

# Management Strategy Evaluation for the Common Spiny Lobster, *Palinurus elephas* (Fabricius, 1787), Stock in Tunisia

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E-ISSN: 2073-3720  
<https://doi.org/10.33997/j.afs.2022.35.1.004>

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## Abstract

The common spiny lobster, *Palinurus elephas* (Fabricius, 1787), fishery in Tunisia has been overexploited. This species is currently managed by temporal closures, minimum legal sizes of landings, and the prohibition of catching berried females. This study aims to develop management procedures (MPs) based on the surplus production model to set total allowable catch (TAC) as a management action for the common spiny lobster. Ten MPs ranging from conservative to more relaxed management procedures were evaluated within a management strategy evaluation (MSE) framework. Several scenarios of the operating model were considered to account for uncertainties. Five performance measures were used to evaluate MPs to identify the management strategies that can achieve the prespecified management objective of recovering the stock size as a priority and ensuring high and stable catches. The results of the MSE showed that the conservative management strategies with the highest control points performed well in terms of management objectives with a probability of biomass exceeding the reference point of higher than 90 % but yielded in the lowest catches. On the other hand, relaxed threshold-based management strategies failed in achieving management objectives with 20 % probability of being below the limit reference point. These MSE results also highlighted the trade-off between conservation and catch performance objectives and showed that some moderate management strategies balanced these objectives efficiently.

**Keywords:** fishery management, management procedures, harvest control rules, performance metrics, quota management

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## Introduction

The common spiny lobster, *Palinurus elephas* (Fabricius, 1787), is one of the most valuable lobster species in the Mediterranean Sea and Tunisia. This species has been exploited by fishing since ancient times in that area, where it has significant economic and social importance (Marengo, 2020; Muñoz et al., 2021). As a result, the common spiny lobster is sold for high prices and supports a critical number of small-scale fishing vessels in the Mediterranean countries. However, this species has undergone overexploitation, especially after replacing the traditional fishing gears, traps with trammel-nets in the 1960s (Goñi and Latrouite, 2005). As a result, and given the low resilience and increased fishing pressure, a decline in the common spiny lobster landing has been observed

in the Mediterranean. Consequently, this species was listed as a vulnerable species in the International Union for Conservation of Nature (IUCN) red list (Goñi and Latrouite, 2005; Cau et al., 2019; Marengo, 2020).

Like other Mediterranean countries, the common spiny lobster is an important resource in Tunisia. Nevertheless, the landings in the Tunisian common spiny lobster fishery also witnessed a decreasing trend starting in the mid-2000s, after a peak of 74 tonnes in 1993 (Goñi and Latrouite, 2005). This decline resulted from the fishing pressure that followed the shift in the fishing gear in 1981, as the trammel nets were introduced and replaced the traditional fishing methods that were used (i.e. traps and pots), and the increase in the number of vessels targeting the species in the 1990s (Rjeibi, 2012). Tunisia's common

spiny lobster fishery is regulated by an annual temporal closure for fishing from mid-September to February end. The minimum legal size for catch is 20 cm total length and the prohibition of fishing the berried females. Despite these management rules, the common spiny lobster stock is considered overexploited according to the previous stock assessment of the species (Rjeibi, 2012).

The regulations applied for the Tunisian common spiny lobster fishery are similar to those used for the fisheries of the same species in other Mediterranean countries (Kampouris et al., 2020). However, different management rules, such as quota management, were proved efficient for managing other lobster species fisheries in other parts of the world. For example, the New Zealand lobster fisheries have been successfully managed using quota management since 1990 (Miller and Breen, 2010).

The appropriate management rules have been developed by applying the management strategy evaluation (MSE) framework (Holland, 2010; Gardner et al., 2013; Punt et al., 2016). The MSE is a simulation-based process that simulates population dynamics and fisheries' systems. It is considered the best practice to develop management procedures, also called management strategies (Butterworth, 2007), that can achieve management goals and are robust to uncertainties (Punt et al., 2016; Kaplan et al., 2021). This process is based on a set of steps necessary for evaluating the management procedures (MPs) (Punt et al., 2016). The first step is to define the fishery's management objectives qualitatively (and sometimes quantitatively), such as maintaining the stock at a sustainable level and maximising the average catch and profit. These objectives are then defined with some quantitative goals to quantify the extent of achievement through a set of performance measures. For example, maintaining the stock at a sustainable level would be translated to maintaining the biomass level above 20 % of the unfished biomass over 10 years. Then, a wide range of uncertainties is identified to test the robustness of the management procedures. These uncertainties include process error related to the underlying randomness in the modelled population dynamics, observation error related data and measurement errors, model error related to the model's ability to apprehend and represent the population dynamic, and implementation error related to the implementation of the management action (Amar et al., 2008; Kell et al., 2016). The uncertainties are integrated into the operating models (OMs), developed in the next step to simulate the "true" fishing system by mimicking the underlying population dynamics and generating data for management procedures use. Alternative MPs are then developed and are simulated into the future over a management period to set management actions such as total allowable catch (TAC) fed back to the operating models. Finally, this closed-loop system is used to extract the performance measures. The

performance measures are analysed and summarised to compare the performance of the management procedures and their ability to achieve the management goals (Goethel et al., 2019).

In this study, the development of several model-based management procedures to set quota management (i.e., TAC) of the common spiny lobster fishery in Tunisia was made. The model-based MPs incorporate a stock assessment model to assess the population status and whose results are used in the harvest control rules (Rademeyer et al., 2007). Another class of MPs, the empirical management procedures, are model free, where the management action is determined from feedback about the data (e.g., recent trends in abundance indexes). These management procedures are normally tested within an MSE framework. However, due to the lack of continuous abundance index for the targeted species, the model-based MPs are focused and evaluated based on the operating models conditioned on the state-space delay difference models. The main objectives of this study were to i) develop model-based management procedures and test their performance in achieving prespecified management objectives for the common spiny lobster fishery in Tunisia; ii) identify the possible trade-offs between management objectives and determine which MPs achieve the best balance among them.

## Materials and Methods

The MSE is based on defining an operating model to represent the best population dynamic and then projecting it in the future using the management action (e.g., TAC). The harvest control rule sets the management action using the assessment model results within the management procedure.

### Operating models

The operating model is a fundamental component of the MSE. Ideally, it must consider all the essential biological components and processes of the population (Punt et al., 2016). Given the limited data (absence of age and size data), the state-space delay-difference model (Hilborn and Walters, 1992; Meyer and Millar, 1999) was used as an operating model to represent the common spiny lobster population dynamic in Tunisian water. This model represents an intermediate between surplus production models and a more complicated age-structured model. It does not aggregate the growth, recruitment and natural mortality in one term; instead expresses these parameters are individually in the model (Hilborn and Walters, 1992). The delay-difference model keeps the age-structure model setting and its advantages without the requirement of catch at age data. This model has been successfully used to assess crustacean species such as lobsters (Hall, 1997) and prawns (Dichmont et al., 2003).

The population biomass  $B_t$  (t) in year  $t$  is assumed to be obtained from past 2 years' biomass, survival, growth, and recruitment parameters (Equation 1):

$$B_{t+1} = (1 + \rho)S_t B_t - \rho S_t S_{t-1} B_{t-1} - \rho S_t W_{k-1} R_t + W_k R_{t+1} \quad (1)$$

where  $\rho$  is the Brody growth parameter;  $S_t$  is the total survival rate (Equation 2):

$$S_t = e^{-M}(1 - H_t) \quad (2)$$

where  $R_t$  is the recruitment at age  $k$ ;  $W_k$  (g) is the weight at recruitment;  $W_{k-1}$  (g) is the weight one year before the recruitment;  $M$  ( $y^{-1}$ ) is the natural mortality and  $H_t$  is the harvest rate (Equation 3):

$$H_t = \frac{C_t}{B_t} \quad (3)$$

The recruitment followed the Beverton-Holt stock-recruitment relationship (Equation 4). The process error  $\delta_t$  was included in the state process to account for the recruitment deviation.

$$R_t = \frac{4hR_0 B_{t-k}}{B_0(1-h) + B_{t-k}(5h-1)} e^{\delta_t - 0.5\sigma_r^2} \quad (4)$$

where  $h$  is the stock-recruitment steepness;  $R_0$  is the unfished recruitment;  $B_0$  is the unfished biomass, and  $\sigma_r^2$  is the variance of the log-normally distributed process error (Equation 5):

$$\delta_t \sim N(0, \sigma_r^2) \quad (5)$$

The unfished recruitment  $R_0$  (Equation 6) is derived from the biomass equation, if it is assumed that the population is in equilibrium:

$$R_0 = \frac{(1 - (1 + \rho)e^{-M} + \rho e^{-2M})B_0}{\rho W_k W_{k-1} e^{-M}} \quad (6)$$

The exploitation of the common spiny lobster fishery in Tunisia dates to 1936 (Rjeibi, 2012), thus, the model was initiated by assuming that the common spiny lobster stock had already undergone a level of

depletion at the beginning of the time series (i.e., 1995) (Equation 7).

$$B_{1995} = \theta B_0 \quad (7)$$

where  $\theta$  is a coefficient for the initial depletion level.

In the observation process, the catch per unit effort (CPUE)  $I_t$  (Equation 8) is assumed to be available every year over the management period as an abundance indicator. Here, the CPUE is assumed to be proportional to the true abundance through the catchability coefficient  $q$ :

$$I_t = q B_t e^{\mu_t} \quad (8)$$

where  $\mu_t$  is the log-normally distributed observation error:  $\mu_t \sim N(0, \sigma_c^2)$ .

The data used for the conditioning of the models are time series of catch from 1995–2019 provided by the Tunisian Ministry of Agriculture, Water Resources and Fisheries and catch per unit effort from 2000–2008 provided by Rjeibi (2012). The likelihood functions of the model can be written as in equations 9 and 10:

$$R_t \sim \text{log-normal}(\log R_t - 0.5\sigma_r^2, \sigma_r^2) \quad (9)$$

$$I_t \sim \text{log-normal}(\log q B_t, \sigma_c^2) \quad (10)$$

The estimation was conducted within a state-space framework. The parameters  $\theta$ ,  $B_0$  and  $q$  are estimated within the model, and the rest were prespecified and fixed. The model parameters and their specifications are summarised in Table 1. All the computation was executed using Stan v2.21.2 through the Rstan interface (Stan Development Team, 2020) in R v4.0.3 (R Core Team, 2020).

Eight scenarios in the simulations to test alternative MPs. They include the uncertainty in key biological parameters such as natural mortality and steepness. The specifications of the scenarios are listed in Table 2. The OMs, including natural mortality values that correspond to those estimated for the common spiny

Table 1. Parameter specifications of the operating models developed for the common spiny lobster *Palinurus elephas* management strategy evaluation.

Parameter	Value	Source
Natural mortality $M$ ( $y^{-1}$ )	0.15, 0.31	(Marin, 1987; Rjeibi, 2012)
Steepness $h$	0.9, 0.8, 0.7, 0.6	Assumed
Age at recruitment $k$ (y)	4	Calculated
Weight at recruitment $W_k$ (g)	597.63	(Rjeibi, 2012)
Weight one year before the recruitment $W_{k-1}$ (g)	370.51	(Rjeibi, 2012)
Standard deviation of process error $\sigma_R$	0.2	Assumed
Standard deviation of observation error $\sigma_c$	0.15	Assumed

Table 2. Prespecified and fixed parameters of the operating model scenarios considered for the common spiny lobster *Palinurus elephas* management strategy evaluation. The first four considered scenarios (S1–S4) represent the base case scenarios and the last four considered scenarios (S5–S8) represent the robustness case scenarios.

	Prespecified parameters		Estimated parameters		
	$h$	$M(y^{-1})$	$B_0(t)$	$\theta$	$B_{2019}/B_0$
S1	0.9	0.31	405	0.59	0.33
S2	0.8	0.31	435	0.59	0.30
S3	0.7	0.31	479	0.58	0.28
S4	0.6	0.31	531	0.58	0.24
S5	0.9	0.15	756	0.57	0.19
S6	0.8	0.15	817	0.57	0.18
S7	0.7	0.15	889	0.56	0.16
S8	0.6	0.15	983	0.56	0.14

lobster in Tunisia by Rjeibi (2012) are considered base case scenarios. Alternatively, the robustness case scenarios represented the OMs with highly depleted stocks which included lower natural mortality values that coincide with those registered same species in other Mediterranean areas (Groeneveld et al., 2013). The values assumed for the steepness coincide with those for lobster species in previous studies (Punt et al., 2009; Plagányi et al., 2018).

### Management procedures

This study considered model-based management procedures composed of an assessment model and a harvest control rule. The management procedure shows how the stock assessment would be conducted and what effect would the management action have on the population dynamic during the projection period.

The stock assessment model used is the Schaefer surplus production model (Equation 11), where the biomass is given by:

$$B_{t+1} = B_t + rB_t \left(1 - \frac{B_t}{k}\right) - C_t \quad (11)$$

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 catch. The model is fitted and updated annually in the future management period. For this purpose, the data generated from the operating model are used. The assessment results are then used by the harvest control rule to determine the management action setting the TAC in applying this MSE. The TAC is set annually based on the estimated biomass and then implemented to the population dynamic in the OM to generate the future biomass and CPUE data.

More specifically, the assessment model within the management procedure is fitted to CPUE data generated each year by the operating model. The parameters of the model, such as intrinsic growth

rate  $r$ , carrying capacity  $k$ , catchability  $q$ , the initial depletion and the fishing mortality at MSY  $F_{MSY}$  were estimated using the maximum likelihood method under the following distributional assumption (Equation 12):

$$I_t \sim \text{log-normal}(\log[qB_t], \sigma_c^2), \quad (12)$$

where  $\sigma_c$ , the standard deviation for the observation error and is fixed to 0.1 in the model. The results of the assessment, such as estimated biomass and  $F_{MSY}$  are used by the harvest control rules to set TAC as described in Equation 13.

$$TAC = \begin{cases} 0 & \text{if } B_t < B_{lim} \\ F_{MSY} \frac{B_t - B_{lim}}{B_{tar} - B_{lim}} B_t & \text{if } B_{lim} \leq B_t \leq B_{tar} \\ F_{MSY} B_t & \text{if } B_t > B_{tar} \end{cases} \quad (13)$$

The exploitation is not allowed if the current biomass level  $B_t$  is under a biomass limit  $B_{lim}$  where the stock is considered depleted. If  $B_t$  is between  $B_{lim}$  and a target biomass  $B_{tar}$ , the exploitation is reduced linearly until the stock is rebuilt. If  $B_t$  exceeds  $B_{tar}$ , the exploitation is maintained at a target fishing mortality rate  $F_{MSY}$ . A range of conservative and moderate management procedures were considered in addition to relaxed management procedures to take into account stakeholders' potential preference to the latter form. The control points defined for the different harvest strategies are summarised in Table 3. A maximum of 20 % inter-annual change in the TAC was defined for each harvest strategy.

### Management objectives and performance measures

The management objective of the MSE consists of conservation and catch performance objectives. In this study, the conservation objectives are prioritised

Table 3. Summary table of the biomass limit ( $B_{lim}$ ), target biomass ( $B_{tar}$ ) and target fishing mortality ( $F_{tar}$ ) set for each management procedure.

Management procedure (MP)	$B_{lim}$	$B_{tar}$	$F_{tar}$
MP1	$0.3B_0$	$0.6B_0$	$F_{MSY}$
MP2	$0.2B_0$	$0.6B_0$	$F_{MSY}$
MP3	$0.2B_0$	$0.5B_0$	$F_{MSY}$
MP4	$0.2B_0$	$0.4B_0$	$F_{MSY}$
MP5	$0.1B_0$	$0.5B_0$	$F_{MSY}$
MP6	$0.1B_0$	$0.4B_0$	$F_{MSY}$
MP7	$0.1B_0$	$0.5B_0$	$0.8F_{MSY}$
MP8	$0.1B_0$	$0.4B_0$	$0.8F_{MSY}$
MP9	$0.3B_0$	$0.3B_0$	$F_{MSY}$
MP10	$0.1B_0$	$0.1B_0$	$F_{MSY}$

so that the population can recover in the short term and prevent overfishing. This is ensured by maintaining the biomass above 50 % of  $B_0$  and preventing the biomass from dropping below 20 % of  $B_0$ . This limit reference biomass to 20 % of  $B_0$  and target reference biomass was set to 40–48 % of  $B_0$  have also been defined for managing other rock lobster species (Punt et al., 2013; Breen et al., 2016; Plagányi 2018). Catch performance management goals were also considered to maximise the catch while maintaining its stability over the years.

Several performance measures were established to help evaluate the performance of the management procedures and their ability to achieve management goals. The conservation performance was evaluated based on:

- $P(B_{2019-29} < 0.2B_0)$ : The probability of the number of years (out of the 10-year projected period) where stock biomass is below 20 % of  $B_0$  should be equal or smaller than 10 %.
- $P(B_{2029} > 0.5B_0)$ : The probability of the stock depletion at the last year of projection being above 50% of  $B_0$  is equal or greater than 90 %
- $B_{2029}/B_0$ : The medians (over simulations) of the final depletion of the stock after the 10-year projection period.

While the catch performance was evaluated based on:

- $\bar{C}$ : The median (over simulations) of the average catches over the projection period.
- AAV: The average annual variation (Wetzel et al., 2018) in catches from one year to the next over 10-year projection period (Equation 14) must be equal or smaller to 15 %.

$$AAV = \frac{\sum_{y=1}^{10} |C_y - C_{y-1}|}{\sum_{y=1}^{10} |C_{y-1}|} \quad (14)$$

where  $C_y$  is the catch applied in year  $y$ .

## Simulation and projection

In this study, each OM scenario was simulated 100 times considering the different specifications and to account for the process (the recruitment deviation) and observation (sampling) uncertainties. In each simulation, the population was projected for 10 years where the estimation model of the management procedures assessed the data generated by the OM. The TAC feeds the set annually to update the actual population dynamics of the operating model and hence the closed-loop framework. The results of these simulations are presented as:

- Figures of projected biomass, stock depletion, and catches trajectories for a base case scenario and a robustness case scenario under three management procedures.
- A table summarising the performance metrics of each MP and their ability in achieving conservation and catch performance objectives.
- Figures comparing the performance of each MPs and showing trade-offs among management objectives.

## Results

### Projection results: Biomass, stock depletion, and catch trajectories

The biomass trajectories showed an increasing trend

for base case scenarios at the beginning of the projection period under the different management strategies (Figs. 1a, b, c). Under MP3, which is a relatively conservative management procedure (Table 4), the biomass increased steeply for the first scenario S1; it reached and exceeded the target biomass (i.e., 50 % of  $B_0$ ) during the first 4 years of the projection (Figs. 1a, d). The stock recovery was followed by an increase in the catch values after a slight decrease at the end of the historical period (Fig. 1g). Similarly, the biomass reached the target biomass level at the beginning of the projection period and stabilised at that level for the rest of the projection period under MP6 and MP9, respectively moderate and less conservative management procedures. The low allowable catch values initially set increased and reached high values at the end of the projection period allowing the stock to be at the target level (Figs. 1h, i).

Despite the increasing trend of the projected biomass trajectories in the robustness case scenarios, the recovery of the stock was not achieved in most of the scenarios. Panels a, b, and c in Figure 2 show the biomass increase for scenario S7 under the different

management procedures (MP3, MP6 and MP9). The biomass reached the target level at the last year of the projection period only under the conservative management procedure MP3 (Fig. 2e). Given the high depletion of this stock at the beginning of the projection period in this scenario, and despite the decrease of the catches to low levels under the MP6 and MP9 (Figs. 2h, i), reaching the target biomass level requires longer periods under the less conservative strategies (Figs. 2e, f).

### Performance of the management procedures

Figure 3 shows the performance of each management procedure, in terms of biomass in the last year of projection being above 50 % of unfished biomass, for different base case scenarios. Most of the management procedures seem to perform well, with the median of the last year's depletion above 0.5. The MP1, MP2, and MP3, which have the more conservative control points, and MP7 and MP8, which have a reduced target fishing mortality, met that objective with more than 90 % Probability under base case scenario S1 (Table 4).

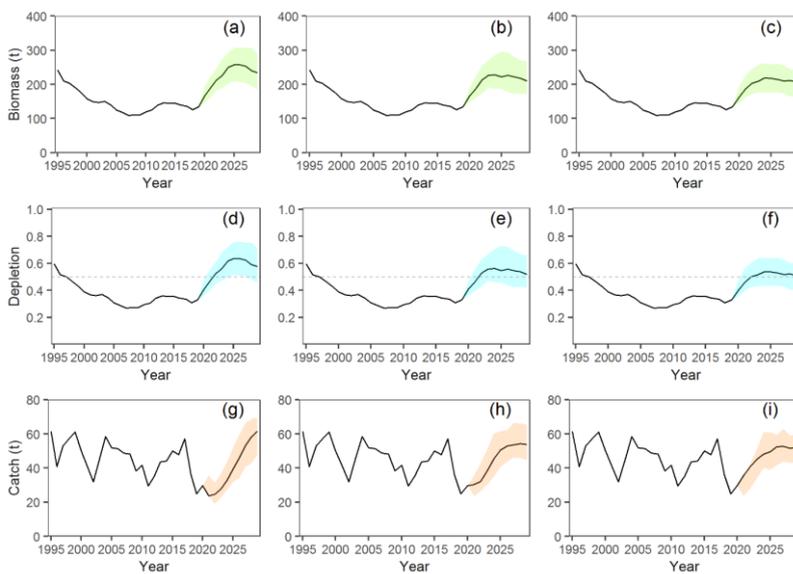


Fig. 1. Trajectories (dark lines are medians; light shading covers the 90 % intervals) of historical and projected biomass for one of the base case scenarios (S1) and three management strategies (left panel: MP3, middle panel: MP6 and right panel: MP9). The horizontal dashed line indicates where the stock status is at 50 % of the unfished biomass.

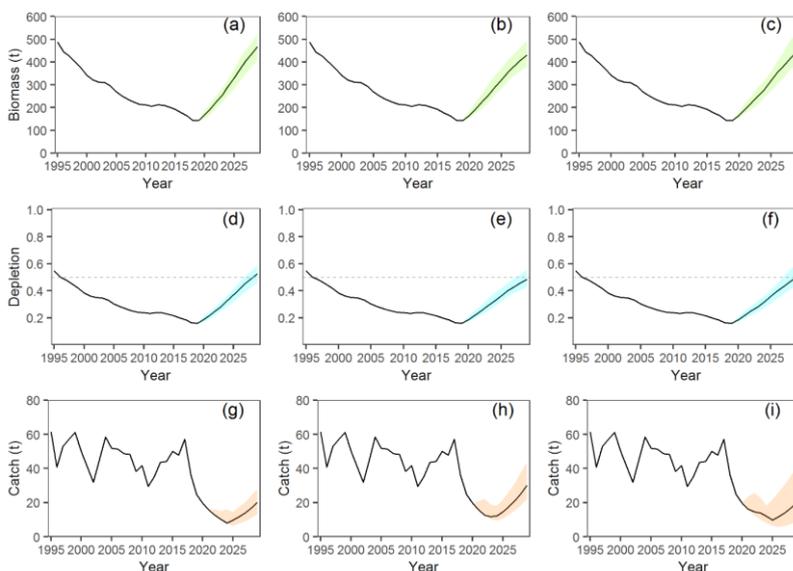


Fig. 2. Trajectories (dark lines are medians; light shading covers the 90 % intervals) of historical and projected biomass for one of the robustness case scenarios (S7) and three management strategies (left panel: MP3, middle panel: MP6 and right panel: MP9). The horizontal dashed line indicates stock status at 50 % of the unfished biomass.

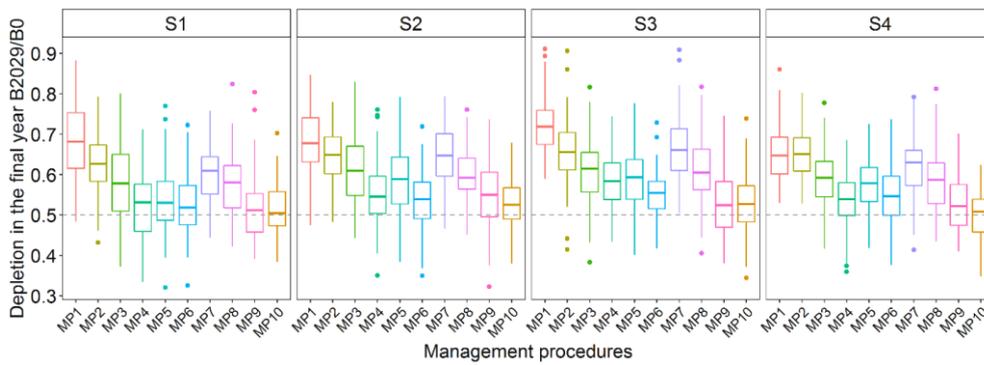


Fig. 3. Boxplots compare the performance of management procedures of the biomass reaching or exceeding 50 % of the unfished biomass in the final year of the management period for the base case scenarios (S1-S4) of the operating models. The dark horizontal lines are median values. The bottom and top of the box are respectively the 25<sup>th</sup> and 75<sup>th</sup> percentiles.

Table 4. Summary table of the 10 management procedures (MPs) under one base case scenario S1 and one robustness case scenario S7. The performance is evaluated based on five performance measures.

MP	Conservation objectives			Catch objectives		
	$P(B_{2019-29} < 0.2B_0)$	$P(B_{2029} > 0.5B_0)$	$B_{2029}/B_0$	AAV	$\bar{C}$	
S1	MP1	0	99	0.67	18.38	29.03
	MP2	0	96	0.64	19.25	33.36
	MP3	0	92	0.57	18.80	33.94
	MP4	0	77	0.54	14.88	37.43
	MP5	0	86	0.58	15.92	36.32
	MP6	0	65	0.51	13.09	39.36
	MP7	0	98	0.64	17.27	32.67
	MP8	0	97	0.59	14.28	38.37
	MP9	0	73	0.51	13.08	38.39
	MP10	0	72	0.51	8.60	43.21
S7	MP1	20	87	0.54	20.00	12.05
	MP2	20	85	0.53	19.94	12.95
	MP3	20	71	0.52	19.47	14.86
	MP4	20	50	0.50	19.86	15.60
	MP5	20	52	0.50	19.34	17.28
	MP6	20	34	0.48	19.2	18.59
	MP7	20	67	0.51	19.91	14.07
	MP8	20	55	0.50	19.50	14.99
	MP9	20	48	0.49	20.00	16.01
	MP10	20	0	0.41	11.75	26.20

These management procedures performed similarly under two robustness case scenarios S5 and S6 but failed to meet that objective under the more pessimistic scenarios S7 and S8 (Fig. 4). Under S7, MP1, MP2 and MP3 has respectively 87 %, 85 % and 70 % probability of keeping the last year's biomass above 50 % of  $B_0$  (Table 4).

Less conservative management procedures have lower probabilities of meeting the requirement of objective 1 in base case and robustness case

scenarios. Under S1, MP9 and MP10 have less than 75 % probability of the last year's biomass being above 50 %  $B_0$ . Under S7, MP 9 has only 48 % probability of meeting that objective (Table 4).

None of the management procedures risks the biomass falling below the limit reference point during the projection period (i.e., 20% of  $B_0$ ) under the base case scenarios. Still, this risk is higher under the robustness case scenarios as the median biomass may drop below the limit reference point at 20 % of

the years under all the scenarios (Table 4).

In terms of catch performances, as expected, less conservative management procedures performed better in maximising the catch over the projection period under the base case scenarios (Fig. 5). MP9 and MP10 yielded higher average catches, 38.39 and 43.21 tonnes, respectively, which is 1.55 and 1.75 times higher than the catch in the last year before the projection period. Some of the conservative management procedures yielded acceptable catch values under S1, as the average catches for MP2 and MP3 were 33.36 t and 33.94 t.

Figure 6 summarises the average catches under the robustness case scenarios during the projection period. Unsurprisingly, the depleted stock status led to low average catches. Under S7, the lowest average catch values were under MP1, 12.05 t around 50 % lower than the catch in the previous year before the projection period.

Four out of the ten management procedures, MP4,

MP6, MP8 and MP10 met the acceptable annual average variation in catch under S1 (i.e., less or equal to 15 %). Robustness case scenarios showed higher AAV, and only MP10 met that objective under S7 (Table 4).

### Trade-offs between management objectives

None of the management strategies performed the best in all the objectives leading to trade-offs between the most conflicting objectives: ensuring the stock recovery and maintaining higher catches. Given that the conservation objectives are prioritised for this MSE, it was concluded that the conservative management strategies with stricter control points (i.e., MP1, MP2, MP3) and reduced target fishing mortality (MP7, MP8) performed better than the other management strategies.

Figure 7 illustrates the trade-offs of these five management strategies' abilities in achieving the management objectives. MP1, with the highest target

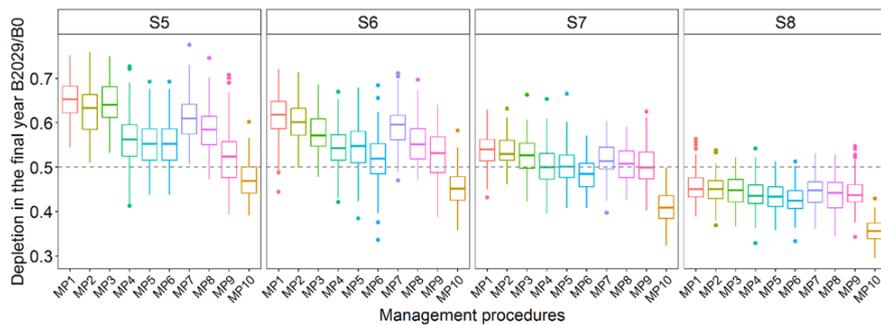


Fig. 4. Boxplots compare the performance of management procedures of the biomass reaching or exceeding 50 % of the unfished biomass in the final year of the management period for the robustness case scenarios (S5–S8) of the operating models. The dark horizontal lines are median values. The bottom and top of the box are respectively the 25<sup>th</sup> and 75<sup>th</sup> percentiles.

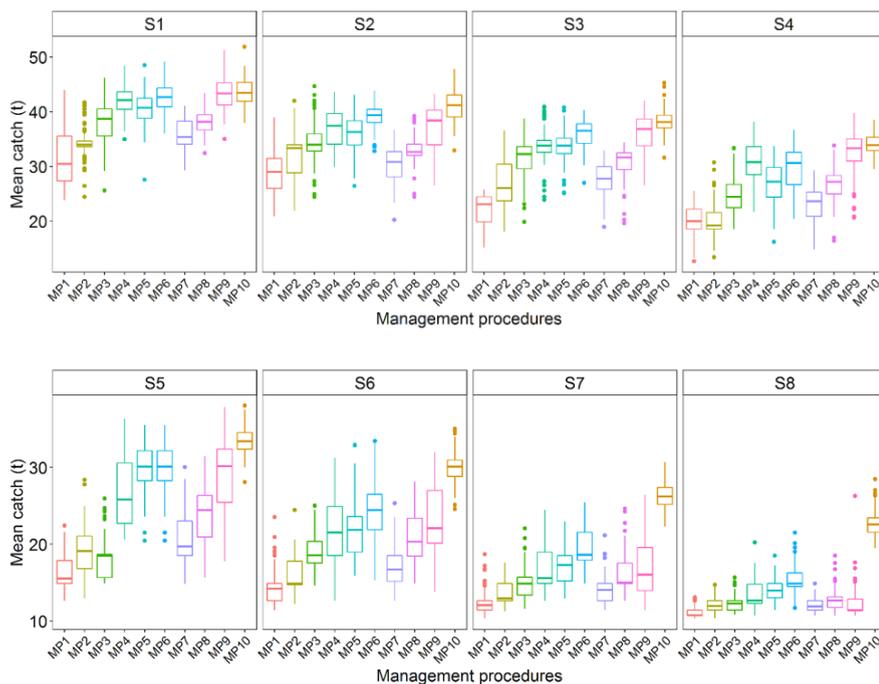


Fig. 5. Box plot compares the performance of management procedures reaching high mean catches over the projected period for the base case scenarios (S1–S4) of the operating models.

Fig. 6. Boxplot compares the performance of management procedures to reach high mean catches over the projected period for the robustness case scenarios (S5–S8) of the operating models.

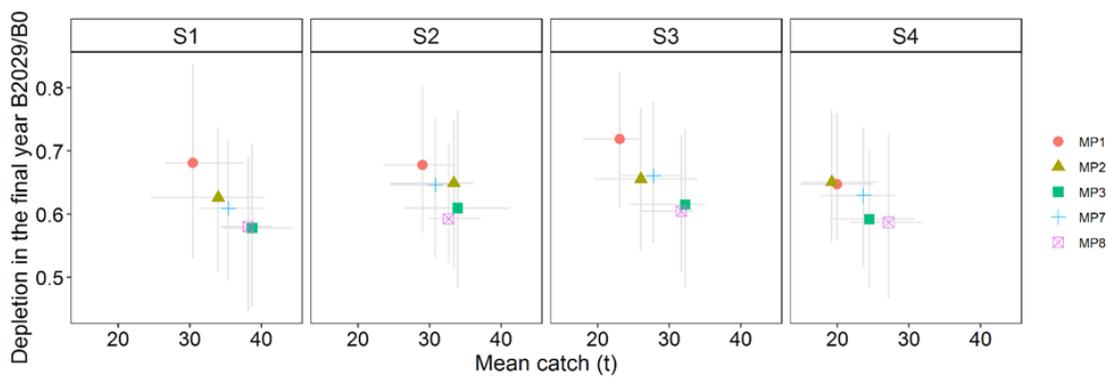


Fig. 7. Trade off plots illustrating the performance of five management strategies in achieving conservation objectives (depletion at the end of 10 years projection) and catch objective (average catch over the projection period) under the base case scenarios (S1–S4) of the operating models (Median values with 90 % error bars are plotted).

and limit biomass, was on the left side of the plots indicating lower average catches under all the base case scenarios. The MP3 and MP8, with the lowest target and limit biomass among these five management strategies, have higher catch values suggesting that these management strategies ensure the balance between conservation and catch performance objectives.

The high AAV in catches among the different management strategies introduces another important trade-off between the variation of interannual catches and average catches. Figure 8 shows that higher AAV were associated with the management strategies with higher biomass limits (i.e., MP1 and MP2); and that MP8 ensured the lowest AAV while maintaining high average catches.

## Discussion

The results of this MSE shows that model-based management procedure may perform well and achieve the objectives proposed to the conservation of the spiny lobster stock in Tunisia in most of the scenarios. The simplicity of the assessment model and the low requirement in data has allowed to implement and evaluate the quota management for the lobster stock in this study.

The MSE has been successfully used for testing and implementing quota management strategies for different lobster fisheries around the world, such as the rock lobster, *Jasus lalandii* (Milne Edwards, 1837), and *Palinurus gilchristi* Stebbing, 1900 (Johnston and Butterworth, 2005) in South Africa; *Jasus edwardsii* (Hutton, 1875), and *Panulirus ornatus* (Fabricius, 1798), in Australia (Punt and Hobday, 2009; Punt et al., 2013; Plagányi et al., 2018) and *J. edwardsii* in New Zealand (Breen and Starr, 2009). The reference points employed in the present study are in general agreement with those employed in the MSE applications mentioned above. The limit reference point is often set at 20 % of  $B_0$  to ensure the recovery of the stock, such as in Punt et al., (2013), while the target reference point can be set at 40 % of  $B_0$  (Punt and Hobday, 2009; Breen and Starr, 2009) or 50 % of  $B_0$  (Johnston and Butterworth, 2005), as proxies for  $B_{MSY}$  to ensure rebuilding the stock and its sustainability.

In Tunisia, studies undertaking the bio-ecology, socio-economy, and the assessment of the common spiny lobster fishery have been conducted (Rjeibi et al., 2011; Rjeibi, 2012; Jaziri et al., 2014). However, to the best of our knowledge, MSE is still not applied to manage the common spiny lobster fishery in Tunisia.

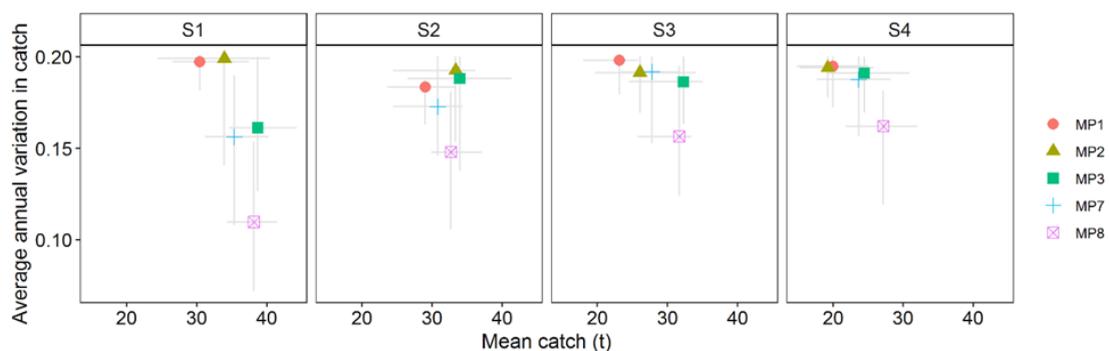


Fig. 8. Trade-off plots illustrate the performance of five management strategies in achieving catch objectives: average annual variation in catch and median average catch over the projection period under the base case scenarios (S1–S4) of the operating models.

The studies of MSE for lobster fisheries mentioned above included both empirical management procedures (data-based that does not require assessment model for the HCR), and model-based management procedures. Punt et al. (2013) used the latter to evaluate the robustness of management procedures based on an age-structured assessment model for the rock lobster fishery in Australia, to non-stationarity in natural mortality, growth, and recruitment (Punt et al., 2013). In the present study, the management procedures are based on an age-aggregated surplus production model, given it's suited to the data-limitation for the common spiny lobster fishery in Tunisia and the simplicity of its implementation. In addition, these MPs can be as useful as more complex model-based MPs (Rademeyer et al., 2007).

Although the key parameters' time variability was not accounted for, the uncertainties related to stock-recruitment steepness and natural mortality were examined. The simulations showed that the management strategies' performance was not sensitive to the different specifications of the steepness parameter. Conversely, changes in natural mortality affected the performance of the MPs. The scenarios with lower natural mortality values had the highest initial depletion and led to the poorest performance of the MPs. This result agrees with the previous study about MSE for the rock lobster fishery (Punt and Hobday, 2009), where a lower natural mortality rate led to poor performance of conservation objectives.

The simulations in this study indicated that MP1 and MP2, the most conservative management procedures with the highest control points, achieved the conservation management goals. They maintained the stock above the biomass limit in the base case and some robustness scenarios. However, they performed poorly and failed to achieve the catch performance management goals resulting in the highest AAV values, which is expected given the frequent reduction in catch values in this type of MPs. Similar findings were observed in the pacific code management strategy evaluation, where the higher variation in annual catches was observed in the MPs with the most precautionary control points (Forrest, 2018).

MP9 and MP10, based on threshold control rules (constant fishing mortality is allowed below  $0.3B_0$  and  $0.1B_0$ ), performed well in yielding high catches in the best-case scenarios but did not achieve conservation management objectives. Among the alternative management strategies, MP3 ( $B_{lim} = 0.2B_0$ ,  $B_{tar} = 0.5B_0$ ) and MP8 ( $B_{lim} = 0.2B_0$ ,  $B_{tar} = 0.4B_0$  and  $F_{tar} = 0.8F_{MSY}$ ) performed satisfactorily in balancing the trade-off between conservation and catch performance objectives. As a result, these MSE outcomes highlighted the trade-off between conservation and catch performance objectives and showed that

moderate management strategies (MP3 and MP8) balanced these objectives well.

None of the management procedures was able to ensure the recovery of the stock under the worst cases of robustness scenarios S7 and S8 that had the highest depletion values at the start of the management period. This indicates that stricter management strategies (such as fishery closure) might be needed in the case of severely depleted stocks and highlights the importance of selecting the appropriate natural mortality values to ensure better management of the species. This is in line with the recommendation of Zhang et al. (2011), where he stressed the necessity of stricter management procedures to prevent the collapse of the stock in the face of the non-recovery of the stock despite the low fishing mortality.

In this paper, the importance of developing and choosing the appropriate management procedure was highlighted for managing the common spiny lobster stock in Tunisian water and the support of the MSE framework to this process. Future studies should include some major sources of uncertainties that were not addressed in this research, impacting the management of lobster fisheries, such as the age at maturity and the species' survival. There is no specific information regarding the stock-recruitment relationship for the common spiny lobster (Goñi and Latrouite, 2005), so it is advisable to increase the operating model scenarios to include different stock-recruitment relationships. The quota management increases the economic yield compared to the minimum legal size management for the rock lobster in Australia (McGarvey et al., 2015). Given that the latter is one of the management strategies applied for the common spiny lobster in Tunisian water, it would be beneficial to test both types of MPs within an MSE framework to encourage introducing new management rules for the better management of this species. Small lobster fisheries in Asia are suffering a fishing pressure and probably undergoing recruitment overfishing in the face of the lack of regulations and management (Penn, 2015). This study may provide an example of the management strategy evaluation of these fisheries by evaluating simple management procedures in case of limitation of data.

## Conclusion

In this study, the application of management strategy evaluation (MSE) was examined for the common spiny lobster *Palinurus elephas* fisheries in Tunisia and the ability of the developed management procedures to meet the management objectives. After projecting the population dynamics for 10 years under the implementation of alternative management procedures, the study was able to identify the management procedures that ensured the recovery of the common spiny lobster stock and the increase and stability in yield and that were robust to

observation and process uncertainties. The results also revealed that quota management, which is currently not used in the common spiny lobster fisheries, enabled the recovery of the species in the short term under several scenarios. The results may vary if the population is projected for a longer period, hence the need to implement management procedures for a longer management period to investigate their efficiency in the long term.

Future research should investigate the robustness of the management procedures to alternative scenarios in the operating model considering alternative stock-recruitment relationships. Furthermore, alternative assumptions regarding the survival and the maturity age of this species should be considered, given the high uncertainty related to these parameters. In addition, the effect of climate change should also be investigated within the MSE for the common spiny lobster, given the species' sensitivity to abiotic parameters such as temperature.

## Acknowledgements

The authors are grateful to the editor and two anonymous reviewers for their constructive and helpful comments on the original version of this manuscript. The authors thank the General Directorate of Fisheries and Aquaculture, Ministry of Agriculture, Water Resources and Fisheries in Tunisia for providing us with the catch data for the common spiny lobster. The authors also thank Okbi Rjeibi, National Institute of Marine Sciences and Technology, for providing the CPUE data that was used in the analysis.

**Conflict of interest:** The authors declare that they have no conflict of interest.

**Author contributions:** Manel Gharsalli: Conducted all the necessary computation, including simulations. Toshihide Kitakado: Inspired and guided the research including technical and statistical aspects, as an expert of the MSE.

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