SCIENTIA MARINA 87(3)
September 2023, e071, Barcelona (Spain)
ISSN-L: 0214-8358
https://doi.org/10.3989/scimar.05335.071

Co-management of a high-value species with territorial use rights for fisheries: a spatial bioeconomic approach with environmental variability

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Summary: Abalone is a high-value resource that is an important export market fishery of Mexico that is managed through territorial use rights for fisheries allocated to a coastal community. A specific age-structured spatial bioeconomic model was applied to this fishery to undertake stock recovery to target levels. The model incorporates uncertainty in the parameter *k* of a von Bertalanffy growth function with environmental variability. The risk of falling below and exceeding the target and bioeconomic limit reference points of the population with alternative fisheries management strategies was studied using a Monte Carlo analysis. The management strategy evaluation showed that E_{min} (minimum effort) and E_{maxNPV} (resource rent maximization effort) generated higher biomass levels and higher present value of resource rent than E_{msy} (effort in maximum sustainable yield) at the end of the simulation period, regardless of the bioeconomic reference points and assuming a reduction in fishing effort. E_{min} and E_{maxNPV} increased and maximized the present value of resource rent generated by the species while avoiding its overexploitation. The social consequences of the management strategies were considered with the participation of fishers of this co-managed fishery.

Keywords: abalone; spatial bioeconomic model; management strategy evaluation; climate change; uncertainty.

Co-manejo de una especie de alto valor con derechos de uso territorial para la pesca: un enfoque bioeconómico espacial con variabilidad ambiental

Resumen: El abulón es un recurso de alto valor que constituye un importante mercado de exportación pesquera en México, gestionado a través de derechos de uso territorial para la pesca (TURF) asignados a una comunidad costera. Se aplicó un modelo bioeconómico espacial específico estructurado por edades a esta pesquería para llevar a cabo la recuperación de las poblaciones hasta niveles objetivos. El modelo incorpora la incertidumbre en el parámetro *k* de la Función de Crecimiento de von Bertalanffy con variabilidad ambiental. Se realizó un análisis de Monte Carlo para evaluar el riesgo de caer por debajo o superar los puntos de referencia bioeconómicos objetivo y límite de la población con estrategias alternativas de manejo pesquero. La evaluación de las estrategias de manejo mostró que E_{min} (esfuerzo mínimo) y E_{maxNPV} (maximización de la renta que genera el recurso) en comparación con E_{msy} (esfuerzo en el rendimiento máximo sostenible) son estrategias que generan niveles de biomasa más altos y un mayor valor presente de la renta que genera el recurso al final del período de simulación. Independientemente de los puntos de referencia bioeconómicos, las estrategias que presentaron las mejores condiciones fueron E_{min} y E_{maxNPV}, asumiendo una reducción en el esfuerzo pesquero, aumentando y maximizando el valor presente de la renta del recurso generado por la especie al evitar su sobreexplotación. Se consideraron las consecuencias sociales de las estrategias de manejo con la participación de los pescadores de esta pesquería co-gestionada.

Palabras clave: abulón; modelo bioeconómico espacial; evaluación de estrategias de manejo; cambio climático; incertidumbre.

Citation/Como citar este artículo: Vargas-López V.G., Arreguín-Sánchez F., Gutiérrez-González J.L., Seijo J.C. 2023. Co-management of a high-value species with territorial use rights for fisheries: a spatial bioeconomic approach with environmental variability. Sci. Mar. 87(3): e071. https://doi.org/10.3989/scimar.05335.071

Editor: K. Hamon.

Received: September 2, 2022. **Accepted:** May 26, 2023. **Published:** September 20, 2023.

INTRODUCTION

Conventionally, fisheries management has been given a monospecific and biological approach based on the effect of fishing on the population dynamics of a target species (Ulrich et al. 2002, Lewy and Vinther 2004, Kell et al. 2006), without considering that fisheries management is regularly characterized by multiple objectives, which include a range of environmental, social and economic factors (Erisman et al. 2011, FAO 2018, Hilborn 2011).

In addition, some fisheries have been commercially exploited above the maximum sustainable yield level, thus leading to a depletion in stock renewal (FAO 2018, Martinet et al. 2007). This is the case of *Haliotis corrugata* W. Wood, 1828, an abalone from the western region of the Baja California Peninsula. *H. corrugata* is a gastropod mollusc that inhabits the area from the intertidal zone to rocky reefs up to 27 m deep. This species is one of the mainstays of the abalone fishery in Mexico, which dates back to the 19th century. This activity operates through territorial use rights for fisheries (TURFs), by which groups are granted exclusive privileges to fish in geographically designated fishing grounds. Since 1996, the National Fisheries Institute (INAPESCA) has managed this fishery based on catch quota recommendations determined by a risk analysis of two reference points derived from the dynamic biomass model (Muciño Díaz et al. 2000); however, the stock has not been satisfactorily recovered. There are many hypotheses on the causes of this depletion in the stock, including overfishing, illegal and unregulated fishing or a combination of these factors (Castro-Ortiz and Guzmán del Próo 2018, Gutiérrez-González 2012, Ponce-Díaz 2008).

Therefore, since 2017, the fishery has had a moratorium under an agreement between the resource users and the fishery managers. Recent population assessments indicate a slight recovery of the stock, perhaps favoured by zero fishing mortality and non-high variable environmental conditions; after the regime change in the mid-1970s, there have been no recent strong El Niño or La Niña events that affect the benthic community by decreasing the availability of food (Castro-Ortiz and Guzmán del Próo 2018, Guzmán del Próo et al. 2003).

Models based only on time-dynamic assumptions are not suitable for the low-mobility abalone, because this species does not fulfil model assumptions of 1) homogeneous distribution, 2) perfectly mixed ages, 3) uniformly applied fishing effort, and 4) ability of abalone to redistribute according to 1 and 2 after the fishing effort has been applied. To avoid overestimating the productive potential of the stock, it is necessary to consider that not only the fishing effort but also the abundance of organisms (patchy distribution), their size and their age structure are heterogeneous. Therefore, management strategies should be based on a spatial age-structured bioeconomic model (Anderson and Seijo 2010, Sanchirico and Wilen 1999, Seijo and Caddy 2008).

The yellow abalone fishery and its co-management were taken as a case study to solve the above assumptions. This fishery is characterized by a collective TURF for extraction, capture and commercial exploitation with co-management strategies based on a variable annual catch quota per species and fishing zone, each with economic consequences. The management strategies established in the law are as follows: effort control at maximum sustainable yield; minimum catch size per species and fishing zone; fixed temporary reproductive closure per zone; regulation of fishing gear and methods; and estimated reference points based on management objectives (DOF 1993, 2018).

Concerning bioeconomic and ecological-economic fisheries models, in a review of 35 models used worldwide Nielsen et al. (2018) suggest that stakeholders should be involved in considering alternative management strategies and understanding the relevant elements of the fishery under study. It is also important to present results understandably to the fishing community and fisheries managers.

It is therefore imperative to analyse the fishery through management strategy evaluation (MSE) (Amar et al. 2008, Hoshino et al. 2012, Nielsen et al. 2018, Punt et al. 2016), considering a more suitable model to determine the rate of exploitation required to achieve the target and limit bioeconomic reference points. An age-structured dynamic spatial bioeconomic model was developed to evaluate alternative management strategies to allow the stock to recover to a target level, incorporating risk and uncertainty determined by environmental variability associated with climate change. In addition to evaluating management strategies, it is essential to take up the approach and analysis conducted by Caddy and Seijo (1998) regarding the rationale behind rotating harvest schemes for stocks where dynamic pool assumptions are inappropriate. The rotational harvest schemes are frequently used in fisheries management of sessile or sedentary stocks to give some specified level of stock protection and help alleviate the effect of growth and recruitment overfishing (Caddy 1993, DEEDI 2011, Kewes et al. 2014). The present study aims to answer the following research questions: 1) Is any alternative management strategy more likely to meet the biological and economic objectives? (2) Given the prevailing environmental variability, what is the risk of falling below target and limit reference points?

MATERIALS AND METHODS

Spatial bioeconomic model

Management strategies were evaluated using a spatial bioeconomic model (SBEM) (Anderson and Seijo 2010, Seijo and Caddy 2008). This model simulates the dynamics of an age-structured population with a heterogeneous distribution for a single species: *H. corrugata*. The distribution area of the stock was divided into 625 cells in a 25×25 array, each covering an area of 0.25 km^2 for a total of 156 km^2. The spatial distribution of stock abundance was obtained through the assessments in the fishing banks from 2000 to 2017 carried out by the National Fisheries Institute (INAPESCA).

This database contains the number of organisms per 50 m^2 transect (sample unit), geographically georeferenced using a global positioning system. The database has 21576 vectors, with the following information: Year, Abundance (Number of organisms), Zone, X-coordinate and Y-coordinate (INAPESCA 2019). To represent and compare a continuous spatial density for the year in which the historical series begins (2000) and the year in which the moratorium starts (2017), the inverse distance weighted (IDW) interpolation method was applied through a geographic information system (QGIS.org 2022).

The commercial catch was included in the model through a database that incorporates the number of organisms captured, thus generating a specific spatially explicit harvest matrix from the year 2000 to the year 2017. The *H. corrugata* harvest database has 35513 vectors, with the following information. Year, Zone, Subzone, X-coordinate, Y-coordinate and number of organisms captured (Progreso 2020).

The growth parameters incorporating environmental variability and the 17 ages (species longevity) to be considered in the spatial model correspond to *H. corrugata* on the north Pacific coast of Mexico. Parameters are taken from Vargas-López et al. (2021). The model functions and parameters are presented in Table 1. The heterogeneous distribution in spatial recruitment was modelled using the recruitment function of Beverton

Table 1. – Parameters of the SBEM of *H. corrugata*.

Parameters	Symbol	Value	Unit of measurement	Source
Maximum age of species	λ	17	years	1
Age at first maturity		5	years	1
Age at first capture		5	years	1
Parameter t_0 of the growth equation	t_0	-0.55	proportion	1
Natural mortality coefficient	M	0.37	$year^{-1}$	2
Parameter *k* of von Bertalanffy growth equation	k	0.35	$year^{-1}$	1
Maximum length	L_∞	15.1	cm	1
Maximum weight	W_∞	5465	g	1
Alpha parameter of B-H recruitment function	α	329351	recruits	2
Beta parameter of B-H recruitment function	β	300	tonnes	2
L50% gear retention	$L_{50\%}$	13.0	cm	2
L75% gear retention	$L_{75\%}$	14.5	cm	2
s1 parameter of selectivity equation	$s1$	4.14	-	2
s2 parameter of selectivity equation	$s2$	0.32	-	2
Area swept per day	a	0.228	km^2	2
Total area of stock distribution	*area*	32	km^2	2
Price of specie	p	41180	$/tonnes	2
Probability of capture	c	0.9	(0.1)	2
Exit/entry parameter	φ	0.0001	vessel/$MX	2
Alpha parameter of age-specific natural mortality		0.24	$Year^{-1}$	2
Beta parameter of age-specific natural mortality		0.68	-	2
Initial number of vessels	V_0	25	vessels	2
Average fishing trips per vessel	FD	30	days/year	2
Discount rate	td	0.05	$Year^{-1}$	2
Length of trip	L	1	Days	2
Steaming speed of the vessel	v	30	km/day	2
Operating cost of a vessel steaming	C_1	120	$/day	2
Operating cost of vessel fishing	C_2	70	$/day	2
Fixed costs	FC	100	$/year/vessel	2
Parameter ε of the negative binomial distribution	ε	15	-	2
Parameter μ of the negative binomial distribution	μ	5	-	2

[1] Vargas-López et al. (2021)
[2] This study

and Holt (1957), multiplied by a negative binomial function (ε=15, μ=5), which allows spatially explicit patches to be generated with a probability of zero recruitment (Anderson and Seijo 2010). Additionally, this function has been used in simulation works of sedentary species that colonize different sites (González-Durán et al. 2018, Seijo et al. 2004, Seijo and Caddy 2008). Because of the highly selective nature of the fishery, no fishing mortality on sub-legal individuals occurs. An excel sheet developed by Anderson and Seijo (2010) was adapted to the specific spatial characteristics of the abalone fishery in the study region to conduct the spatial management simulations with the mathematical models described in Table 2.

This abalone fishery is managed by catch quota recommendations and in 2010 caught about 24 tonnes with an effort in fishing trips of 1125. As observed in other studies (e.g. Sanchirico and Wilen 1999; Cabrera and Defeo 2001; Hernández-Flores et al. 2018), the spatial allocation of fishing intensity (effort per unit of area) was based on the quasi-rents of the variable costs obtained in alternative fishing sites over time. The spatial allocation of effort over time was allocated over space in proportion to the site-specific profits obtained in the previous periods; when the income fell to zero in any area, the function stopped allocating fishing effort to it (Caddy and Seijo 1998). Thus, the number of daily fishing trips in each management strategy is determined by changes in abundance in the resource's distribution area, the costs of fishing in alternative sites and the price of abalone. The Vt dynamic is calculated by numerically integrating (using Euler numerical integration with DT=1 in this case) the spatially adapted Vernon Smith (1969) function. A vessel makes one fishing trip per day, targeting only one species. Therefore, a single commercially exploited species determines the total costs and profits. The yellow abalone fishery is assumed to be price-taking, so its harvest does not affect the corresponding market prices. To simplify the analysis, constant prices were assumed over the simulation run. This dynamic bioeconomic model allows vessel exit in case of negative profits and restricts fishing not exceeding the maximum catch observed in 2010. Employment effects are negligible because community fishers have access rights to another high-value species (red spiny lobster, *Panulirus interruptus*), so they would not become unemployed when effort is at a level that maximizes the present value of resource rent, which involves less employment than operating at maximum sustainable yield.

To calibrate the SBEM, a comparison of the observed yield (Y_{obs}) and the calculated yield (Y_{cal}) for the first period (2000-2017) was carried out (Fig. 1). Statistical comparison of Y_{obs} and Y_{cal} was performed using the two-sample Kolmogorov-Smirnov (KS) test. The KS test statistic is D=0.333 and the corresponding *p*-value = 0.27. Since the *p*-value is greater than 0.05, we accept the null hypothesis. This indicates that the Y_{obs} and Y_{cal} datasets do not exhibit statistically significant differences. This allows us to infer that the suitable sensitivity of the SBEM foresaw a decrease in biomass and therefore calculated yields appropriate to this trend.

Once the SBEM was calibrated, management strategies for the yellow abalone fishery in the Mexican North Pacific were simulated and compared. The comparison between management strategies was based on the effect on biomass, predicted yield and present value of resource rent. The strategies evaluated are described in Table 3.

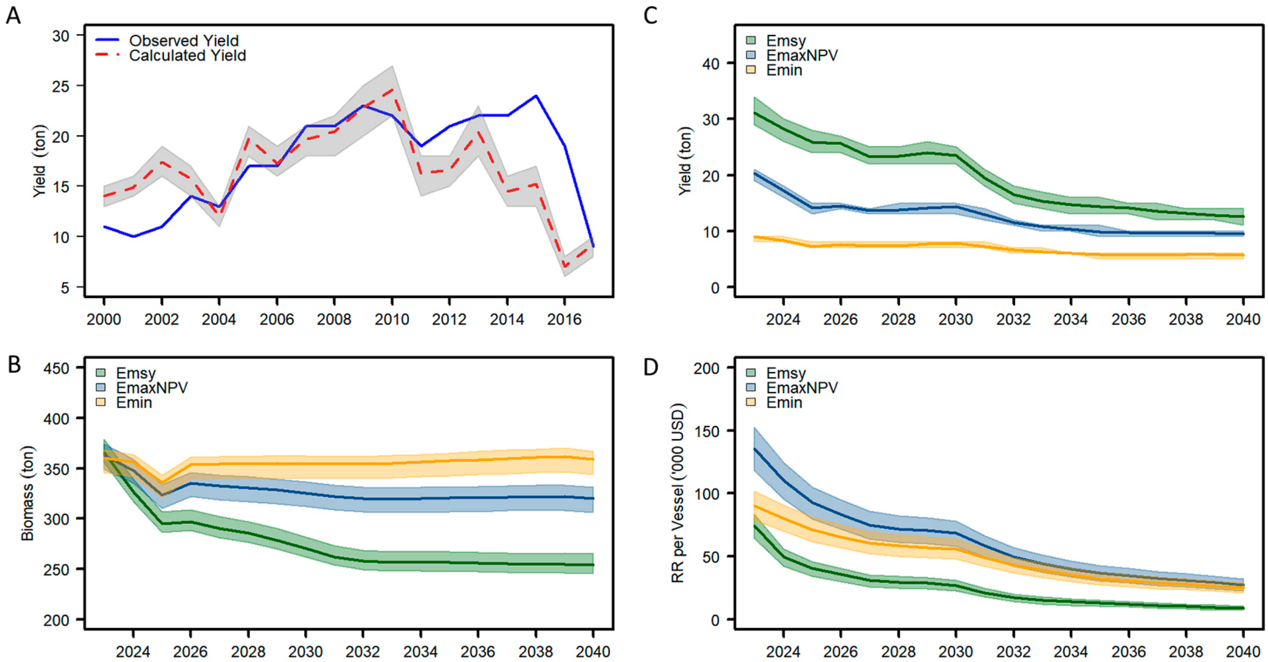

Fig. 1. – Observed yield and yield calculated by the SBEM (A); trajectories of biomass (B), yield (C) and resource rent per vessel (D) forecasted by the SBEM using MSE. (grey and coloured area are uncertainty associated with simulations).

Table 2. – Spatial bioeconomic equations for the *H. corrugata* fishery in the study area.

Description	Equation	Definition	Reference
Recruitment	$R_{s,t} = \frac{\Sigma_s SSB_{s,t}\alpha}{\beta + \Sigma_s SSB_{s,t}} P(s,d)$	$\Sigma_s SSB_{s,t}$ = total spawning biomass in time $SSB_{s,t} = \Sigma_{i=sm}^{\lambda} X_i$, α = maximum annual recruitment sm = age of sexual maturity β = total spawning biomass for $\alpha/2$	(Seijo et al. 2004)
Age-specific natural mortality	$M_i \frac{\phi_1 + \phi_2}{i}$	ϕ_1 = alpha parameter of age-specific natural mortality ϕ_2 = beta parameter of age-specific natural mortality	(Caddy 2018, 1991)
Survival of cohort	$\frac{dN_{i,s}}{dt} = -(F_{i,s,t} + M)N_{i,s,t}$	$N_{i,s,t}$ = number of individuals of age *i* in site *s* in time *t* $F_{i,s,t}$ = specific mortality at age *i* in site *s* in time *t* M = instantaneous natural mortality rate	(Anderson and Seijo 2010)
Fishing mortality	$F_{i,s,t} = E_{s,t} q_i$	$E_{s,t}$ = total fishing effort in site *s* in time *t* q_i = catchability coefficient specific to the cohort	(Rikhter and Efanov 1976)
Catchability coefficient	$q_i = -ln\left[1 - \left(\frac{aSEL_i c}{Area}\right)\right]$	a = area swept per day in km^2 $Area$ = area of stock distribution in km^2 c = probability of capture	(Baranov 1918, Sparre and Venema 1998)
Selectivity	$Sel_i = \frac{1}{1 + e^{s_1 - s_2 * L_i}}$	s_1 from s_2 Sparre and Venema (1998)	(Sparre and Willman 1993)
S1 ; S2	$L_{50\%} ln\left(\frac{3}{L_{75\%} - L_{50\%}}\right) \quad \forall \; s_2 = \frac{s_1}{L_{50\%}}$	$L_{50\%}$ = length at 50% gear retention $L_{75\%}$ = length at 75% gear retention	(Sparre and Venema 1998)
Total biomass available	$B_{s,t} = \sum_{i=1}^{i=k} N_{i,s,t} W_i$	W_i = weight of individuals at age	(Anderson and Seijo 2010)
Total profits per vessel per year	$\pi_t = \sum_s (py_{st} - C_{st}E_{st}) - FC * V_t$	py_{st} = total revenues per vessel in site *s* in time *t* E_{st} = fishing effort in fishing days FC = fixed costs per vessel V_t = number of vessels in time *t*	(Anderson and Seijo 2010)
Spatial allocation of fishing effort	$E_{s,t+1} = \frac{quasi\ \pi_{s,t}}{\sum_s quasi\ \pi_{s,t}} V_{t+1}\text{fd}$	fd = average number of fishing days per vessel per year $quasi\ \pi_{s,t}$ = quasi-profits of the variable costs of a vessel fishing in site *s* in time *t*	(Anderson and Seijo 2010, Seijo and Caddy 2008)
Quasi-rents	$quasi\ \pi_{s,t} = py_{st} - C_{st}E_{st}$		-
Variable costs	$C_{st} = \frac{\frac{D_s}{v}c_1 + (L - \frac{D_s}{v})c_2}{L}$	D_s = round trip distance between port of origin and fishing site *s* (km) v = steaming speed of vessels (km/day) c_1 = cost per day of operating a vessel when steaming ($/day) c_2 = cost per day of operating a vessel when fishing ($/day) L = average length of trip in days	(Anderson 2002)
Spatial yield	$y_{st} = \sum_i X_{ist}\left[\frac{F_{ist}}{F_{ist} + M}\right](1 - e^{[-(F_{ist}+M)]})$		(Seijo and Caddy, 2008)
Minimum catch per unit of effort	$CPUEmin_s = \frac{\left[\frac{\frac{D_s}{v}c_1 + \left(L - \frac{D_s}{v}\right)c_2}{L}\right]}{p}$		(Anderson and Seijo 2010)
Dynamic yield per unit of effort	$CPUE_{st} = \sum_i (q_i X_{ist})$		(Anderson and Seijo 2010)
Number of vessels per year	$V_{t+1} = V_t + \emptyset\left[\sum(pY_{st} - C_{st}) - FCV_t\right]$	$\emptyset$ = enter/exit parameter	(Smith 1969)
Net present value	$VPN = \int_{y=0}^{Y} \prod_y e^{-\delta_y}$	Y = simulation horizon δ_y = discount rate	

At the request by resource users in this co-managed fishery to lift the moratorium on the fishery, the aim was to identify the minimum effort (fishing days) at which the fishers can obtain an above-zero resource rent to cover the operating cost of four vessels and their opportunity cost of labour of moving to another high-value species such as the red spiny lobster *Panulirus interruptus.* As an assumption in the simulation period, the fishery management authority is considering this minimum effort when it reopens the fishery.

Simulations using these management strategies began with the assumption of lifting the moratorium on the fishery starting in 2023 and continuing for a simulation period of 17 years until 2040. This period is equivalent to one life cycle of *H. corrugata.*

Table 3. – Management strategies considered in this study.

Management Strategy	Name	Description
E_{msy}	Effort at maximum sustainable yield	Status quo. This is based on the Mexican government's current and official fishing regulations, which explicitly state that the abalone fishery effort must operate at maximum sustainable yield (DOF, 2018).
E_{maxNPV}	Effort at maximum present value of resource rent	Fisheries managers can adjust the overall level of fishing effort such that present value of resource rent is maximized and biomass is higher than the one resulting from operating at MSY.
E_{min}	Community-determined minimum fishing effort when the fishery reopens	Minimum level of effort to obtain quasi-profits of the variable costs of fishing equal to or above the ones currently obtained from the spiny lobster fishery.

Sensitivity analysis

The SBEM used a set of biological, economic and technological parameters that contribute to the calculated performance of biomass and present value of resource rent, so a sensitivity analysis was undertaken on the following parameters: parameter *k* of the von Bertalanffy growth equation, α and β stock-recruitment parameters, natural mortality *M*, price of species and catchability. The sensitivity analysis of the parameters was related to the performance variables such as final biomass B_{2040} and present value of resource rent. The results were expressed as correlation coefficients between the parameter and the output variable.

Risk analysis of environmental variability affecting individual growth

A Monte Carlo analysis was carried out using Crystal Ball Pro software (ver. 11.1.2.4.850) to estimate the risk of exceeding the limit reference point (LRP) for the yellow abalone fishery in the study area. With the appropriate probability density function (distribution of the parameter data to be analysed), this software allows the primary sources of parameter uncertainty to be represented by generating random variables of these parameters and estimating the risk of exceeding the LRP. Under controlled conditions (e.g. aquaculture), abalone growth is influenced by factors such as temperature and food availability (Britz et al. 1997; Morash and Alter 2016). Vargas-López et al. (2021) found that the relationship between growth and sea surface temperature (SST) was statistically significant for abalone species in wild conditions. Temperature regulates the expression of growth (Day and Fleming 1992, Pérez 2010, Vilchis et al. 2017); this effect is reflected by an acceleration of metabolism, which allows it to gain robustness faster, or a slowing of metabolism, which delays some vital functions (Essington et al. 2001, Renner-Martin et al. 2018). Also, SST had a direct effect on abalone growth. These changes in size have been described as the "third ecological response to global warming" (Daufresne et al. 2009). Uncertainty was incorporated within the SBEM in the parameter *k* of the von Bertalanffy growth equation. The SST variability predicted for 2023 to 2040 was undertaken by varying, with a uniform probability density function, the reported environmentally driven *k'* values ranging from 0.32 to 0.38 for *H. corrugata* (Vargas-López et al. 2021).

Bioeconomic reference points are shown in Table 4. The biological LRP is determined by the biomass level that conditioned the closure of the fishery for the yellow abalone in 2017, while the biological target reference point (TRP) is determined by the biomass level at maximum sustainable yield. The economic LRP is determined by the resource rent that covers the operating costs per vessel (RR_{pv}) and the opportunity cost of work when another high-value species such as the red lobster *Panulirus interruptus* is targeted. This value will be known as the minimum resource rent (RR_{min}). The economic TRP is based on the proposal of the fishing sector, in which they suggest that the optimum resource rent RR_{opt} be 50% higher than RR_{min}.

RESULTS

Spatial distribution and density

To represent the variation in abalone density, two plots were made using IDW interpolation (Fig. 2A and B). At the beginning of the historical series (2000), there was extensive coverage of abalone in the fishing zone; in 2017, this coverage fell considerably, as shown in Figure 1A and B, and the average density per sample unit decreased from 0.144 to 0.062 ind/50m^2 during that period. These changes and the reduction in density were the reason for the moratorium agreement for the fishery.

Table 4. – Bioeconomic reference points for the *H. corrugata* fishery.

Performance variables	Reference point	Value	Definition
Biomass (tonnes)	Limit reference point	190	Biomass level that conditioned the closure of the fishery in 2017.
	Target reference point	244	Biomass level at Maximum Sustainable Yield.
Resource rent per vessel (USD/year per vessel)	Limit reference point	15000	Minimum resource rent (RR_{min}) covers the operation costs per vessel and the opportunity cost of labour when catching another high-value species, such as the red lobster *Panulirus interruptus*.
	Target reference point	23000	Proposal of the fishing sector, where they suggest that the optimum resource rent RR_{opt} be 50% higher than RR_{min}

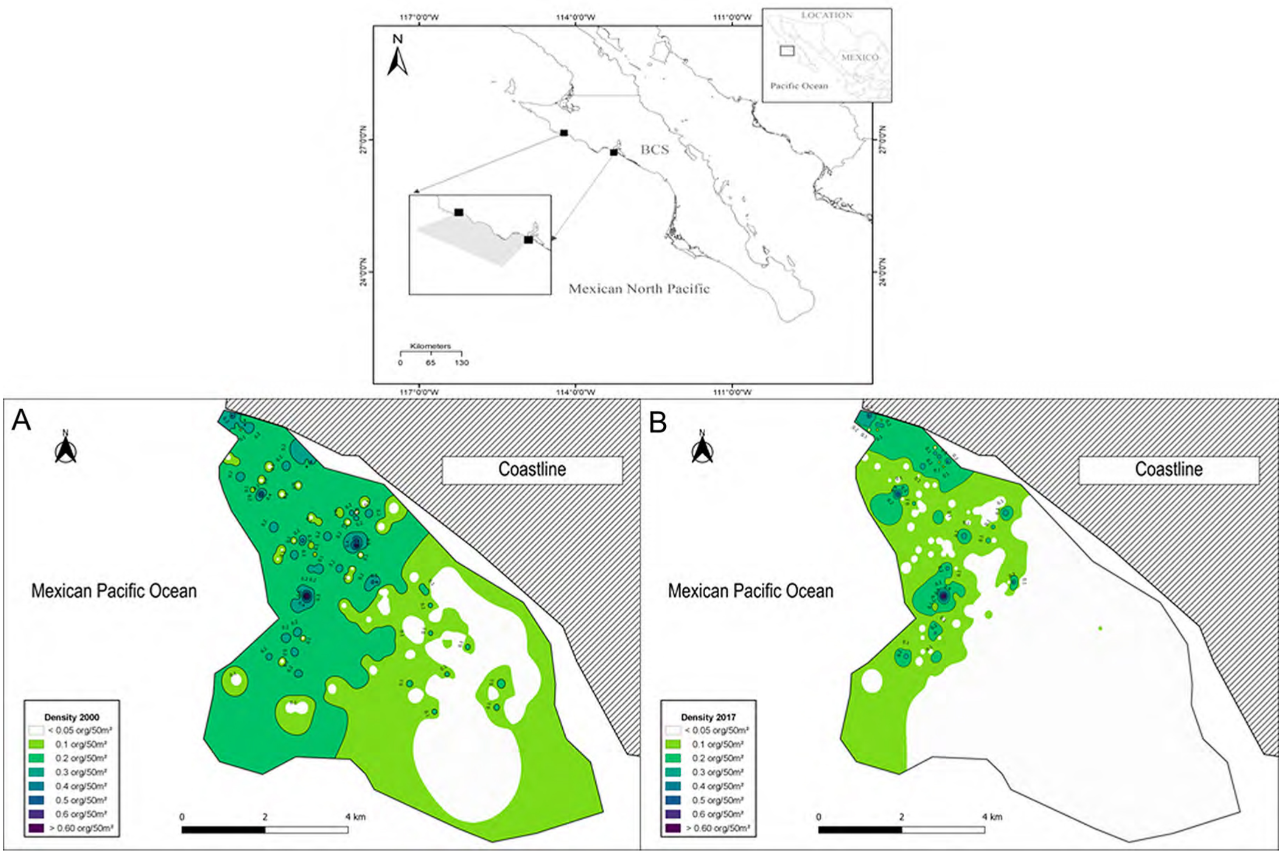

Fig. 2. – Spatial distribution of yellow abalone in the study area as observed in 2000 (A) and 2017 (B).

Sensitivity analysis

Biomass sensitivity results for the three management strategies under consideration are shown in Table 5. The range of values are the following: natural mortality (-54.1%-39.5%) and parameter *k* of growth function (21.2%-35.2 %), followed by beta (-12.7%-0.9%) and alpha (9.7%-22.3%) parameters of recruitment function. Biomass sensitivity to catchability ranged from -0.4% to 6.0%.

The present value of resource rent sensitivity to the above-mentioned parameters for the three management strategies under consideration is presented in Table 6. The range of sensitivity values are the following: natural mortality (-61.1%-38.8%), catchability (10.9%-14.6%), parameter *k* of growth function (6.5%-13.9%), price of species (7.5%-20.4%), and alpha (8.6%-13.7%) and beta (–6.9%-0.4%) parameters of recruitment function. In addition to the Monte Carlo calculated magnitude, the indication of positive or negative sensitivity to changes in parameters resulted in the direction expected for final biomass and present value of resource rent.

Management strategy evaluation

When performing one thousand simulations of the calculated values for the observed period, incorporating uncertainty in the parameter *k'* of the von Bertalanffy growth function, variability in the calculated values was observed; this was mainly determined by the wide range of the assumed value (*k'*) in the uncertainty analysis (Fig. 1A). It can be inferred that during the period 2004 to 2010, the values of Y_{obs} and Y_{cal} were very similar. After this period, there was a difference to consider. As of 2011, the SBEM was already calculating lower catch values than those observed. It is noteworthy that for 2013, the Y_{obs} coincided with the outlier value of the Y_{cal} trajectory calculated for that year. From 2011 to 2016, the Y_{obs} was above the values calculated through simulations. The SBEM thus suggests that catches from 2013 to 2017 decreased from approximately 15 to 8 t, a situation leading to closure of the fishery after 2017.

The biomass levels projected by the SBEM considering the MSE are presented in Figure 1B. This graph clearly shows the differences between biomass trajectories. Different levels of fishing effort determined by the management strategies evaluated generate levels of final biomass that are important for consideration by the stakeholders.

Table 5. – Final biomass sensitivity analysis corresponding to three different management strategies.

Biomass sensitivity output (%)			
Parameters	E_{msy}	E_{maxNPV}	E_{min}
	F=0.06	F=0.02	F=0.01
M	-39.50	-41.60	-54.10
k	32.80	35.20	21.20
β	-9.60	-12.70	-0.96
α	17.80	9.70	22.30
q	2.40	6.00	-0.45
p	0.11	0.20	-1.00

Table 6. – Present value of resource rent sensitivity analysis corresponding to three different management strategies.

Present value of resource rent: sensitivity output (%)			
Parameters	E_{msy}	E_{maxNPV}	E_{min}
	F=0.06	F=0.02	F=0.01
M	-38.80	-44.50	-61.10
q	14.60	14.60	10.90
k	13.90	13.70	6.50
p	20.40	11.70	7.50
α	11.40	8.60	13.70
β	-0.80	-6.90	-0.40

In the simulation period, when the moratorium was lifted and harvesting of the resource began, a decrease in biomass levels was observed in the three management strategy trajectories. Subsequently, the dynamic catch quota effect was observed four years after reopening the fishery. Derived from this, the E_{min} management strategy tended to equilibrium biomass in less time than the other management strategies. The E_{min} and E_{maxNPV} management strategies allowed higher biomass levels than the E_{msy} management strategy at the end of the simulation period. As expected, E_{min} (lowest effort) was the management strategy in which the highest biomass level was observed at the end of the simulation.

The yield trajectories projected by the SBEM considering the three management strategies show decreasing trends, although in different magnitudes, towards the end of the simulation period. (Fig. 1C)

As expected, different levels of effort generated different levels of forecasted yield (Fig. 1C). E_{msy} predicted yields above E_{maxNPV} because E_{msy} operates in open access concerning the number of daily fishing trips per season (status quo). E_{maxNPV} has a catch quota restriction based on the assumption of not exceeding the maximum recommended quota in the observed period of the fishery. Nevertheless, it must maximize the economic rent generated by the resource. For this reason, the trajectory of this management strategy was lower throughout the simulation than E_{msy} but higher than E_{min}. The magnitude of the difference in yield trajectories should be recognized by authorities and fishers when they consider reopening the fishery due to the requirements in the number of vessels needed to catch the forecasted values: E_{min} predicted an initial yield of 9 t, and a final yield of 6 t, while, E_{msy} predicted an initial yield of 31 t and a final yield of 12 t. This management strategy suggests higher catch quotas than those recorded in the observed period.

To compare the resource rent for the alternative MSE, resource rent per vessel is likely to be considered as a decision variable by resource users and authorities. At the beginning of the simulation, mainly because of the low mobility, high catchability and consequently high value and low costs of the resource in the fishing operation, the resource rent generated by the fishery was 50% higher in E_{maxNPV} than in E_{min} and 75% higher than in E_{msy} (Fig. 1D). However, it gradually declined as the dynamic catch quotas developed. At the end of the simulation, resource rent per vessel in E_{maxNPV} and E_{min} were higher than resource rent per vessel in E_{msy}.

Other alternative discount rates could be used for different contexts to calculate the present value of resource rent. Table 7 shows the effect on present value of resource rent for the three options for three alternative rates of discount.

In Figure 3, a comparison of net present value (NPV) per vessel for the MSE is shown. The NPV was considerably higher in E_{maxNPV}, three times higher than that in E_{msy}. The high yield at the beginning of the simulation, the high value of the species, and the low total costs are the variables that determine this considerable difference. Another critical factor conditioning this high NPV is the spatial allocation of effort determined by the SBEM.

It is crucial to compare NPV values per vessel, thus generating a fundamental decision criterion for fishers and authorities. Dividing E_{msy} NPV by 25 vessels, we obtained USD 436570 per vessel. In the case of E_{min} NPV divided by four vessels gave USD 866662 per vessel. In the long term, the E_{min} management strategy generated a higher NPV per vessel than E_{msy}, requiring a lower number of vessels and optimal results in final biomass and yield. In the case of E_{maxNPV}, the NPV value divided by the six vessels (six is the total number of vessels needed to perform 471 fishing trips in the fishery season) gave a total of USD 1073520 per vessel, which is the maximization of the NPV in the MSE.

Table 8 shows the management strategies, effort units, final biomass, final yield and final NPV per vessel per strategy at the end of the simulation period. This table offers clear visualization of the SBEM outputs, which implicitly include the fishery's social, economic and biological considerations—crucial characteristics for decision-making.

Table 7. – Effect on present value of resource rent for the three management strategies considering three alternative rates of discount.

Discount rate	E_{msy}	E_{maxNPV}	E_{min}
0.025	$526	$1347	$1101
0.050	$437	$1074	$867
0.075	$399	$956	$770

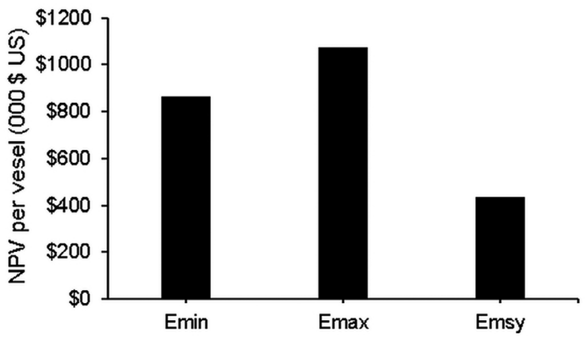

Fig. 3. – Comparison of the net present value through the MSE.

Model validation

A Kolmogorov-Smirnov (KS) test was conducted to compare the observed yield and the calculated yield in the first period (Fig. 1A). The KS test statistic is D=0.333 and the corresponding p-value = 0.27. Since the p-value is greater than 0.05, we accept the null hypothesis. This indicates that the Y_{obs} and Y_{cal} datasets do not exhibit statistically significant differences. This allows us to infer that the suitable sensitivity of the SBEM foresaw a decrease in biomass and therefore calculated yields appropriate to this trend.

Monte Carlo Analyses and probabilities of exceeding the LRP and TRP

After generating 1000 simulations, we calculated the probability of B_{2040} falling below the LRP of B_{min} and the TRP of B_{msy}. In the case of resource rent, we calculated the probability of having an RR_{pv} greater than the LRP of RR_{min} and the TRP of RR_{opt} at the end of the simulation period (RR_{2040}). The biomass at the level in which the fishery went to closure in 2017 (B_{min}: 190 t) and the minimum resource rent to cover the operating cost of one vessel and its opportunity cost of labour of moving to another high-value species (RR_{min}: USD 15000) were used as LRPs; the biomass at maximum sustainable yield (B_{msy}: 244 t) and a fisher-proposed optimum resource rent per vessel (50% higher than RR_{min}) (RR_{opt}: USD 23000) were used as TRPs (Figs 4 and 5).

In the case of biomass, the three management strategies showed probabilities of falling below the TRP (dark area under the probability chart), but E_{msy} was the one that had the greatest risk of falling below it. Operating at this level of effort increased the risk (86%) that the biomass at the end of the simulation would fall below the desirable level point. In addition, with this strategy, there was also a 30% risk of falling below the LRP, the same biomass level that caused the closure of the fishery in 2017. The other two strategies involved zero risk of falling below this undesirable biomass level.

Table 8. – Spatial bioeconomic model outputs from the MSE.

Strategy	Fishing days	Explotation rate (F)	Vessels*	B_{2040}	Y_{2040}	NPV** (000 USD)
E_{min}	196	0.01	4	354	5	867
E_{maxNPV}	471	0.02	6	312	9	1288
E_{msy}	1246	0.06	25	244	12	437

*The minimum number of vessels required to conduct the fishing days per strategy per season.
** 17-year calculation period with a 0.05 discount rate.

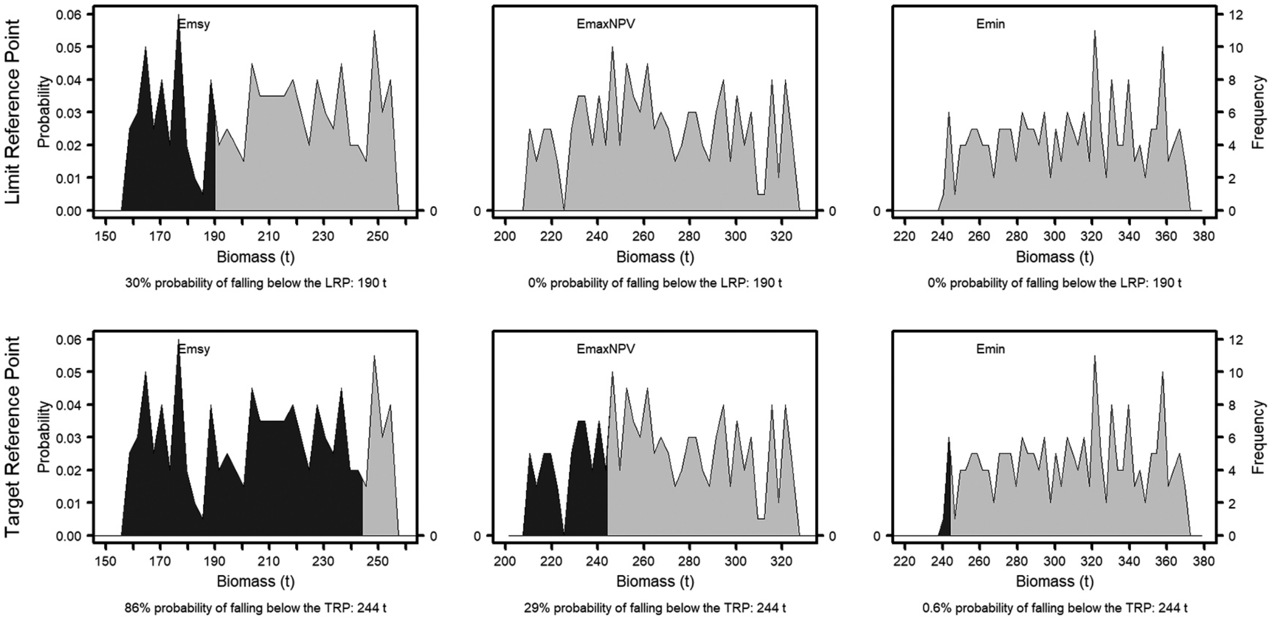

Fig. 4. – Risk (dark area) of falling below the biomass LRP and TRP at the end of the simulation period.

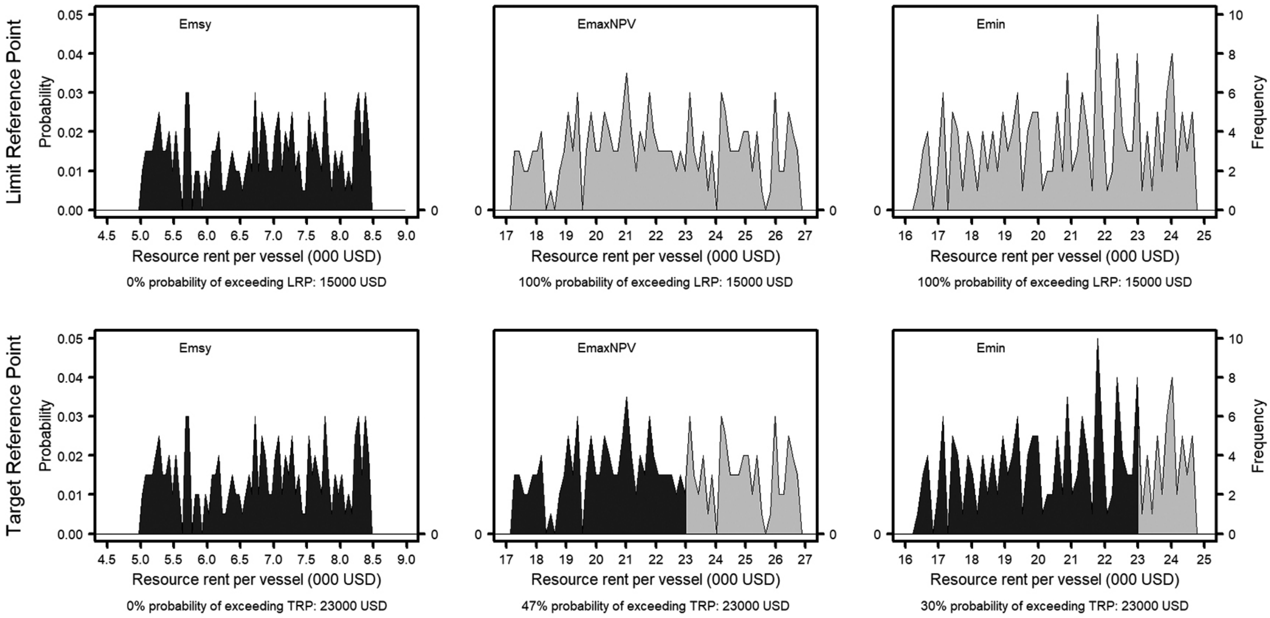

Fig. 5. – Risk (grey area) of exceeding the LRP and TRP of RRpv at the end of the simulation period.

The resource rent is a crucial variable in fishermen's and authorities' decision-making. For this reason, two reference points were evaluated (TRP and LRP). Both E_{min} and E_{maxNPV} had a 100% probability (grey area under the probability chart) of being above the LRP. E_{maxNPV} was the strategy with the highest probability (47%) of exceeding the TRP of USD 23000 per vessel. E_{msy} was the strategy with a 0% probability of being above both reference points. In economic and sustainable terms, it is not a suitable strategy to be employed, because it shows a high risk of falling below biomass at maximum sustainable yield and it generates zero probabilities concerning the economic benefit that fishers could obtain from the resource in terms of reference points. A summary of the probabilities of exceeding LRP and TRP are shown in Table 8.

Once these reference points have been evaluated, as Anderson and Seijo (2010) comment, the fishers and authorities (decision-makers) and their inherent attitude towards risk will determine which strategy should be implemented in the reopening of the fishery and whether to reduce risks of returning to an undesirable biomass level that would suggest another fishery clo-

Table 9. – Probabilities of falling below the LRP and TRP for biomass (B_{2040}) and exceeding the LRP and TRP for resource rent per vessel (RR_{pv2040}).

Strategy	Biomass (t)		RR_{pv} (USD/year per vessel)	
	LRP	TRP	LRP	TRP
	$B<B_{min}$	$B<B_{msy}$	$RR_{pv}>RR_{min}$	$RR_{pv}>RR_{opt}$
	190	244	15000	23000
E_{min}	0	0.6	100	30
E_{maxNPV}	0	29	100	47
E_{msy}	30	86	0	0

Probabilities are expressed in percent.

sure. It is necessary to identify the strategy or strategies that provide resource users with the maximization of the economic rent generated by this species while at the same time avoiding overexploitation.

DISCUSSION

Our results provide the methodological basis for evaluating the potential economic and stock recovery benefits of applying an SBEM. Furthermore, we analyse management strategies for an abalone fishery considering the risks and uncertainty of environmental variability associated with climate change. Like Nielsen et al. (2018), Seung and Waters (2006) and Seijo et al. (1998), we approached the management strategies and spatial data with the collaboration and suggestions of community fishers and fishery managers.

The application of spatial modelling in fisheries resources has been increasing since the initial work of Caddy (1975) and the research of fisheries economists (Holland and Brazee 1996, Holland et al. 2004, Akpalu and Vondolia 2012), but few authors have used spatially explicit age-structured dynamic bioeconomic models (Seijo and Caddy 2008, González-Durán et al. 2018, Hernández-Flores et al. 2018). The impacts of climate change or other long-term changes in productivity can be approximated and examined within the MSE model. It is possible to include long-term trends in natural mortality, growth and recruitment that may be used to understand the likely effects of changes in productivity caused by climate change or other environmental drivers (Hordyk et al. 2017).

Bioeconomic models for managing fisheries globally have been used for a couple of decades (Pascoe et al. 2016). The use of MSE for abalone fisheries is also well documented (Harford et al. 2019). The abalone fishery in Mexico has been the subject of research regarding its population dynamics, stock assessment, reference points and the management of abalone stocks in the region. However, this is the first study that considers three important areas: economic, social and environmental sustainability in the North Pacific region, where many crucial fisheries are located.

This study confirms that abalone, like other semi-sessile resources, are highly vulnerable to overfishing (Ramírez-Rodríguez and Ojeda-Ruíz 2012, Aburto and Stotz 2013, Hernández-Flores et al. 2018), which is mainly due to its high value and low costs in the fishing operation. As mentioned by Herrera (2006), spatial regulation is particularly beneficial when stocks are slow-growing and high-priced.

The MSE allows alternative strategies to be evaluated in addition to the control rules known by fishers and the corresponding authorities within a co-management scheme. E_{msy} is a strategy that recommends a higher effort at the beginning of the simulation than that observed in the historical series, and is likely to generate undesirable biomass levels. Alternatively, E_{min} and E_{maxNPV} offer an effort reduction of 85% and 63% of the maximum observed effort, respectively. By reducing the number of fishing trips, it is possible to increase long-term economic net benefits for the Mexican abalone fishery and to minimize the impact of fishing mortality in varying environmental conditions that have been shown to have a significant effect on growth and other biological processes of this resource (Ponce-Díaz 2008, Castro-Ortiz and Guzmán del Próo 2018, Vargas-López et al. 2021). The above results from the MSE analysis indicate that adapting to possible effects of uncertainty due to climate change can be accomplished using, as a precautionary measure, a reduction of fishing effort in a strategy that maximizes the NPV of the fishery.

It is complicated to compare our results with those of other studies because there are no published references of the consequence of alternative management measures on spatially explicit fisheries like our study case on abalone. Nevertheless, the MSE demonstrates that effort limits could meet the management objectives for this stock. This may incentivize the development of mechanisms to manage the fishery using both input and output controls. Limiting the effort to E_{min} and E_{maxNPV} reduced overfishing of the resource, allowing some recovery of a heavily exploited fishery and producing higher catches and profits in the long term. This study indicates that under current regulations (status quo), dissipation of rent is generated for the fleet, and we conclude that E_{msy} could be indicative of overcapacity in this fishery (Anderson et al. 2015, Asche et al. 2009, Emery et al. 2017).

This study suggests that strategies E_{min} and E_{maxNPV} may help maintain the abalone fishery and yields in the long term. Several studies have reported that biomass associated with maximization of NPV is higher than that associated with MSY (McGarvey et al. 2016, Punt et al. 2010). Others suggest that reference points lower than f_{msy} may be more suitable in terms of higher profits and safer biomass levels (Grafton et al. 2010; Da-Rocha et al. 2015; De Anda-Montañez et al. 2017).

For some years now, fisheries management has been immersed in a transition in which the aim is no longer to manage the resource but to manage the users of the resource. The level of profitability has thus become an essential point for decision-making (Dichmont et al. 2010, Gordon 1954, Grafton et al. 2010). Economists have identified that a fishery that maximizes its economic income commonly also satisfies the objectives of conservation and recovery. The development of this scenario, considering the maximization of economic revenue expected from the abalone fishery, allows us to identify a level of effort and catch which is conceptualized as maximum economic yield (MEY) (Clark 1990, Grafton et al. 2010). In most cases this scenario indicates catch and effort levels that are lower than those at MSY, thus generating stock biomass levels higher than MSY. By incorporating these economic analyses, for the first time a management approach that achieves a combination of biological, economic and social objectives can be proposed for the abalone fishery in Mexico.

Unlike other fisheries where strategies that maximize economic rent have been evaluated, although optimality implies that the gains in MEY will more than compensate for the losses in transition, the transition can be burdensome on a fishing industry that is interested mainly in cash flow and short-term returns. (Dichmont et al. 2010, Kompas et al. 2010). This point alone often makes implementing MEY in fisheries challenging to accomplish. Kell et al. (2006) suggest that adhering strictly to the precautionary approach for overexploited fisheries may imply setting very conservative (low) effort levels, which may be difficult to accept by fishers and fisheries managers. However, in this case, where there is a TURF allocated to a fishing community with suitable governance and co-management, implementing these strategies and reference points will be easier than in other open-access fisheries or fisheries with participants from different fleets or regions.

Traditionally, TRPs have been defined as a desirable management objective, whereas LRPs indicate a state of a fishery and resource that is considered undesirable and should be avoided (Caddy and Mahon 1995). However, we have found no official and public document that explicitly indicates these reference points. Therefore, this study proposes these new bioeconomic reference points.

The Monte Carlo-based simulation analyses also indicate that strategies involving the control of fishing effort can result in lower probabilities of exceeding LRPs. The advantage of incorporating risk and uncertainty in fisheries assessment is that decision-makers in charge of management can have an idea of the potential effect of their decisions. Recognizing the uncertainty present in various parts of the fishery system is fundamental for a precautionary approach to decision-making (Anderson and Seijo 2010).

It is important to add that due to the population dynamics of this stock, which is composed of several substocks, each of which is subjected to periodic (pulse) fishing of high intensity, it is feasible and desirable to analyse the fishery through rotational harvesting schemes based on the proposals of Caddy and Seijo (1998). Also, Sluczanowski (1984) mentions that this type of fishery can be described by a management scheme that is more useful to managers and easier to control in exploitation practice, principally through closure policies, than those based on fishing mortality *F.*

It seems important that future work consider the possibility of whether spatially explicit management alternatives could be applied in this fishery. As suggested by Caddy and Seijo (1998) and Seijo and Caddy (2008), empirical studies considering spatial management strategies for sedentary species (e.g. spatial rotation harvest schemes) should consider the following set of questions: Do de facto exclusive harvesting rights exist? Is preventing poaching in closed areas/seasons feasible, cost effective and supported by fishers? Is there a management authority with the capacity to allocate fishing rights by area to individual participants? Are there a discrete number of population subunits for the resource? Can the stock be separated into subunits of comparable size, between which migration is limited or absent? Are the number of subunits equal to or greater than a calculated optimum period of harvest rotation? Are there alternative means of employment for local fishers and/or processors if a local resource area is closed for several years? Do fishers have access to other stocks in each year of the scheme? Is the method of harvesting selective for the species and sizes most desired? Considering the above questions, the feasibility of establishing a rotating harvest scheme for the yellow abalone fishery could be explored in the future.

CONCLUSIONS

Three management strategies were evaluated through an SBEM for the yellow abalone fishery in the Mexican North Pacific region in order to determine the risks associated with environmental variability for each of the strategies. By evaluating the state of exploitation of this fishery resource, we identified a biomass recovery strategy that would allow the authorities to reopen the fishery. In addition, reference points were explicitly identified in the fishery to represent bioeconomic management scenarios that allowed us to evaluate alternative management strategies such as minimum effort and effort that maximizes NPV. Calculating the risk of falling below the biological reference points and exceeding the economic reference points provides essential information for decision-making regarding the feasibility of employing any of these management strategies.

Thus, it is concluded that, after the moratorium was established to recover the stocks to the desired levels, the exploitation rate should be lower than the one that was being applied in the status quo, and it was considered suitable to use exploitation rates determined by the E_{min} and E_{maxNPV} management strategies. In addition, due to the prevailing environmental variability, there is a risk that the biomass will be below the biological LRP equivalent to 30% in the *H. corrugata* fishery with the E_{msy} management strategy (*status quo*). The risk of achieving a biomass level below the biological LRP is reduced to 0% with the management strategies E_{min} and E_{maxNPV}. The E_{min} and E_{maxNPV} management strategies exceed the economic LRP and TRP, allowing the economic rent generated by the species and its ecosystem to be increased or maximized while avoiding overexploitation. Future research for fisheries targeting sedentary species under TURF co-management schemes could explore rotational harvest schemes within their spatial management approaches.

ACKNOWLEDGEMENTS

The authors are very grateful to INAPESCA and S.C.P.P. Progreso, who provided the data. We also wich to acknowledge all scientific technicians, researchers and fishers who recorded the historical information over all those years. VGVL thanks CONACYT for the PhD fellowship CVU 389845. FAS thanks Instituto Politécnico Nacional for support through the EDI and COFAA programmes and partial support through the SIP20221362 project.

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