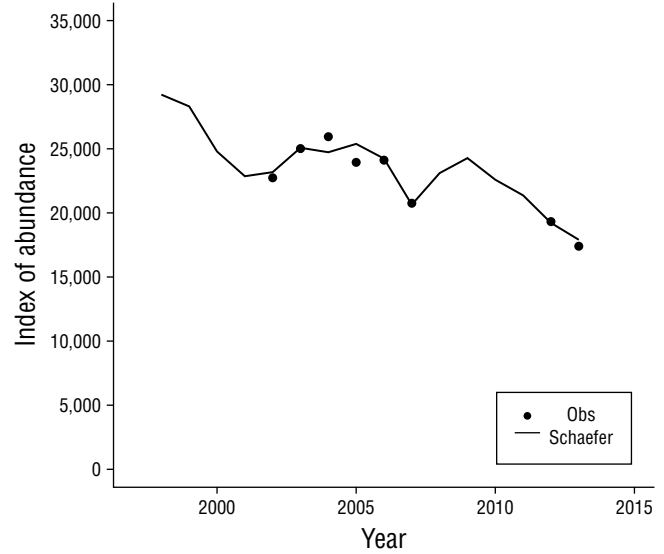


Figure 2. Model fitting to the Red Octopus (*Octopus maya*) observed absolute abundance index in the Yucatán Peninsula. Observed values (Obs); predicted Schaefer model.

and (4) if the probability of net profit being less than the economic triggering reference point (Π_{MSY}) is $\geq 50\%$, then fishers should act based on detailed productive analyses to improve profit. Thus, we conducted a stock assessment and simulations to assess stock status and net profit, and subsequently applied the HCRs.

RESULTS

The Schaefer (1954) model fit the observed data well (Fig. 2). The MLEs of the parameters and their associated uncertainty are shown in Table 1. Results from the Schaefer (1954) model with the MLE approach indicated that biomass exhibited noticeable variability, with an overall decreasing trend (Fig. 3). This downward trend was consistent from 2009 to 2014, with the final estimate falling below the target reference point of B_{MSY} (23,641 t). Based on the Kobe plot, overfishing occurred from 2009 to 2012, and the stock was overfished in 2013 (Fig. 4).

The fishery experienced overfishing in approximately half of the years analyzed (Fig. 4); the MSY estimate was 13,414 t. The results suggest the stock was overfished, and fishing mortality should be decreased according to the HCRs. Preliminary MLE projections suggested that fishing at 90% of F_{MSY} would allow the biomass to recover to the target reference point of B_{MSY} in the short term (by 2018). Accordingly, the TAC for 2014 was set at 10,669 t.

Developing the new biomass-dynamic bioeconomic model required collecting economic data. We conducted 13 interviews, calculated the annual cost per ton, and estimated an average value of $MX\$35,948.00 \pm 5,557.00$. The

Table 1. Maximum likelihood estimates of parameters of the Schaefer model (1954) for the Red Octopus (*Octopus maya*) population in the Yucatán Peninsula. Parameters: carrying capacity (K), intrinsic growth rate (r), percentage of K at the beginning of 1998 ($\%K$), catchability coefficient (q), and standard error (σ).

Parameter	Schaefer model
K (t)	48,952 ± 7,685
r (y^{-1})	1.10 ± 0.20
$\%K$	0.75 ± 0.50
q	0.82 ± 0.11
σ	0.03 ± 0.01
MSY ($t \cdot y^{-1}$)	13,414
B_{MSY} (t)	24,475

average retail price per ton was MX\$69,250.00 ± 2,295.00. Based on Eq. (16), Π_{MSY} was MX\$448,756,772.00.

The results from the Markov chain Monte Carlo projections were consistent with those from the MLE approach. The median of the posterior distribution for the intrinsic growth rate was 1.09 (95% credible interval [0.8, 1.38]) (Fig. 5a), and the probability of r falling between 1.028 and 1.268 was 0.496 (Fig. 5b). The median K was 48,380 t (95% credible interval [39,238 t, 63,371 t]) (Fig. 5c), and the probability of K being between 42,934 t and 53,622 t was 0.58 (Fig. 5d). The median q was 0.80 (95% credible interval [0.618, 0.983]) (Fig. 5e), and the probability of q falling between 0.771 and 0.904 was 0.46 (Fig. 5f).

The marginal posterior distribution indicated that the median biomass in 2013 was 21,420 t (95% credible interval [17,324 t, 28,331 t]) (Fig. 6a), and the probability of biomass falling between 19,000 t and 23,000 t in 2013 was 0.52 (Fig. 6b). Additionally, the probability that biomass in 2013 was below B_{MSY} (23,641 t [MLE]) was 0.76. According to the proposed HCRs, fishing mortality should be reduced to rebuild the stock toward B_{MSY} . In this scenario, implementing F_{MSY} or targeting MSY is not advisable, as it could further deplete the stock. However, the probability that biomass was below the limit reference point associated with impaired recruitment (9,456 t or 20% of K) was zero. Therefore, there was no need to halt fishery operations.

For projections, we did not use F_{MSY} or MSY; instead, we reduced the harvest to 90% of F_{MSY} . Results under this fishing mortality level suggest that the median of the marginal posterior distribution for biomass in 2018 was 25,569 t (95% credible interval [23,516, 26,506 t]) (Fig. 7a). The probability that the biomass in 2018 was below B_{MSY} was 0.04 (Fig. 7b).

The median of the 2018 catch distribution was 13,141 t (95% credible interval [12,022 t, 13,560 t]) (Fig. 7c). The probability that the 2018 catch fell between 12,920 t and 13,320 t was

0.59, and the probability of the 2018 catch being below MSY was 0.95 (Fig. 7d). The median of the marginal posterior distribution for net profit in 2018 was MX\$428.8 million (95% credible interval [MX\$274.0 million, 584.6 million]) (Fig. 7e). The probability of net profit falling between MX\$350 million and MX\$462 million was 0.504, and the probability of net profit being zero at a harvest rate of $0.9F_{MSY}$ was zero. The probability that net profit in 2018 was below Π_{MSY} was 0.61 (Fig. 7f). The results in the short term (2018) and medium term (2023) were similar (Table 2).

DISCUSSION

Fisheries management has traditionally relied on single-species models. However, fisheries also affect ecosystems and constitute economic activities. Therefore, managers should incorporate both ecosystemic and economic considerations into fisheries management. Implementing these additional aspects presents several challenges and requires personnel with multidisciplinary expertise, as well as expanded monitoring programs and increased budgets. In particular, managers could incorporate economic considerations into the *O. maya* fishery due to its high market value and profitability. This species presents a unique opportunity to fully implement key components of a harvest strategy, such as clearly defined objectives, monitoring, stock assessments, and HCRs. Within this framework, managers could establish economic guidelines to support decision-making.

One of the main challenges in achieving this type of management is the reliance on the equilibrium assumption of constant stock size in the Gordon-Schaefer model (Gordon 1954). We have presented an alternative approach to overcome

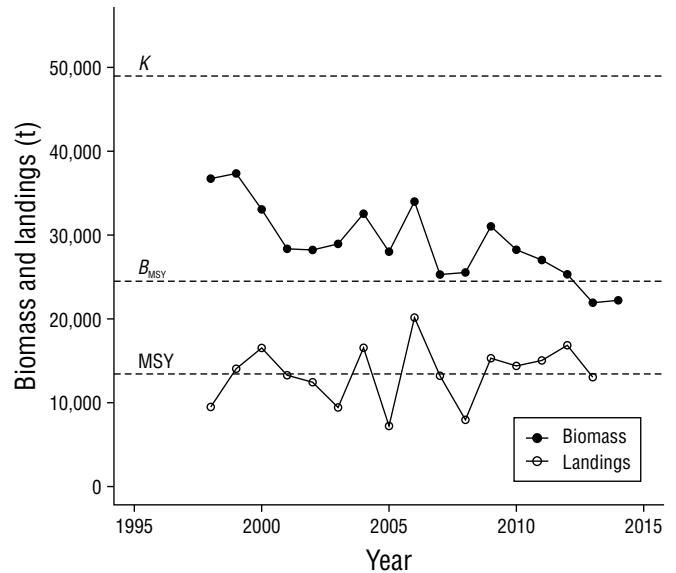


Figure 3. Temporal trend of Red Octopus (*Octopus maya*) biomass and landings in the Yucatán Peninsula. Carrying capacity (K); biomass at maximum sustainable yield (B_{MSY}); maximum sustainable yield (MSY).

Table 2. Results of the projections for the indicators in the medium term (2023).

Indicator	Projection estimates in the medium term
Median of the B_{2023} marginal distribution	25,710 t
95% credible interval	(23,351 t, 26,777 t)
$P(B_{2023} < B_{MSY})$	0.041
Median of the C_{2023} marginal distribution	13,201 t
95% credible interval	(11,853 t, 13,685 t)
$P(C_{2023} < MSY)$	0.928
Median of the Π_{2023} marginal distribution	MX\$428.5 million
95% credible interval	(MX\$273.3 million, MX\$584.9 million)
$P(\Pi_{2023} < \Pi_{MSY})$	0.63

this limitation and incorporate economic guidelines within the current fisheries management framework. We begin by reviewing key aspects of stock assessments and management from a single-species perspective, followed by an examination of economic components.

The National Commission for Fisheries and Aquaculture (CONAPESCA, for its Spanish acronym) and IMIPAS have established objectives related to sustainability and environmental protection (DOF 1993, 2014). IMIPAS also conducts annual monitoring of *O. maya* abundance to generate an absolute index of abundance. This index, along with landings data, are used to assess stock status and determine the annual harvest quota (DOF 2023).

To our knowledge, *O. maya* management in Mexico focuses on sustainability through the use of quotas, fishing permits, gear restrictions, fishing closures, and minimum size regulations. However, IMIPAS and CONAPESCA have not established HCRs for this fishery. In one of the most recent agreements published in the Official Journal of the Federation (DOF 2023), IMIPAS defined the annual quota for the fishery, without referencing the use of HCRs or its current stock status. Similarly, the National Fisheries Charter of Mexico and various national standards (NOM-009-PESC-1993, NOM-034-SCT4-2009, NOM-064-SAG/PESC/SEMARNAT-2013, and NOM-008-SAG/PESC-2015) do not include information on HCRs.

A clear understanding of stock status is essential for determining whether fisheries are experiencing overfishing or are overfished. Managers use this information to implement HCRs and set the harvest levels for the following year, including annual quotas. However, these 2 key indicators of unsustainable practices (e.g., overfishing and overfished statuses) are not included in IMIPAS stock assessments (DOF 2022b, 2023). When an overfished status is identified, managers implement HCRs to reduce fishing mortality. According to our results, this approach allows biomass to recover and reach a target reference point within the medium term.

Another critical issue in the *O. maya* fishery is the lack of effective quota enforcement. Overfishing occurred from 2009 to 2012, resulting in an overfished status in 2013. Despite this, the authorities lacked a monitoring mechanism to halt fishing operations once the annual quota was reached. In several years, landings exceeded the established quotas. For example, landings were 78.7%, 86.6%, and 68.4% above the quotas in 2006, 2009, and 2012, respectively (INAPESCA 2014). In practice, the fleet has continued to operate until the end of the fishing season, regardless of whether the annual quota has been exceeded. This situation effectively resembles an open-access regime, with potential negative consequences, including overfishing and eventual stock collapse.

To prevent exceeding the annual quota, managers require an enforcement system that includes monitoring. Such a system would allow timely closures of the fishing season once the quota is met. A useful model is the system that has been implemented for the Gulf Corvina (*Cynoscion othonopterus*) fishery in the northern Gulf of California (IAES 2014). Given the catch variability observed in the *O. maya* fishery and the

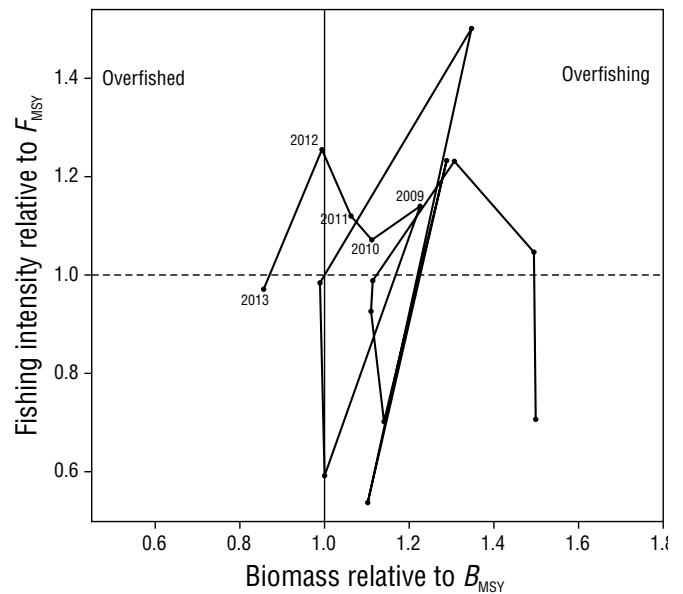


Figure 4. Kobe plot for the stock status of the Red Octopus (*Octopus maya*) in the Yucatán Peninsula. Biomass at MSY (B_{MSY}); fishing mortality at maximum sustainable yield (F_{MSY}).

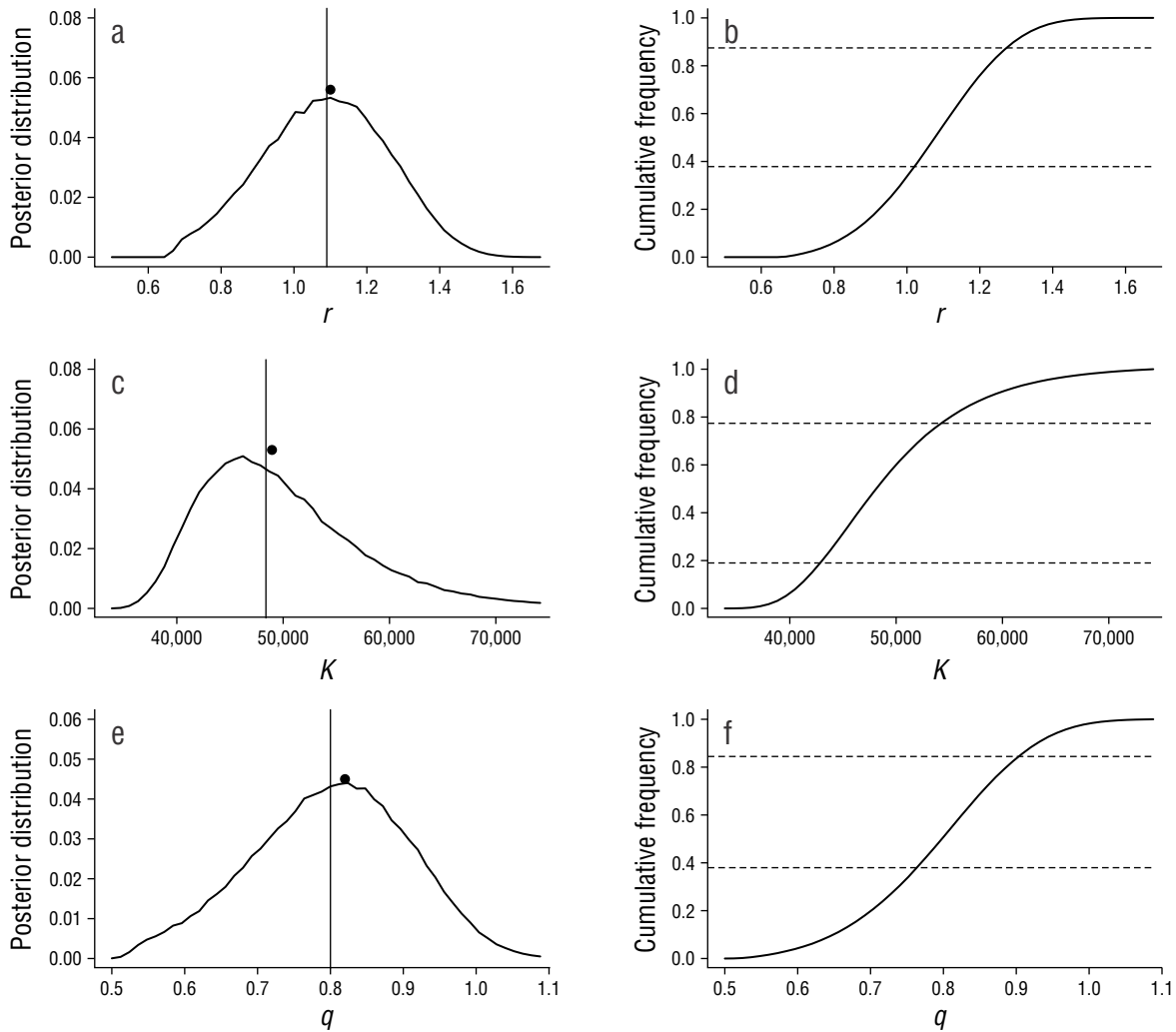


Figure 5. Marginal posterior distribution of the intrinsic growth rate (r) for the Schaefer model (Schaefer 1954) for the Red Octopus (*Octopus maya*) in the Yucatán Peninsula (a), cumulative distribution of the intrinsic growth rate (b), marginal posterior distribution of the carrying capacity (K) (c), cumulative distribution of K (d), marginal posterior distribution of the catchability (e), cumulative distribution of the catchability (f). Black dots indicate the maximum likelihood estimate; vertical lines indicate the median of the distribution.

lack of effective quota enforcement, it may be advisable to introduce an additional regulation, namely a maximum 15% change rule, that constrains annual quota adjustments to $\leq 15\%$. Similar measures have recently been implemented in the Pacific Halibut (*Hippoglossus stenolepis*) and Sablefish (*Anoplopoma fimbria*) fisheries (Ehresmann and Olson 2021) to reduce catch variability. These types of regulations have improved fishery stability, maximized catch, and successfully achieved biological goals in long-term simulations conducted by the International Pacific Halibut Commission (Ehresmann and Olson 2021).

Thus, we propose a single-species management framework that incorporates landings data, an index of absolute abundance, a stock assessment model, biological reference points, and HCRs for the *O. maya* fishery in the Yucatán Peninsula. Additionally, we recommend incorporating a mechanism to

prevent exceeding the annual quota, as well as a maximum 15% change rule to limit interannual catch variability. This approach will support the sustainable exploitation of *O. maya* and provide a foundation for incorporating economic guidelines into the management of this resource.

Current regulations aim to protect reproduction through minimum size limits and season closures and to control fishing effort by issuing permits. However, the existing regulatory framework does not incorporate economic objectives that could promote efficiency or equity in the fishery (Jurado-Molina et al. 2021). One possible reason for this gap is the lack of adequate quantitative tools for economic assessment. In this type of analysis, researchers commonly use the equilibrium Gordon-Schaefer model (Gordon 1954) to estimate net profit and the economic equilibrium point as a function of fishing effort. However, in the *O. maya* fishery,

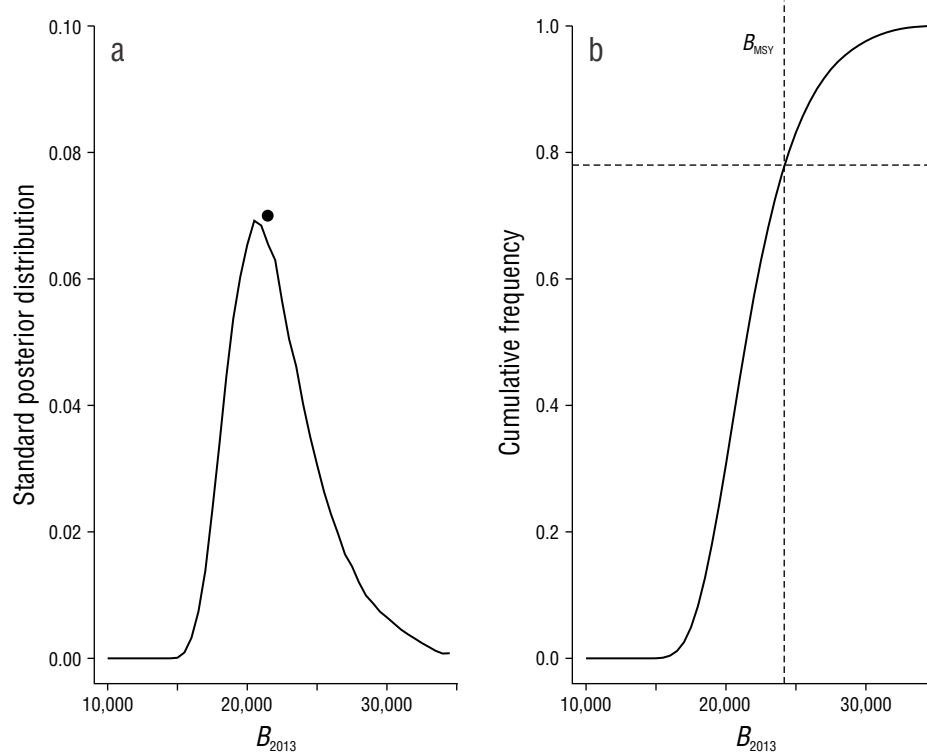


Figure 6. Marginal posterior distribution of the biomass in 2013 (a). Cumulative distribution of Red Octopus (*Octopus maya*) biomass in 2013 in the Yucatán Peninsula (b). The black dot indicates the median of the distribution; the vertical line indicates the biomass at maximum sustainable yield (B_{MSY} ; target reference point).

accurately recording fishing effort, which is typically measured by the number of operating boats, remains challenging. Since 2012, authorities have issued 5,444 permits for artisanal fishing vessels (INAPESCA 2012; DOF 2014, 2018). Nevertheless, annual assessment reports do not include the fishing effort data for each fishing season, making it difficult to apply the Gordon-Schaefer model (Gordon 1954) effectively. Another challenge stems from how fishing effort is quantified. For a more realistic approach, managers should characterize fishing effort in terms of the number of *jimbas* (bamboo poles with attached lines and hooks) or hooks used. This information should be reported in the mandatory logbooks.

The main limitation of the Gordon-Schaefer model (Gordon 1954) is its reliance on the equilibrium assumption. In the case of the *O. maya* fishery, the stock is clearly not in equilibrium. As noted by Hilborn and Walters (1992), equilibrium methods should be avoided in fisheries assessments. For declining stocks, the equilibrium assumptions in surplus-production models lead to a consistent overestimation of sustainable yield. Following this logic, an earlier Gordon-Schaefer analysis of the *O. maya* fishery (Jurado-Molina et al. 2021) may be similarly biased. However, it serves as a preliminary step toward developing more complex models, such as the one proposed in the present study. Our proposed approach does not rely on an equilibrium assumption and incorporates the aforementioned single-species framework, along

with economic data collected from surveys of fishers and permit-holders.

Determining stock status enables managers to take action through HCRs when the stock deviates from or approaches a specific reference point. In general, the recommended response is to reduce fishing mortality. In the case of the *O. maya* fishery, the stock was overfished in 2013; therefore, the harvest rate should have been reduced to $0.9F_{MSY}$. Our projection results, under a harvest rate of $0.9F_{MSY}$, suggest that the biomass would have recovered in the medium term (by 2018) and reached the target reference point. However, net profit in 2018 remained below Π_{MSY} , although it was still far from the economic equilibrium point (i.e., total income is equal to total cost). This finding contrasts with the results from the Gordon-Schaefer model (Gordon 1954), which suggested that the fishery was near economic equilibrium (Jurado-Molina et al. 2021).

If net profit is below Π_{MSY} , the HCRs suggest that fishers should take action based on detailed productive and financial analyses to improve profitability. These actions may include reviewing financial statements (e.g., revenue, costs, and cash flow), reducing variable and fixed costs, improving operational efficiency, increasing revenue through pricing strategies and customer base expansion, evaluating the business model (including the service portfolio and market trends), and managing debt. At this stage, increasing profit by increasing

catch is not a viable option for managers, as doing so could compromise stock sustainability. However, managers and fishers should keep in mind that this result arises from the implementation of a constant harvest rate policy.

In 2018, the harvest rate was set at $0.9F_{MSY}$, which resulted in a catch below MSY. Nevertheless, since biomass in 2018 was close to the target reference point, the 2019 harvest rate could have been allowed to increase to F_{MSY} . Consequently, both the catch and net profit would have been expected to increase. IMIPAS and CONAPESCA should implement this adaptive approach each year to allow harvest levels to increase (subject to a maximum 15% rise) when stock status improves earlier than expected, thereby enhancing profitability while maintaining sustainability.

Predicting future catches enables the estimation of future net profit using economic data. The key information required to convert the Schaefer (1954) model into a biomass-dynamic

bioeconomic model includes the annual average cost per ton of catch, the average catch price per ton, and their uncertainties. These values allow us to move beyond the equilibrium assumption. Our analysis is based on catch and biomass data from 1998 to 2013, sourced from official public reports (INP 2002, 2003, 2004, 2005, 2006, 2007; INAPESCA 2008, 2011, 2013, 2014; DOF 2014). Extending this dataset is challenging for several reasons. First, the official annual landing statistics from CONAPESCA (2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2024) combine data of *O. maya* and the Common Octopus (*Octopus vulgaris*), making them unsuitable for species-specific stock assessments. Second, the only updated biomass survey available corresponds to 2014 (INAPESCA 2014) and requests for species-disaggregated data from CONAPESCA require extended wait periods. Therefore, our projections to 2018 and 2023 are simulation-based. Nevertheless, our primary

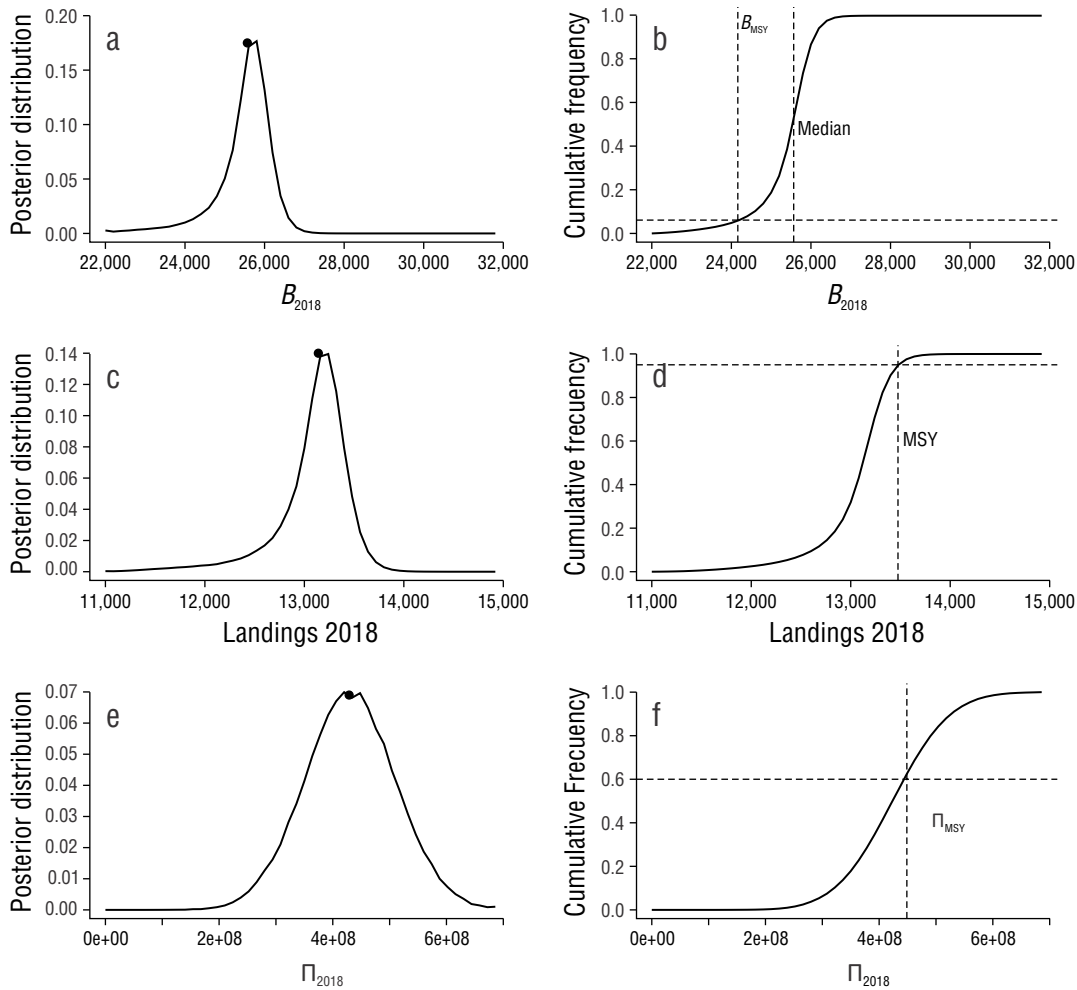


Figure 7. Marginal posterior distribution of the biomass in 2018 (a). Cumulative distribution of the biomass in 2018. Dashed vertical line indicates maximum sustainable yield (MSY) (b). Marginal posterior distribution of the catch in 2018 (c). Cumulative distribution of the catch in 2018 (d). Marginal posterior distribution of the net profit in 2018 (e). Cumulative distribution of the net profit in 2018. Dashed vertical line indicates net profit at MSY (Π_{MSY}) (f). Black dots indicate the medians of the distributions.

objective was to propose a novel methodology for integrating economic and biological reference points. For direct and validated management applications, updated species-specific data are needed.

The economic parameters were estimated from a limited number of interviews conducted during the COVID-19 pandemic, which imposed substantial constraints on data collection, including a reluctance of fishers and boat captains to share private and confidential economic data. As a result, uncertainty in cost and price estimates may have influenced the absolute values of economic reference points. Nevertheless, the primary aim of the present study was to evaluate the relative performance of alternative HCRs within a bioeconomic management framework, rather than to estimate precise economic returns. Relative comparisons among management strategies are generally more robust to uncertainty in absolute parameter values. Future work should incorporate expanded economic datasets and formal sensitivity or uncertainty propagation analyses to assess the robustness of the economic reference points. Improving the quality of economic data requires building collaborative relationships with fishers and boat captains so they understand the value of their contributions to fisheries management. Strengthening this cooperation will help improve both the quantity and quality of economic data for future model implementations.

Although environmental variability, particularly in temperature, is known to influence the growth, reproductive biology, distribution, and physiological condition of *O. maya* (Vargas-Abúndez et al. 2023), explicit environmental or ecological covariates were not included in the present analysis. This study focused on evaluating the performance of HCRs under economic management objectives using stock status indicators commonly applied in fisheries management that reflect the combined effects of fishing and environmental variability observed in the data (Brunel et al. 2010). Incorporating explicit environmental drivers would require additional assumptions regarding their mechanistic links to population and economic dynamics; therefore, this is left for future research extending the proposed bioeconomic framework toward a fully ecosystem-based management approach.

The biomass-dynamic bioeconomic model offers several advantages over the Gordon–Schaefer model (Gordon 1954). Although the model relies on the same fundamental economic relationship (Eq. 8), it does not assume equilibrium. Instead, the biomass-dynamic bioeconomic model is strongly dependent on the average annual cost per ton of catch. This parameter enables the model to be formulated in terms of biomass and catch, rather than fishing effort, thereby allowing the use of a wider range of tools for fisheries management.

CONCLUSIONS

The development of our biomass-dynamic bioeconomic model did not rely on an equilibrium assumption or fishing effort data. Instead, we used cost-per-ton estimates for each

fishing season that were obtained through surveys with fishers and permit holders. Within this framework, we defined the reference points used in the HCRs for the *O. maya* fishery of the Yucatán Peninsula, particularly Π_{MSY} and economic equilibrium. We also specified management actions when either biomass or net profit approached these reference points. The proposed methodology could facilitate the certification of the *O. maya* fishery by the Marine Stewardship Council and provides valuable guidance for the sustainable and profitable management of this fishery, which may be applied to other fisheries.

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Supplementary Material

This work includes no supplementary material.

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Conflict of interest

The authors declare they have no conflict of interest.

Author contributions

Conceptualization: JJM; Data curation: JJGM; Formal analysis: JJM; Investigation: JJM, JJGM; Methodology: JJM, JJGM; Project administration: JJGM; Software: JJM, JJGM; Supervision: JJM, JJGM; Visualization: JJM; Writing—original draft: JJM; Writing—review & editing: JJM, JJGM.

Data availability

The data for this study are available from the corresponding author by reasonable request.

Consent for participation and publication for studies involving people

This study was conducted with the informed consent of all participants; informed consent was also obtained from the participants for the publication of the results.

Use of AI tools

The authors, who are responsible for the content of this publication, employed Grammarly to improve grammar.

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