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Quantitative studies on the stock assessment and management strategy evaluation for the common spiny lobster Palinurus elephas in Tunisia

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Doctoral Dissertation

Quantitative studies on the stock assessment and management strategy evaluation for the common spiny lobster *Palinurus elephas* in Tunisia (チュニジアのヨーロッパイセエビに対する資源評価と資源管理方策評価法に関する数量的研究)

March 2022

Graduate School of Marine Science and Technology
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Manel Gharsalli

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Content

Chapter I

1. General Introduction

1.1. Description of the common spiny lobster (*P. elephas*)

1.1.1. Biology and reproductive cycle

Similar to other palinuridaie, during the eggs hatching, the common spiny lobster releases translucent larvae of 3 mm size. Similar to other palinuridaie, the common spiny lobster releases translucent larvae of 3 mm during the eggs hatching.

Similar to other palinuridaie, the common spiny lobster releases translucent larvae of 3 mm during the eggs hatching. Very flattened dorso-ventrally, they have with their appendices a foliaceous form hence the name of phyllosoma. These phyllosoma lead a sedentary pelagic life. Their development is carried out progressively, by successive moults, through ten larval stages. During the first nine stages, the phyllosoma preserves the original structural characteristics until reaching the size of 21 mm. The phyllosoma at the different stages of their development are found from January to March in the Mediterranean and from July to September in the Atlantic. At the tenth stage, while keeping the same size, the species undergoes two successive metamorphoses before reaching the shape of the adult lobster (Chittleborough, 1976; Marin, 1987).

This new larval form is called Puerulus (Bouvier, 1914; Campillo et al., 1979; Marin, 1985). Puerulus is an organism adapted to swimming. It later transforms into postpuerulus, the first form with the spiny lobster's appearance. It is an exclusively benthic form. Its exoskeleton is not strongly calcified, and its general coloration is brown-red but lighter than the adult. Its total length varies between 24 and 25 mm TL (Goñi et al., 2003; Marin, 1985)

In the Mediterranean, the post-embryonic development of the common spiny lobster, from hatching eggs to postpuerulus, lasts 5 to 6 months (Goñi & Latrouite, 2005). After the postpuerulus phase, the small specimen of common spiny lobster starts growing and increasing the size and weight with the help of moulting. A maturation of the gonads accompanies the growth in size.

The Physiological maturity is reached at the Balearic Island common spiny lobster population at 76 mm CL for females and 82.5 mm CL for males (Goñi et al., 2003). However, one year difference was observed for the age of maturity in Corsica Island's population where the females reached the physiological maturity at 76 to 80 mm CL and males at 76mm CL (Marin, 1987). In Tunisia, Rjeibi (2012) found that physiological maturity for the common spiny lobster is reached at 75.5 mm CL for females and mm 85.19 CL for males.

Mating for the common spiny lobster occurs between a hard-shelled male and a hard-shelled female. The male deposits two white gelatinous masses, the spermatophores, on the posterior part of the female's sternal plate. During the oviposition, the females constitute an egg receptacle by folding the abdomen and tears the spermatophores envelop to release the spermatozoa. The ovules are then fertilized, and the eggs are moved to the endopodites, where they prepare for incubation. The incubation lasts five months in the Mediterranean while it lasts approximately nine months in the Atlantic. This variability has been explained by the influence of temperature on the egg incubation for the Palinuridae species. Examples of the relationship between temperature and eggs' incubation have been demonstrated for the Australian spiny lobster, where the incubation time lasted 70 days at 19° C while it lasted only 25 days at 25°C (Chittleborough, 1976; Marin, 1987).

The fecundity of *P.elephas* is lower than other Palinurus species. Its maximum relative fecundity is 119 eggs/g and is reached at a size of 100 to 110 mm CL (Groenveld et al., 2013).

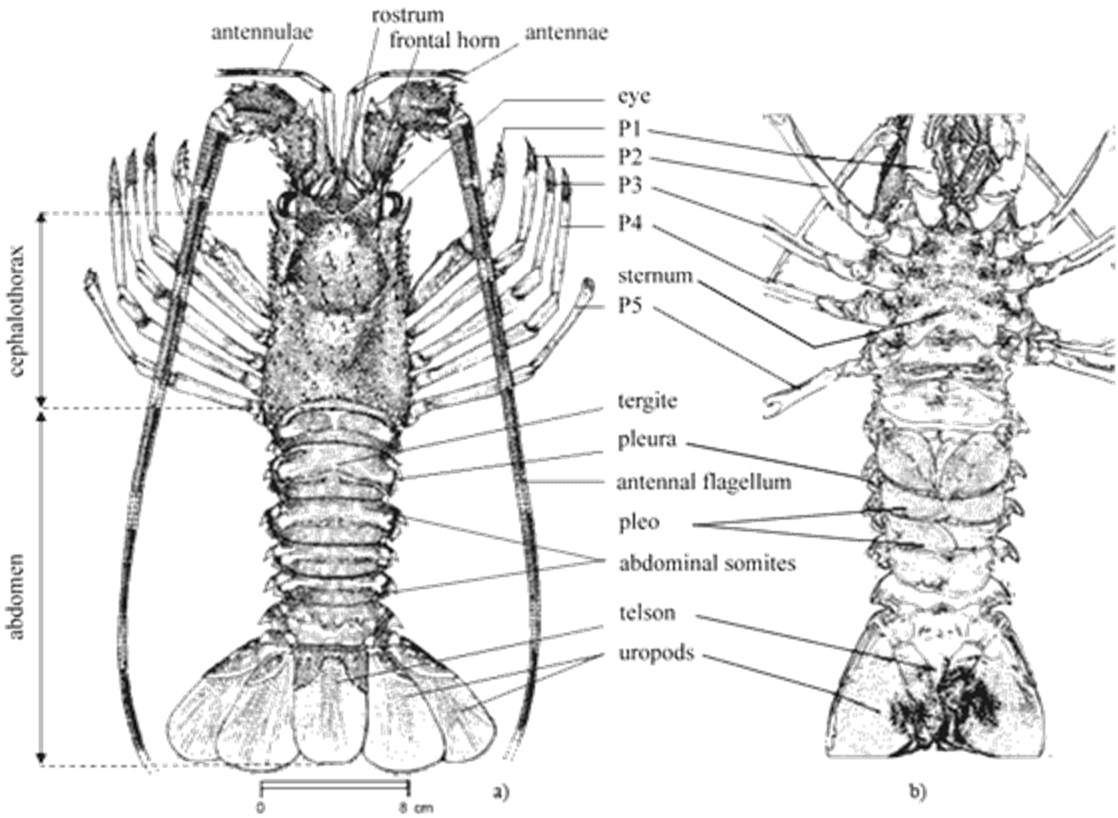

Figure 1- Dorsal and ventral presentation of the common spiny lobster *Palinurus elephas* (Rjeibi, 2012).

1.1.2. Growth and moulting

The life of the spiny lobster is defined by moults. The growth of the animal imposes the rejection of its rigid and inextensible skeleton periodically. Between two successive moults, the red lobster undergoes a series of internal transformations known as the intermoult cycle (Marin, 1987).

In the Mediterranean, moults can occur, with an average of 2 to 3 moults per year. However, the greatest proportion of lobsters in premolt and postmolt phases are observed in the spring. The spiny lobster can make several moults during a single year. The frequency of moulting decreases with the increase of the age and is lower in adult females than in males.

In the past, the larger maximum sizes for the common lobster spiny lobster were believed to be found in the Atlantic at respectively 200mm CL and 170mm CL for male and female in Britanny (Latrouite & Noel, 1997). Compared to those found in Corsica, North-western Mediterranean, where the maximum sizes for males were 175 mm CL, and for females were equal 160 mm CL (Campillo et al., 1979). However, larger specimens are currently observed (186 mm CL and 171.5mm CL for male and female respectively) in the Columbretes Marine reserve that has undergone 20 years of protection (Goñi et al., 2010). Additionally, Quetglas et al., (2004) reported that larger sizes were observed in the Tunisian fisheries (200mm CL and 180mm CL for males and females, respectively).

1.1.3. Habitat and ecology

The Common spiny lobster is found on or near rigid substrates such as rocky bottoms. It is a decapod crustacean living in the temperate waters in the Northeast Atlantic. *P.elephas* firstly appears in the Hebrides and on the west coast of Scotland. Then it is commonly found toward the South, until Cape Bojador in West Africa, especially on the west and south coasts of Ireland, South of England, the Iberian Peninsula, Morocco, the Azores, and Madeira (Ceccaldi & Latrouite, 1994 ; Marin, 1985).

In the Mediterranean, this species colonizes the entire western basin. In the recent decade, the Mediterranean lobster fisheries have been located in the east of the Adriatic Sea (Soldo et al., 2001), in the Balearics (Iglesias et al., 1994), in Corsica (Marin, 1987), in Sardinia (Secci et al., 1995, 1999), in Sicily and northern Tunisia (Quetglas et al., 2004). This lobster species also exists in the North Sea but is not found in the eastern part of the Mediterranean (Figure 1).

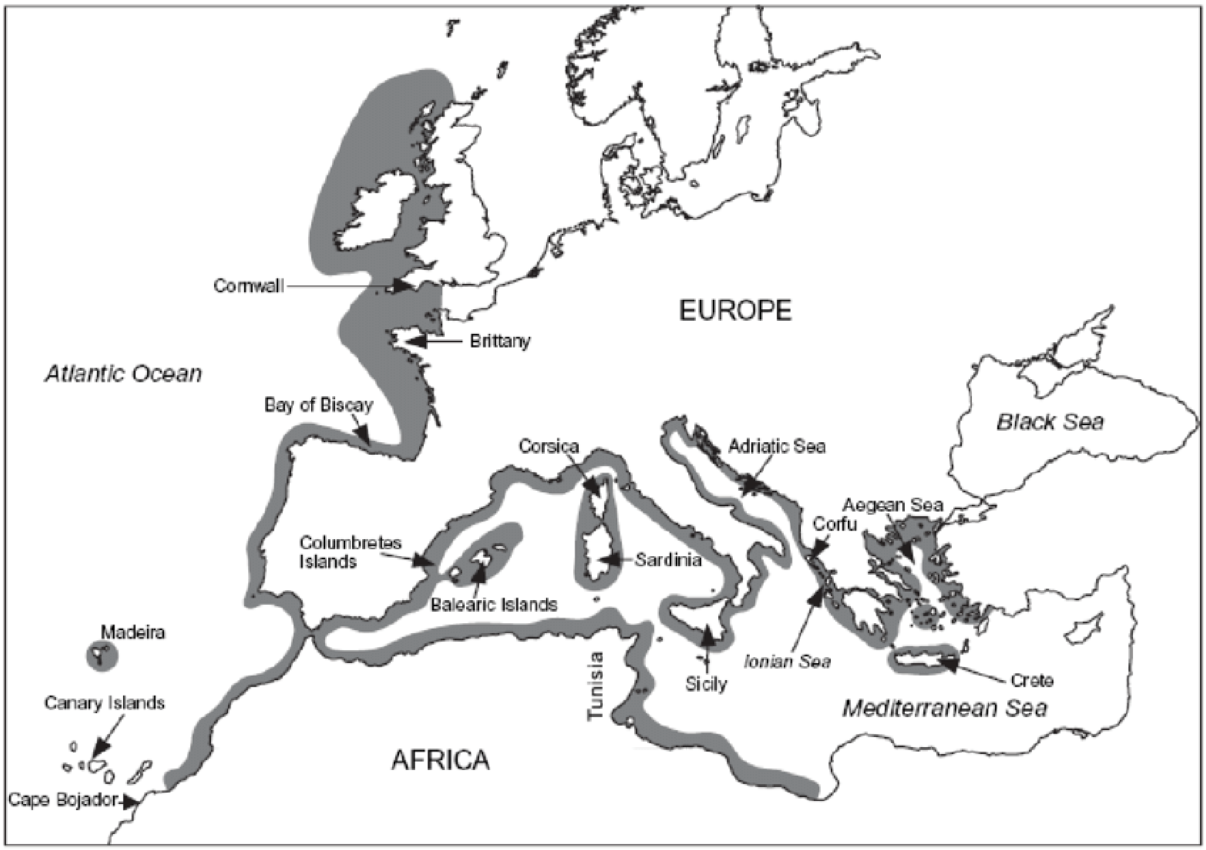

Figure 2- Distribution of *Palinurus elephas* in the Mediterranean Sea and the Atlantic Ocean. (Groeneveld et al., 2013).

The common spiny lobster is a demersal species with a bathymetric distribution that varies with latitude, season, and age. Its habitat must fulfil some thermal and food conditions. The species should be protected against predators there (*Octopus vulgaris, Epinephelus marginatus, Dentex dentex, Sparus pagrus, Labrus spp. Scorpaena spp.)* especially during molting. Its bathymetric distribution spatially distinguishes the common spiny from other Palinuridae.(Marin, 1987)

The common spiny lobster has a tolerable temperature range from 4 to 15 °C. Its biological cycle is related to the seasonal variation of temperature. Its reproduction is stimulated by a slight rise in temperature during the summer season.

During its juvenile phase, this species generally lives at lower bathymetric levels, especially in depths between 15 and 25 m. The young lobsters protect themselves against their predators between the rhizomes of Posidonia. In spring and summer, *Palinurus elephas* is located at depths of 30 to 80 m to meet thermal requirements above 15 °C and photoperiodic requirements necessary for the reproductive cycle (Marin, 1985).

In its adult phase, this crustacean frequents depths of 50 to 200 m (Goñi & Latrouite, 2005). This distribution is linked to thermal and bathymetric requirements. In fact, its minimum tolerable temperature is 4 °C and it lives on rocky and coralligenous bottoms that require a certain luminosity.

The lobster performs a great seasonal movement between the bottom and the surface (Goñi et al., 2003); this can be generalized for all lobsters, it has also been confirmed for Atlantic lobster (Mercer, 1973) and lobster from temperate zones (Hernking, 1980). This movement is dependent on sexual characteristics and on reproductive conditions. Compared to other species of the Palinuridae family, the distribution of common spiny lobster is geographically restricted due to their ecological requirements.

The movement of the common spiny lobster are usually related to feeding, reproduction, and refuge. This species does not perform large movement; studies about the Mediterranean *P.elephas* has shown that it performs small distance of 5 km with some exceptions of 20 km (Goni et al., 2001). Although rare movements of long distances of 50 km and 70 km were observed (Relini & Torchia, 1998; Secci *et al.*, 1999).

1.1.4. Fisheries and management

The common spiny lobster has been exploited for a long time, and its commercial activities related to this species date to the 19^{th} century (Groeneveld et al., 2013). In the Mediterranean, this species has a significant economic value, as its price may hit 120 euro per kg, which explains that it is a highly harvested species (Kampouris et al., 2020).

During the 1960s, a shift in the fishing gears occurred, and trammel-nets replaced the traditional traps. Consequently, and given the low resilience and the increase of the fishing pressure of the common spiny lobster, a decline in its abundance has been observed in the Mediterranean and led to including it as Vulnerable in the IUCN red list (Raquel Goñi & Latrouite, 2005; Groeneveld et al., 2013). In fact, according to FAO official statistics, landings of *P.elephas* in European countries have decreased greatly from 1100 t in 1969 to 434 t in 2017(Marengo, 2020) and in general the species is considered overexploited in the Mediterranean. Goñi & Latrouite (2005), indicated that official landings from Mediterranean coutries might be underestimated given that some proprtions of the captures are sold directly and unreported which suggest greater fishing mortality rates and overexploited stocks.

In the Mediterranean, common spiny lobster is managed by defining the minimum landing size (MLS), which varies slightly for the different fisheries, controlling fishing efforts by temporal closure and the prohibition of the landing of berried females. In addition, marine protected areas (MPA) are also used to manage *P.elephas* in some Mediterranean countries such as the Columbretes in Spain and Les Bouches de Bonifacioin France (Goñi & Latrouite, 2005; Groeneveld et al., 2013).

1.2. Overview of Tunisian fisheries: Stock assessment methods and management context in Tunisia

1.2.1. Fisheries and stock assessment in Tunisia

Fishing is considered an important activity in Tunisia. It represents 8% of the national agricultural production. The total national production in 2019 reached 152890 t, with 27971 t are destined for exportation. The fishing sector counts 12000 fishing boats, contributing to the employment of 50621 fishermen (DGPA, 2019). Tunisia has more than 41 maritime fishing ports distributed along the coast and covering the fishing zones in Tunisia (North, east, south); these ports are classified into two categories according to their importance: 10 large deep ports allowing to accost the trawler, the Tuna fishing vessels, the sardine fishing vessels, and other coastal fishing vessels. The second category includes the ports for artisanal and coastal fisheries.

In Tunisia, four principal methods are employed for stock assessment:

- Length cohort-analysis which is a simplified form of the VPA method where the real cohort term is replaced by the pseudo-cohort that have been identified based on age with the assumption that, in equilibrium, with the assumption that, in a system where parameters are constant the set of length classes captured during a year reflects a single cohort during its existence(Sparre & Venema, 1996). This method allows the reconstruction of population-based on length data. It has been used to assess the common spiny lobster by Rjeibi (2012).

- Scanned areas method is based on the realization of a series of surveys by transect and sampling operations in the study area (Gulland, 1969). This method is commonly used to assess the stocks and the distribution of bivalve species in Tunisia (Charef et al., 2012; Cheour et al., 2014; Derbali, A. et al., 2012)

- Echo-integration technique is employed to assess Tunisian small pelagic stocks (Djemali et al., 2009; Hattour et al., 2004). This technique is the most suitable for small pelagics, known by their migrations and their dependence on environmental conditions (Pauly, 1980).

Hydroacoustic surveys allow estimation of biomass indices and tracking of the spatiotemporal evolution of abundance (Hattour et al., 2004)

- Surplus production models like Schaefer, Fox, and Pella-Tomlinson are also used to assess several stocks such as hake fishery (Khoufi, 2015) and the caramot shrimp fishery. (Jaziri, 2017)

1.2.2. The common spiny lobster fishery in Tunisia

The common spiny lobster is exploited in the North region, especially around the Galite island, where reports about the exploitation of this species in that area date to 1936 (Rjeibi, 2012). According to the Tunisian Ministry of Agriculture, Water Resources, and fisheries data in 2020, around 100 fishing boats are targeting this species in that area.

In the past, the exploitation of this species was made by traps and pots. However, from 1981, trammel nets (Figure 2b, 2d) fishing was introduced and replaced those fishing gears, which resulted in high yields. However, some fishermen are still using the traps (Figure 2c) to keep the caught lobsters during the fishing operation alive. The fishing operations last from 3 to 10 days, depending on the weather conditions and the quantity of lobster that is caught. The trammel nets are usually based on rocky and hard bottoms in-depth varying from 50 to 200m (Rjeibi, 2012).

Currently, this fishery is managed by the following regulations:

- The fishing campaign runs from March 1 to June 30 in territorial waters and from March 1 to September 15 in international waters.
- The Minimum legal size for catch is 20 cm in total length
- The lobster fishing boats must contain trammel nets of 70 mm or more mesh side.
- Fishing for grained females is prohibited regardless of the time of year

a) b) c) d)

Figure 3- Lobster fishing boats "langoustier" in the fishing port of Bizerte (a) and traps (c) and trammel nets used as fishing gear (b-d) .

1.3.Review of the management strategy evaluation approach

1.3.1. What is MSE?

The management strategy evaluation (MSE) is a management tool that uses computer simulations to simulate "virtual" fisheries systems. It is used to test the robustness and the ability of alternative candidate management strategies in achieving the management objective of a fishery. This approach is considered the best practice to develop management procedures that can achieve management goals and are robust to uncertainties (Butterworth, 2007; Punt et al., 2016; Kaplan et al., 2021). The MSE approach has the merit of ensuring the development of several Management Procedures (MPs) and the ability to dismiss the ones that will not achieve management goals (Butterworth, 2010). It also allows to assess the effect of uncertainties on the efficiency of the management actions and to evaluate the trade-offs amongst the management goals (Kaplan et al., 2021).

The MSE process starts by defining the fishery's management objectives. These management objectives will be represented and quantified by a set of performance metrics. The next step would be identifying a range of uncertainties 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 associated with the implementation of the management action (Amar et al., 2008; Kell et al., 2016). The operating models (OMs) are later developed to simulate the "true" population dynamics and mimic the fishing system. These OMs will account for the identified uncertainties and generate the data to inform the management procedures. Alternative MPs are developed and are simulated into the future over a management period to define management actions such as total allowable catch (TAC) that will be fed back to the operating models to update the population dynamics. Depending on the availability of the data, the MPs may be empirical (i.e., model-free) in which the management action is determined from feedback about the data (e.g., recent trends in abundance indexes), or model-based that incorporate a stock assessment model to get the population status and other reference points as inputs for the harvest control rules and the management action (Rademeyer et al., 2007). Finally, this closed-loop system is used to extract the performance measures (Figure 2). The performance measures are analysed and summarised to compare the performance of the management procedures and their ability to achieve the management goals and then, to provide advice to the decision makers (Goethel et al., 2019a). It is important for the success of the MSE process to include, in addition to the scientists and MSE experts, the managers, the decision-makers, and the stakeholders such as the fishermen that are related to the concerned fishery (Goethel et al., 2019b; Sampedro et al., 2017). MSE has the merit of identifying the trade-offs between the management goals and the presence of several representatives of the fishery during the steps of the process would not only reduce the sources of conflict and distrust among the different parties but also help to find solutions that ensure the protection of the resource while considering the wellbeing and profitability of the fishermen (Goethel et al., 2019b).

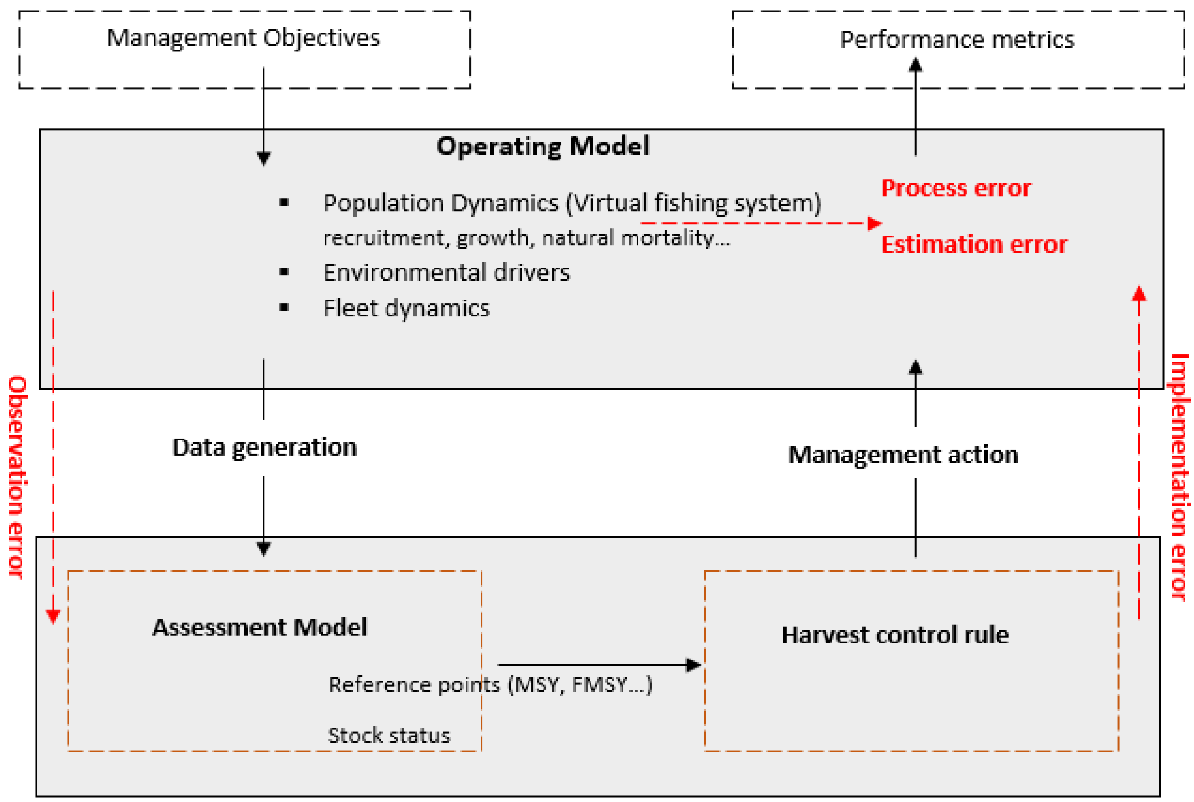

Figure 4- Conceptual model of the management strategy evaluation framework

1.3.2. History and applications of MSE

MSE framework was initially developed and applied, by the Scientific Committee of the International Whaling Commission, in the 1980s for the management of commercial and aboriginal whaling (Punt & Donovan, 2007). It was since then applied to several fisheries, especially in South Africa, New Zealand, and Australia (Holland, 2010). In the 2000s, a significant and quick increase in the application of this method as a management tool was observed internationally (Goethel et al., 2019a).

was firstly limited to the management of single-species fisheries. It was used to manage the southern rock lobster fishery by defining catch quotas in New Zealand (Breen and Kim, 2006). Cox & Kronlund (2008) also applied MSE to develop and evaluate management strategies for the sablefish fishery in Canada. Similarly, MSE was used for the halibut fishery in Greenland (Butterworth & Rademeyer, 2010) and for the management of the fishing of eastern Baltic cod (Bastardie et al., 2010), which included both input controls (effort control) and output controls (catch). MSE has also been applied to manage the rock lobster while assessing the

sensitivity of the alternative management procedures to the stochasticity in recruitment (Punt et al., 2013).
The use of MSE was not limited to the single-species fisheries but was extended to multi-species fisheries and ecosystems to implement ecosystem-based fisheries (EBFM) (Punt et al., 2016 ; Smith et al., 2007). For instance, Punt et al., (2002) applied MSE to test management procedures to 4 key species of Australia's South East fishery where the operating models included biological and fleet dynamic components, taking into account the technical interactions of multi-species fisheries. Dichmont et al., (2008) evaluated the management strategies applied for four prawn species in the prawn fishery in northern Australia within an MSE framework in which the operating model accounted for the populating dynamics, the effort allocation and the impact of fishing to the benthic population.
The implementation of EFBM approaches encompasses not only the management of a target species in the fishery but other components of the ecosystem such as other key species that are not targeted, habitats, interaction amongst the species and ecological communities. It also takes into consideration the socio-economic component of the fishery and of the ecosystem (Smith et al., 2007). To test the performance of such management procedures, the operating model was based on full ecosystem models within the MSE framework for some fisheries. Such was the case for the complex Southern and Eastern scalefish and shark multi-species fishery in Australia, where the end-to-end ecosystem model, Atlantis, was used as the operating model accounting for the environmental and climate drivers, the dynamics of the resources, and their interactions, to test the robustness and performance of a combination of management strategies in achieving ecological and socio-economic management objectives (Fulton et al., 2011, Fulton et al., 2014)

1.4. Problematic and objectives of this thesis

The main objective of this thesis is to assess and develop management procedures for the common spiny lobster fishery in Tunisia. In order to do this, several questions emerged during this research. How to choose the correct assessment model especially when we are in a data-limited situation? How can we use data-moderate assessment models, and would the Bayesian approach benefit the assessment? How to choose among the management strategies and evaluate their performances while making sure that they are robust to the uncertainties associated with the assessment of the models?

In order to answer these questions, we started by assessing the stock of common spiny lobster using data-limited methods in the second chapter. In the next chapter, we investigated the outcomes of applying the delay-difference model using a state-space Bayesian framework. That model was used in chapter four for the conditioning of the operating model used in the management strategy evaluation framework applied to the common spiny lobster fishery to evaluate several model-based management strategies. Finally, the fifth chapter consists of a general discussion of the main results of this thesis and highlights the benefit of using the MSE framework in the interest of the collaboration between scientists, stakeholders, and fishermen to improve the management of the common spiny lobster in Tunisia.

Chapter II

2. Stock assessment for the common spiny lobster fishery in Tunisia using data-limited assessment models

2.1. Introduction

Most of the stocks in developing countries remain unassessed. In fact, the Mediterranean Sea is considered a data-poor region given the low number of assessed stocks and limited available data (Demirel et al., 2020). Despite being one of the highest producers, in terms of total landings, in the Mediterranean Sea with 12.2% of total landings (FAO. 2020), Tunisian fisheries are part of these stocks, where only a few stocks of commercial species are assessed with traditional methods. The most commonly available data for several stocks are the fish landings.

For data-limited stocks, given that the scarcity of the information prevents applying classic age-based stock assessment methods (Prince & Hordyk, 2019), alternative methods are needed for the assessment and management of fisheries. The increasing concern about global stocks status and the growing demand for all the stocks to be assessed had led to the development of several data-limited assessment methods. The choice of the model to use depends on the quality and type of available data. When only catch data are available, Depletion Corrected Average Catch (DCAC) (MacCall, 2009) is used. However, this method is not recommended for when the natural mortality is greater than 0.2 years-1 (Geromont, 2016). When life-history trait information is added to catch data, Simple Stock Synthesis (SSS) (Cope, 2013), the Depletion-Based Stock Reduction Analysis (DB-SRA) developed by Dick & MacCall (2011), Catch-MSY (Martell & Froese, 2013) and its advanced version CMSY developed by Froese et al., (2017), can be used. These models require assumptions about the stock status in various forms. On the other hand, when catch data are not available or sparse, but size-frequency data are available, length-based reference points or length-based indicators and length cohort analysis methods may be used.

CMSY is one of the methods being used to assess the data-limited fisheries given its simplicity and low requirement in data where the biomass and the fisheries' reference points can be estimated using catch data and prior information regarding the stock to be managed (Froese et al., 2017). This method's performance was tested against traditional stock assessment methods for 128 stocks, including crustaceans, in Froese et al (2017) and showed good performance where no significant difference was reported for 76% of the results. This method has also undergone continuous improvements and advances since its development (Palomares et al., 2020).

In this chapter, we assess the common spiny lobster fishery in Tunisia. A valuable fishery with significant socio-economic importance in the country. The huge and continuously growing demand for the common spiny lobster and its high prices in the markets makes it a targeted species vulnerable to overexploitation. Indeed, a decrease in landings has been noticed since the mid-2000s (Rjeibi, 2012). Unfortunately, this species may be considered as a data-limited stock in this situation, given that the only available data for this fishery is the annual landing and a short abundance index times series. Despite its importance, this fishery hasn't been assessed since 2009. In this chapter, we apply the CMSY method to evaluate the common spiny lobster stock in Tunisia and to explore the sensitivity of this method to different assumptions about the stock's final depletion and prior ranges of key model parameters (intrinsic growth rates and carrying capacity). We also apply the state-space Bayesian Surplus Production Model BSPM by fitting the model to a short time-series of Catch Per Unit Effort (CPUE) data; and we finally compare the results of the two methods.

2.2.Material and methods

2.2.1. Data

The data used is a time series of catch from 1995 to 2018 provided by Tunisian Ministry of Agriculture, Water Resources, and fisheries and a time series of CPUE data provided by Rjeibi (2012). The CPUE data is used for the fitting of the Bayesian state space Surplus Production model

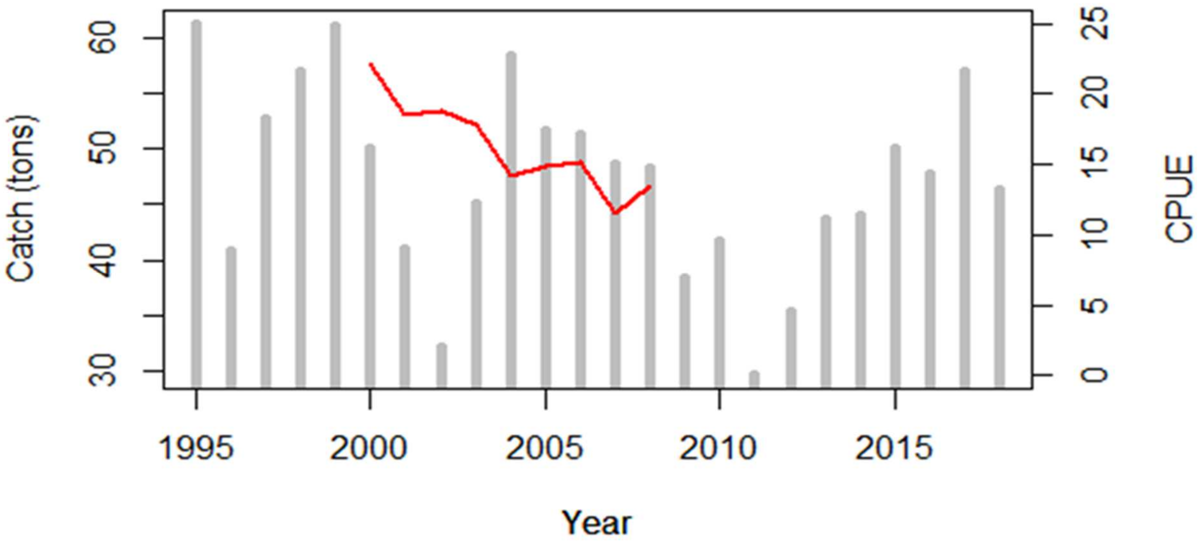

Figure 5-Catch (bars) and CPUE (red line) data for the common spiny lobster in Tunisia.

2.2.2. Description of CMSY method

The CMSY method allows to estimate biomass and other fishery's reference points (MSY, FMSY, BMSY) using catch data, priors on intrinsic growth rate (r) and carrying capacity (K) in addition to priors ranges on the stock depletion at the beginning and at the end of the time series.

2.2.3. Assumption of the underlying population dynamic

The population dynamic is based on the Schaefer surplus production model:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{Bt}{K}\right) - C_t \qquad 2.1$$

Where B_t is the biomass in year t, r is intrinsic growth rate, K is carrying capacity and C_t is the catch in year t.

2.2.4. Estimation method

The method is based on Monte Carlo filtering for the parameters r and K in order to choose the ones that will help produce biomass trajectories that does not collapse and does not crash the stock and that falls within the prespecified prior range of stock depletion (Froese et al., 2017).

Froese et al, 2017 indicate that the prior range of r could be set based on the knowledge about the species resilience provided in FishBase[1] as SeaLifeBase[2] as indicated in Table 1.

Table 1- prior ranges for intrinsic growth rates based on Fishbase classifications (Froese et al., 2016).

Resilience	Prior r range
High	0.6-1.5
Medium	0.2-0.8
Low	0.05-0.5
Very low	0.015-0.1

The priors for K are calculated from the maximum catch and the upper and lower bounds for r . When the prior of the stock's final depletion is low priors are set as follow:

$$K_{Low} = \frac{Maximum\ Catch}{r_{high}}, K_{high=} \frac{4\ Maximum\ Catch}{r_{low}} \quad 2.2$$

While when the prior of the final depletion of the stock is high it is modified as follow:

$$K_{Low} = \frac{2Maximum\ Catch}{r_{high}}, K_{high=} \frac{12\ Maximum\ Catch}{r_{low}} \quad 2.3$$

While in the First version of CMSY, the prior ranges for r and K are sampled from a uniform distribution; this was modified in the advanced version of CMSY (CMSY+) where the prior ranges for r and K are sampled from a multivariate normal distribution (Froese et al., 2017)

The prior range for initial and final depletion of the stock are determined based on the catch history and described in Table 2.

Table 2- prior range for the initial and final depletion of the stock.

Very strong depletion	Strong depletion	Medium depletion	Low depletion	Nearly unexploited
0.01-0.2	0.1-0.4	0.2-0.6	0.4-0.8	0.75-1

We assumed several prior ranges for r, K and final depletion for *P.elephas*. to test the sensitivity of the CMSY method change in those parameters (Table 3). According to Sealifebase the common spiny lobster has a low resilience and its intrinsic growth rate (https://www.sealifebase.ca/summary/Palinurus-elephas.html accessed in December 2021).

In the first model " default specifications" we consider the default prior ranges set and calculated internally within the method. In M1 model, we assume that the stock is strongly depleted, and we set the priors for the final depletion accordingly. In M2, M3 and M4 we assumed alternative ranges of r and K to test the model's sensitivity to changes in these parameters. (Table 3).

Table 3- Prior ranges defined for the common spiny lobster stock.

Species	r	K	Initial depletion	Final depletion
Default specification	0.05-0.5	402-1205	0.2-0.6	0.2-0.6
M1	0.05-0.5	402-1205	0.2-0.6	0.1-0.4
M2	0.05-0.5	60-5000	0.2-0.6	0.2-0.6
M3	0.1-1	60-5000	0.2-0.6	0.2-0.6
M4	0.05-0.5	402-1205	0.2-0.6	0.01-0.7
M5	0.05-0.5	402-1205	0.2-0.6	0.01-0.9

The analysis was conducted using the R-code (CMSY_2019_9f.R) for CMSY+ the advanced version of CMSY (downloaded from the documents accompanying Froese et al. 2017 at http://oceanrep.geomar.de/33076/ accessed in December 2021).

2.2.5. Description of BSPM model

State-space production models has been widely used in the assessment of several stocks especially when data is limited.(Best & Punt, 2020). The application of these models allows for considering for the process error which is linked to the uncertainties in the modelled population dynamics, in addition to the observation error which is associated to uncertainties related to the observed data.

2.2.6. Assumption for the underlying population dynamics

We used the different function of the surplus production model, Schaefer , Fox , and Pella-Tomlinson models where the population dynamics are described as follow:

$$B_{t+1=} B_t + g(B_t) - C_t \qquad 2.4$$

Where $g(B_t)$ is the surplus production function.

$$g(B) = rB\left(1 - \frac{B}{K}\right) \qquad 2.5$$

$$g(B) = rB\left(log\frac{K}{B}\right) \qquad 2.6$$

$$g(B) = rB\left(1 - \left(\frac{B}{K}\right)^z\right) \qquad 2.7$$

Where z is the shape parameter for Pella-Tomlinson model was fixed to 0.3.

The following equation relates the abundance index I_t the biomass B_t with the proportionality coefficient the catchability q :

$$I_t = qB_t \qquad 2.8$$

2.2.7. Estimation method

We used the state-space method, so we assumed multiplicative errors following the normal distribution with mean equal to 0 and variances $\sigma_c{}^2$ and $\sigma_p{}^2$ for observation and process errors, η_t, ε_t ,respectively.

The process function, that describes the dynamic of the system taking into account the underlaying errors is:

$$B_{t+1} = (B_t + g(B_t) - C_t)e^{\varepsilon_t} \qquad 2.9$$

$$\text{Where } \varepsilon_t \sim N(0, \sigma_p{}^2) \qquad 2.10$$

The observation function that describes observation errors such as measurement or sampling errors is:

$$I_t = qB_t e^{\eta_t} \qquad 2.11$$

$$\text{Where } \eta_t \sim N(0, \sigma_c{}^2) \qquad 2.12$$

Given that the exploitation of the fishery is date to the beginning of the 1900, we assumed that the stock at the beginning of the time series (i.e., 1995) has undergone a certain level of depletion:

$$B_{1995} = \theta K \qquad 2.13$$

where θ is a coefficient for the initial depletion.

We used non-informative priors for the parameters estimated within the model, a uniform distribution was assumed for these priors as follow:

$$r \sim U(0.01,1) \qquad 2.14$$

$$K \sim U(0.01,5000) \qquad 2.15$$

$$q \sim U(10^{-9},1) \qquad 2.16$$

$$\theta \sim U(0.4,0.8) \qquad 2.17$$

$$\sigma_p \sim U(10^{-6},0.2) \qquad 2.18$$

$$\sigma_c \sim U(10^{-6},0.2) \quad 2.19$$

For the fitting of the we used 4 MCMC chains each was run for 30000 iterations with 5000 iterations set for the warmup for each model. The computations were made on the rstan interface in R (R Core Team, 2020; Stan development Team, 2020). We used the Widley Applicable Criterion (WAIC) to compare the models

2.3. Results

2.3.1. Results of CMSY method

The estimated biomass trajectory, under the default assumptions, showed an almost stable trend where the biomass, as the biomass estimates in 1995 was 265t, and 261t in 2018 similarly for the depletion trajectory where the medial depletion for the initial year was 0.45 and 0.43 in the final year. A similar behaviour was noticed for M4 and where a wider range for the prior final depletion was assumed (Figure 6e,6f), while the biomass increased slightly from 264t in 1995 to 271 in 2018 (Figure 6g, 6h)

Under M2, where we specify higher values for the final depletion as we assume that the stock is depleted, we notice that the biomass trajectory has a decreasing trend where the biomass decreases from 291t in 1995 to 169t in 2018, similarly the stock depletion moves from 0.47 to 0.27 (Figure 6c, 6d).

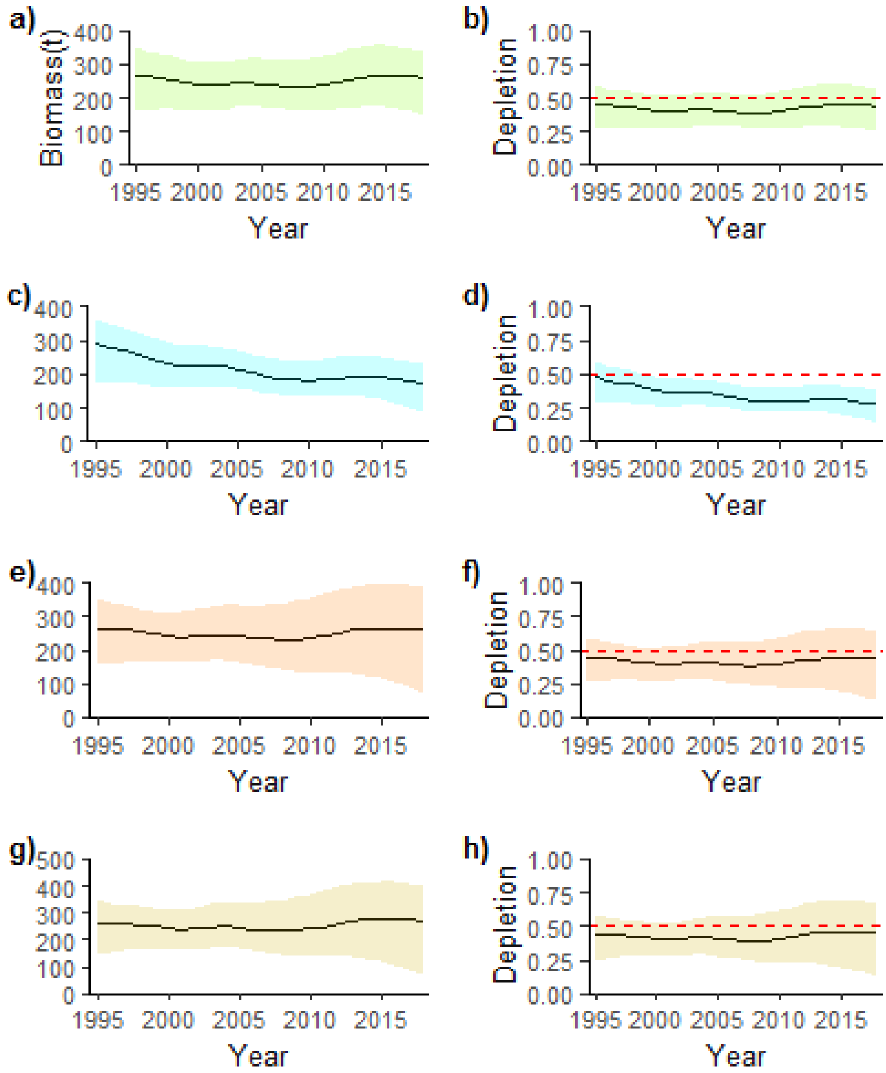

Figure 6-Trajectories (solid line are the medians and the light shading covers 95% confidence level) of estimated biomass and stock depletions under the different assumptions.

In fact, the values of B/BMSY among the different models' assumptions were below 1 which indicates that the stock is overfished. Only under M1, the value of F/FMSY was above 1 indicating that the stock was overfished and that overfishing is accruing (Table 1).

This is also shown on the Kobe plots summarizing the time series of B/BMSY and F/FMSY (Figure7). The right panel shows that for the default assumptions the probability of the stock has a 19.6% probability of being in the red zone 47.2% probability of being in the yellow zone. While in the left panel, showing the model with high depletion prior M1, the stock's probability of being in the red zone is 82.3%.

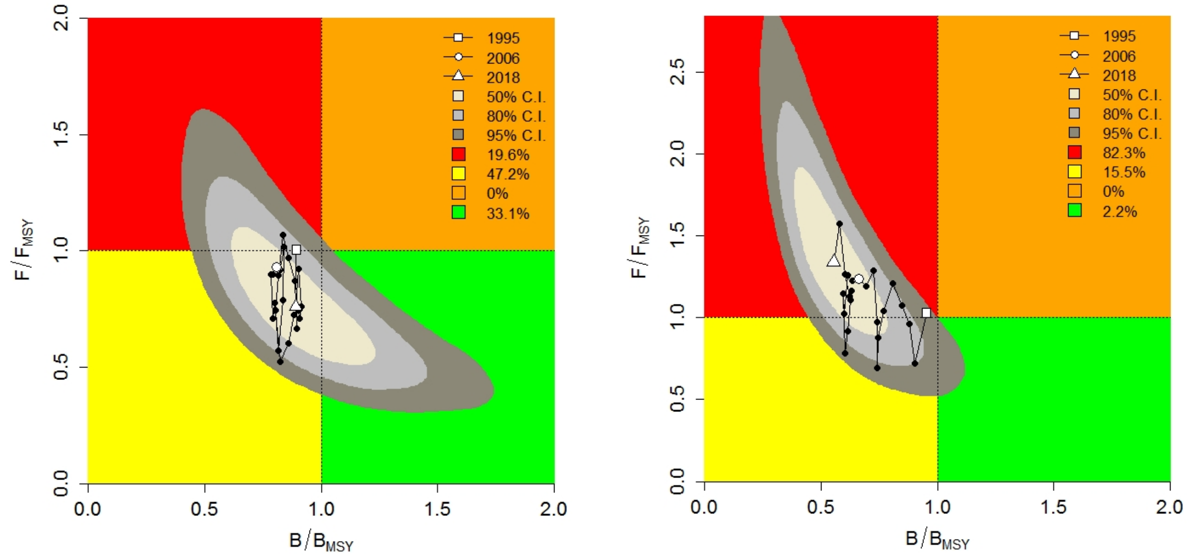

Figure 7-Kobe plots showing the exploitation (F/FMSY) and relative biomass (B/BMSY) time-series for the default assumption model (right panel) and M1 (left panel). The red zone reflects that the stock is overfished and in overfishing, the green zone indicates that the stock is safe, and the yellow zone indicates a reducing fishing pressure with too low biomass level.

A retrospective analysis is also provided within the CMSY method, where three years of the catch were omitted from the catch time series subsequently and was compared to the complete time series. Figure 8 shows the times series of exploitation (F/FMSY) and relative biomass (B/BMSY) where three years of data were omitted (i.e., 2015, 2016, 2017), for M1 model. We notice a similar trend where there is not a big change in the estimation between the retrospective analysis and the current trend for both time series.

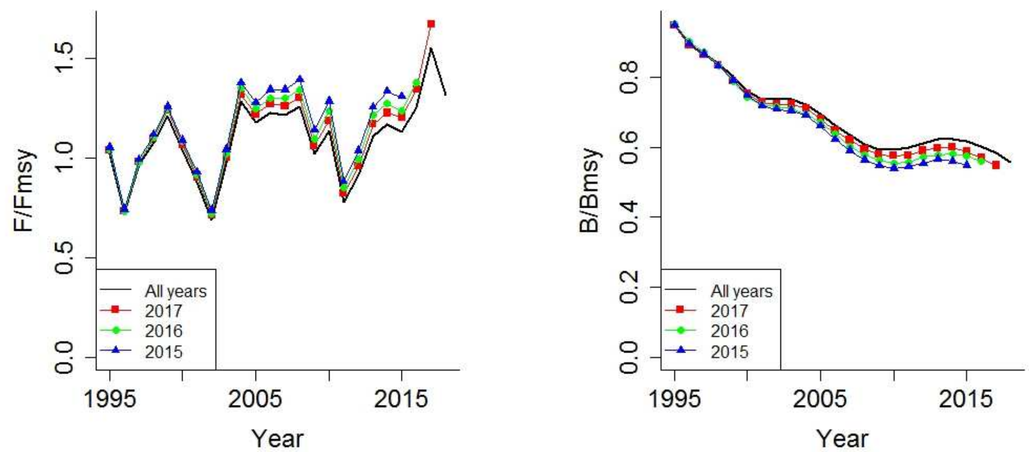

Figure 8-Trajectories of exploitation (F/FMSY) and relative biomass (B/BMSY) time-series comparing the Retrospective analysis to current analysis for the M1 model.

The estimates of r were consistent among the different assumptions, except for M3 where a wide prior range for r was assumed, which resulted in higher estimate for r values and consequently lower estimates for the carrying capacity K. The estimates for K were also consistent amongst the different models, however the estimated value was slightly higher in M2 were we assumed a wide range for t the priors of K. The final depletion value has also shown a consistency and was below 0.5 under the different model assumptions. M1 had the lowest final depletion value equal to 0.28 (Table 4).

Table4- Estimates of the model parameter and reference points by CMSY method with 90% credible intervals.

	R	K	MSY	Bend/K	B/BMSY	F/FMSY
Default specification	0.23 (0.19-0.3)	592 (501-700)	50.4 (41.7-61.3)	0.44 (0.26-0.49)	0.89 (0.52-1.15)	0.76 (0.58-97.5)
M1	0.20 (0.17-0.25)	612 (519-722)	46 (39-53.6)	0.28 (0.13-0.37)	0.55 (0.27-0.75)	1.34 (0.97-2.71)
M2	0.19 (0.12-0.26)	727 (512-1033)	48.7 (38.4-64.4)	0.45 (0.26-0.58)	0.91 (0.53-1.16)	0.76 (0.60-1.33)
M3	0.43 (0.29-0.62)	342 (240-488)	53.5 (43.5-65.5)	0.49 (0.30-0.58)	1 (0.61-1.17)	0.63 (0.54-1.04)
M4	0.23 (0.18-0.3)	600 (508-709)	51.6 (42.4-64.2)	0.43 (0.12-0.64)	0.87 (0.24-1.3)	0.75 (0.51-2.65)
M5	0.24 (0.18-0.31)	597 (500-713)	52.3 (42.5-66.3)	0.45 (0.12-0.67)	0.9 (0.24-1.35)	0.711 (0.48-2.66)

2.3.2. Results of BSPM model

The estimated biomass trajectories have as similar trend slightly decreasing trend in the different models for Schaefer and Fox model (Figure 9a, 9b) and steeply decreasing for Pella-Tomlinson (Figure 6c). Despite this similarity, there is a difference in the values of the estimated biomass. It drops from 800 t to 522t in 2018 for Schaefer model, while in fox model the biomass drops from 700t in 1995 to 459t in 2018 for fox model and from 1000t to 500t for Pella-Tomlinson model.

The depletion trajectories showed a similar trend and was steeper in the Pella-Tomlinson model were the depletion coefficient value decreased from 0.6 in 1995 to 0.3 in 2018; while it was higher in the Schaeffer and Fox models (0.48 and 0.52 respectively)

The CPUE trajectories show that the models seem to fit well the data (Figure 9, left panel). We used the Widely Applicable Information Criterion WAIC to select the model that fits better the data and Pella-Tomlinson had the lowest value equal to 35.9 compared to Schafer and Fox model that had 38.5 and 38.4 respectively.

There is a consistency among the estimates for r and K parameter within Schaefer and Fox models. However, within the Pella-Tomlinson model the estimates of r and K are higher, while MSY and final depletion are lower than Fox and Schaefer model. The estimated values have a wide confidence level for the three models (Table 5)

The B/BMSY values are below 1 for both Schaefer and Pella-Tomlinson model, while the F/FMSY is above 1 only for Pella-Tomlinson model.

Table 5- Estimates of the model parameter and reference points by BSPM method with 90% credible intervals

	R	K	MSY	Bend/K	B/BMSY	F/FMSY
BSPM (Schaefer)	0.21 (0.03-0.73)	1388 (586-3232)	53.5 (35.7-196.3)	0.48 (0.13-0.9)	0.86 (0.41-1.53)	0.84 (0.63-1.65)
BSPM (Fox)	0.21 (0.02-0.71)	1140 (407-2885)	57.58 (38.7-202.7)	0.54 (0.2-0.9)	1.1 (0.76-2)	0.81 (0.22-1.19)
BSPM (Pella-Tomlinson)	0.29 (0.04-0.44)	1600 (758-2692)	45.23 (28.4-87.5)	0.32 (0.1-0.7)	0.68 (0.35-1.2)	1.02 (0.52-1.63)

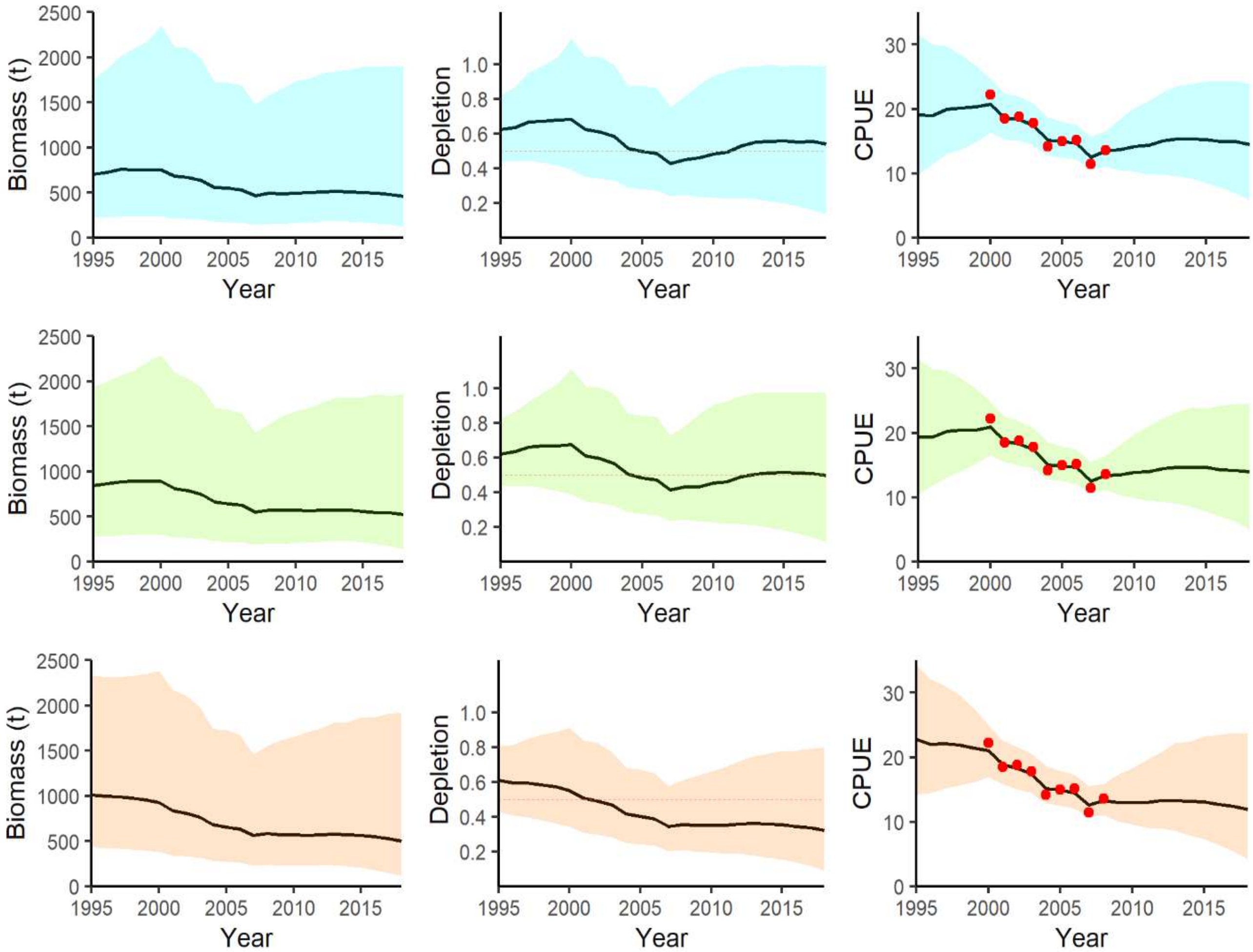

Figure 9- Trajectories (solid line are the medians and the light shading covers 95% confidence level) of estimated biomass (left panel), stock depletions (middle panel) and predicted CPUE (right panel) under the different models Shaefer (a), Fox (b) and Pella-Tomlinson (c). The observed CPUE is represented by the red dots

2.4. Discussion

We were able in this study to apply and assess the common spiny lobster stock in Tunisia using CMSY and BSPM models. The results of this study showed that the spiny lobster stock is overfished and depleted under the current specifications.

CMSY method showed that the stock seemed to be overfished under different assumptions or depleted with a biomass level below BMSY. The Kobe plots showed a high probability of the stock being in the red zone, which indicates that the stock is depleted. The sensitivity analysis showed the importance of choosing the "correct" prior ranges of the key model parameters. As expected, the model was sensitive to the prior ranges of final depletion, which is one of the limits of not only the CMSY method but for the catch-based methods in general (Carruthers et al., 2014; Pons et al., 2020). Among intrinsic growth rate, carrying capacity, and the final depletion, changes on the prior ranges of the final depletion had the most significant effect on the stock status determination. The retrospective analysis showed a similar trend and no difference within the three years of analysis which supports the hypothesis of the model's liability in estimating the fisheries reference point.

The results of the BSPM models showed that the biomass trajectories have a slightly decreasing trend and that the stock is slightly depleted under Schaeffer and fox model; however, the depletion was steeper in the Pella-Tomlinson model. The latter fitted better the data according to the WAIC. B/BMSY and F/FMSY values indicated that the stock is overfished, and overfishing is occurring in Schaefer and Pella-Tomlinson model. The latter model fits better the data. Despite the consistency in the parameter estimates by BSPM, the wide range of variation reflects the quality and the limitation of the data. The short time series of observed CPUE and the absence of any abundance index data at the end of the time series are a source of uncertainty for this model. Which highlights the importance of collecting the abundance indices related to data fishery-dependent and independent data should be collected in order to reduce the sources of observation error within these models.

The parameter estimates for intrinsic growth rate are consistent between BSPM and CMSY methods and coincide with the values of intrinsic growth rates for *P.elephas* species according to SeaLifeBase[2]. Similarly, there is consistency between the fisheries reference point such as MSY, F/FMSY, and B/BMSY but estimates for carrying capacity differed and were higher for BSPM. On the other hand, the estimated biomass values were inconsistent among both methods, as the biomass estimates were higher within BSPM. This difference may be explained by the contribution of the abundance index data to the assessment of the population dynamic, but further sensitivity analysis is recommended for the BSPM method.

In this study we used non-informative prior information for the model's parameter as it has been recommended to use these priors when knowledge about the fishery and the species are lacking (Punt & Hilborn, 1997). However, despite the debates regarding the choice of the priors, it is thought that the informative once may result in decreasing the uncertainties (Punt & Hilborn, 1997). For that reason, in addition to improving the abundance index-related data, developing approaches to elicit the expert to use their expertise and the information they can provide about the common spiny lobster species and the fishery to develop informative priors could improve the assessment approach used for this species.

The use of CMSY and BSPM had the advantages of getting information about the stock status and some of the reference points, such as MSY, despite the simplicity of their application and the low requirement in data. However, this simplicity can also be disadvantageous as these models can not include important processes reflecting the underlying dynamics, such as recruitment. Hence, the need to apply models that allows us to account for such processes.

Chapter III

3. Application of the delay difference model for the assessment of the common spiny lobster, *Palinurus elephas*, in Tunisia

3.1. Introduction

In the previous chapter, we focused on the use of data-limited methods and age-aggregated population dynamic models such as the Bayesian surplus production models in assessing the stock of common spiny lobster in Tunisia. The advantage of these models is their ability to inform on stock status and provide management reference points despite the simplicity of their application and their low requirement in terms of data (Geromont, 2016). However, these models are criticized for their inability to use the age-structure information and incorporate important processes such as recruitment, leading to a lack of biological realism in their underlying dynamics (Bonfil, 2005; Geromont, 2016; Meyer & Millar, 1999). On the other hand, the application of a more advanced and realistic age-structured model requires in addition to the catch data that may encompass the bycatch and the discards and the abundance data, maturity and sometimes tagging data, age composition data, and length data, length and weight at age data (Hilborn & Walters, 1992). These data can reflect the changes in structure of the population, the growth, the natural mortality, and the recruitment (Ono et al., 2013). However, these are unavailable or difficult to collect in some fisheries, especially in developing countries (Bonfil, 2005; Demirel et al., 2020). Hence, the need for a method that would allow us to include the biological information of the species in the assessment and to account for the key process in the underlying population dynamics in a simple way with a low requirement in data which brings us to the delay difference model.

The delay difference model is an intermediate between the age-aggregated surplus production models and the age-structures models. They offer a more realistic representation of the population dynamic by including recruitment, growth, and survival processes, hence accounting for the age-structure implicitly, without the data requirement and complexity of age-structured models (Hilborn & Walters, 1992). These terms are simplified in one population dynamics equation that allows for the estimation of the model's parameters and the biomass by fitting the model to catch and abundance index data only. Delay difference models have been used to assess alternative species, including crustaceans such as the western rock lobster in Australia (Hall, 1997) and tiger prawn fishery in Australia (Dichmont et al., 2003).

In this chapter, we apply the state-space delay difference model to evaluate the stock the common spiny lobster stock in Tunisia using the available biologic information. In addition, alternative scenarios regarding the model's parameter were also considered to check the sensitivity of this model.

3.2. Materials and methods

3.2.1. Population dynamic:

The population biomass B_t is in year t obtained from past two years' biomass, survival, growth, and recruitment parameters:

$$B_{t+1} = (1+\rho)S_t B_t - \rho S_t S_{t-1} B_{t-1} - \rho S_t W_{k-1} R_t + W_k R_{t+1} \quad 3.1$$

where ρ is the Brody growth parameter; S_t is the total survival rate:

$$S_{t=} e^{-M}(1-H_t) \quad 3.2$$

R_t is the recruitment at age k; W_k is the weight at recruitment; W_{k-1} is the weight one year before the recruitment; M is the natural mortality and H_t is the harvest rate:

$$H_t = \frac{C_t}{B_t} \quad 3.3$$

3.2.2. Stock-recruitment relationship

The recruitment followed the Beverton-Holt stock-recruitment relationship assuming that the recruitment tends towards an asymptotic value as the spawning biomass increases .

$$R_t = \frac{4hR_0 B_{t-k}}{B_0(1-h)+B_{t-k}(5h-1)} \quad 3.4$$

where h is the stock-recruitment steepness; R_0 is the unfished recruitment; B_0 is the unfished biomass.

The unfished recruitment R_0 is derived from the biomass equation, if we assume that the population is in equilibrium:

$$R_0 = \frac{\left(1-(1+\rho)e^{-M}+\rho e^{-2M}\right)B_0}{\rho W_k W_{k-1} e^{-M}} \quad 3.4$$

3.2.3. Parameter estimation

The estimation was conducted within a state-space framework.

The process error δ_t was included in the state process to account for the recruitment deviation.

$$R_t = \frac{4hR_0B_{t-k}}{B_0(1-h)+B_{t-k}(5h-1)}e^{\delta_t - 0.5\sigma_r{}^2} \quad 3.5$$

where $\sigma_r{}^2$ is the variance of the log-normally distributed process error:

$$\delta_t \sim N(0, \sigma_r{}^2) \quad 3.6$$

In the observation process, the catch per unit effort I_t is expressed as follows:

$$I_t = qB_te^{\mu_t} \quad 3.7$$

Where μ_t is the log-normally distributed observation error: $\mu_t \sim N(0, \sigma_c{}^2)$

The model was initiated by assuming that the common spiny lobster stock was already depleted at the beginning of the assessment since the exploitation of the fishery has started since the early 90s.

$$B_{1995} = \theta B_0 \quad 3.8$$

where θ is a coefficient for the initial depletion.

The parameters θ, B_0, q , $\sigma_r^2 and\ \sigma_c^2$ are estimated within the model, the rest of parameters were fixed. The model parameters and their specifications are summarized in Table 6. The likelihood functions of the model can be written as:

$$R_t \sim \text{lognormal}(\log R_t - 0.5\sigma_r^2, \sigma_r^2) \quad 3.9$$

$$I_t \sim \text{lognormal}(\log qB_t , \sigma_c^2) \quad 3.10$$

The model was written and executed by the mean of Stan v2.21.2 through the rstan interface (Stan Development Team, 2020) in R v4.0.3 (R Core Team, 2020).

Table 6- Biological parameter used for the delay difference model.

Parameter	Value	Source
$\boldsymbol{M}$	0.31 y^{-1} , 0.15y^{-1}	Rjeibi 2011, Marin1987
$\boldsymbol{h}$	0.9, 0.8,0.7,0.6	Assumed
k	4	estimated
$\boldsymbol{W_k}$	597.63g	Rjeibi 2011
$\boldsymbol{W_{k-1}}$	370.51g	Rjeibi 2011

3.2.4. Data and Model assumptions

The data used for the fitting of the model are time series of catch from the years 1995-2019 provided by the Tunisian Ministry of Agriculture, Water Resources and Fisheries and catch per unit effort (CPUE) from the years 2000-2008 (Rjeibi et al., 2011).

A sensitivity analysis conducted where we accounted for change in steepness, natural mortality, and the process error coefficient of variation (Table 7). The natural mortality values are those registered for the common spiny lobster in in Tunisia by Rjeibi (2012) and other Mediterranean area (Groeneveld et al., 2013). The values assumed for the steepness coincides with those assumed for lobster species in previous studies (Punt et al., 2009; Plagányi et al., 2018).

Table 7- Model specifications for the delay difference model's parameters.

Model	h	M	σ_r	σ_c
Model 1	0.8	0.31	0.1	0.15
Model 2	0.8	0.31	0.2	0.15
Model 3	0.8	0.31	03	0.15
Model 4	0.7	0.31	0.2	0.15
Model 5	0.6	0.31	0.2	0.15
Model 6	0.8	0.15	0.2	0.15

3.3.Results

The biomass trajectories within the different models had a similar decreasing trend but we observe different estimates for the biomass (Figure10). In model 1 the biomass decreases from 250t in 1995 to 95t in 2019 while in model 6 where lower natural mortality values are assumed, the biomass decreases from 460 t in 1995 to 150 t in 2019. The stock is depleted within the alternative models with steepest depletion registered in Model 5 and Model 6 where the depletion decreases from 0.6 in 1995 to 0.24 in 2019 and from 0.6 to 0.18 2019 respectively. The values of the stock depletion in 2019 is below 0.5 within the different assumptions.

CPUE trajectories follows a similar trend to the biomass trajectories and shows that the model seems to fit well the data in the different scenarios (Figure 10 right panel). The confidence level for recruitment variation is wide in the different models but it is wider in the scenarios with higher coefficient of variation for recruitment which is model 3 while it is the thinnest for model 1 (Figure 10d, 10a). The recruitment trajectories show a general decreasing trend where the recruitment decreases in 2000 to stabilize and then increases slightly from 2005 to decreases again from 2008 to 2019 (Figure 11).

There is a consistency between the estimated R_0 estimates within the alternative models. However, Model 1 has the lowest estimate for B_0, and Model 6 has the highest value. In term of final depletion Model 6 has the lowest value (Table 8).

Table 8- Estimates of the model parameter by the delay difference model with 90% credible intervals .

	B_0	R_0	Bend/K
Model1	350 (328-402)	0.101 (0.095-0.116)	0.28 (0.17-0.49)
Model2	435 (394-577)	0.126 (0.114-0.167)	0.30 (0.15-0.71)
Model 3	579 (505-881)	0.167 (0.146-0.255)	0.33 (0.13-0.9)
Model 4	479 (431-602)	0.139 (0.125-0.174)	0.28 (0.13-0.64)
Model 5	531 (475-658)	0.153 (0.137-0.190)	0.24 (0.10-0.58)
Model 6	817 (737-957)	0.103 (0.093-0.121)	0.18 (0.07-0.4)

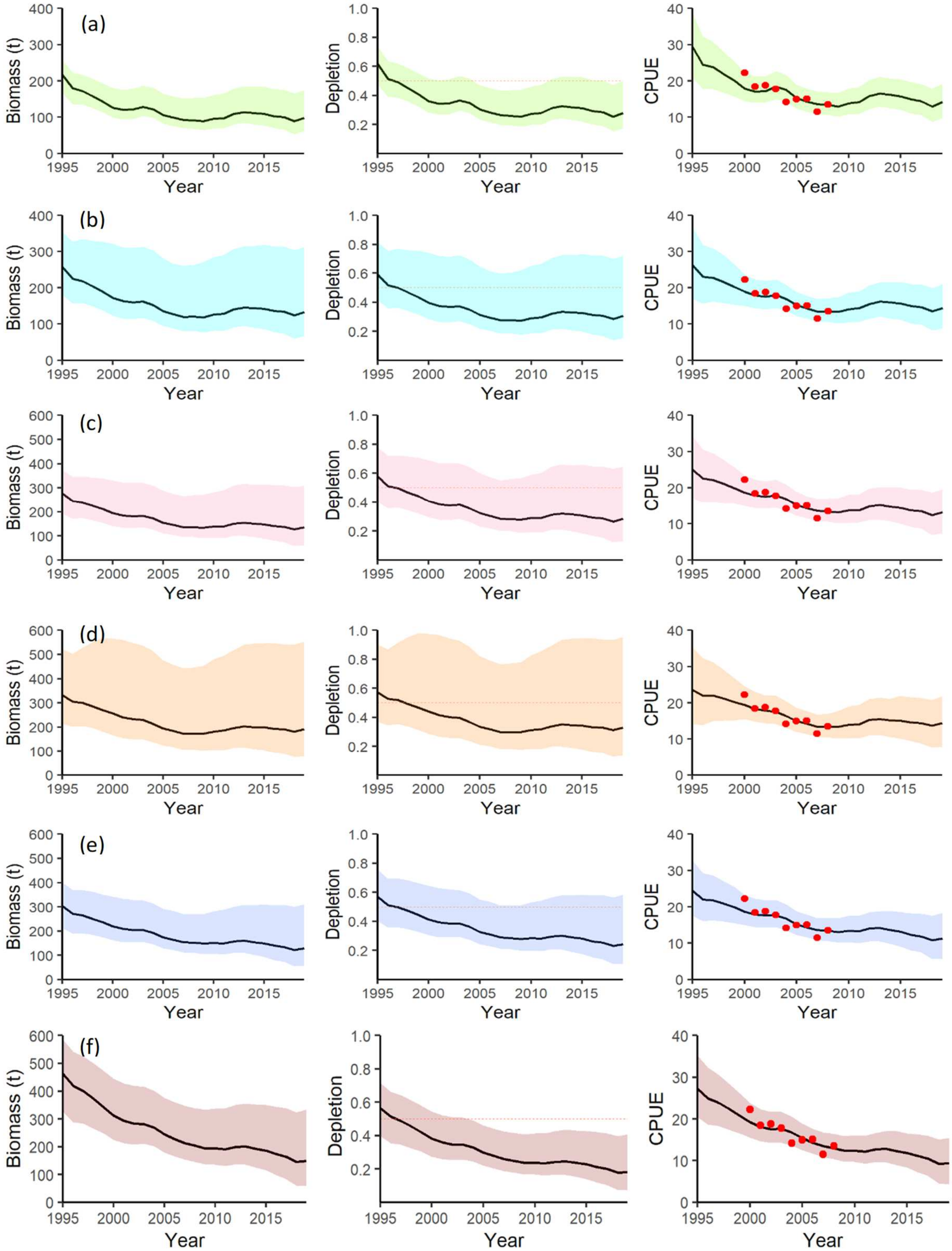

Figure 10- Trajectories (solid line are the medians and the light shading covers 95% confidence level) of estimated biomass (left panel), stock depletions (middle panel) and predicted CPUE (right panel) under the different models 1-6, a-f respectively.

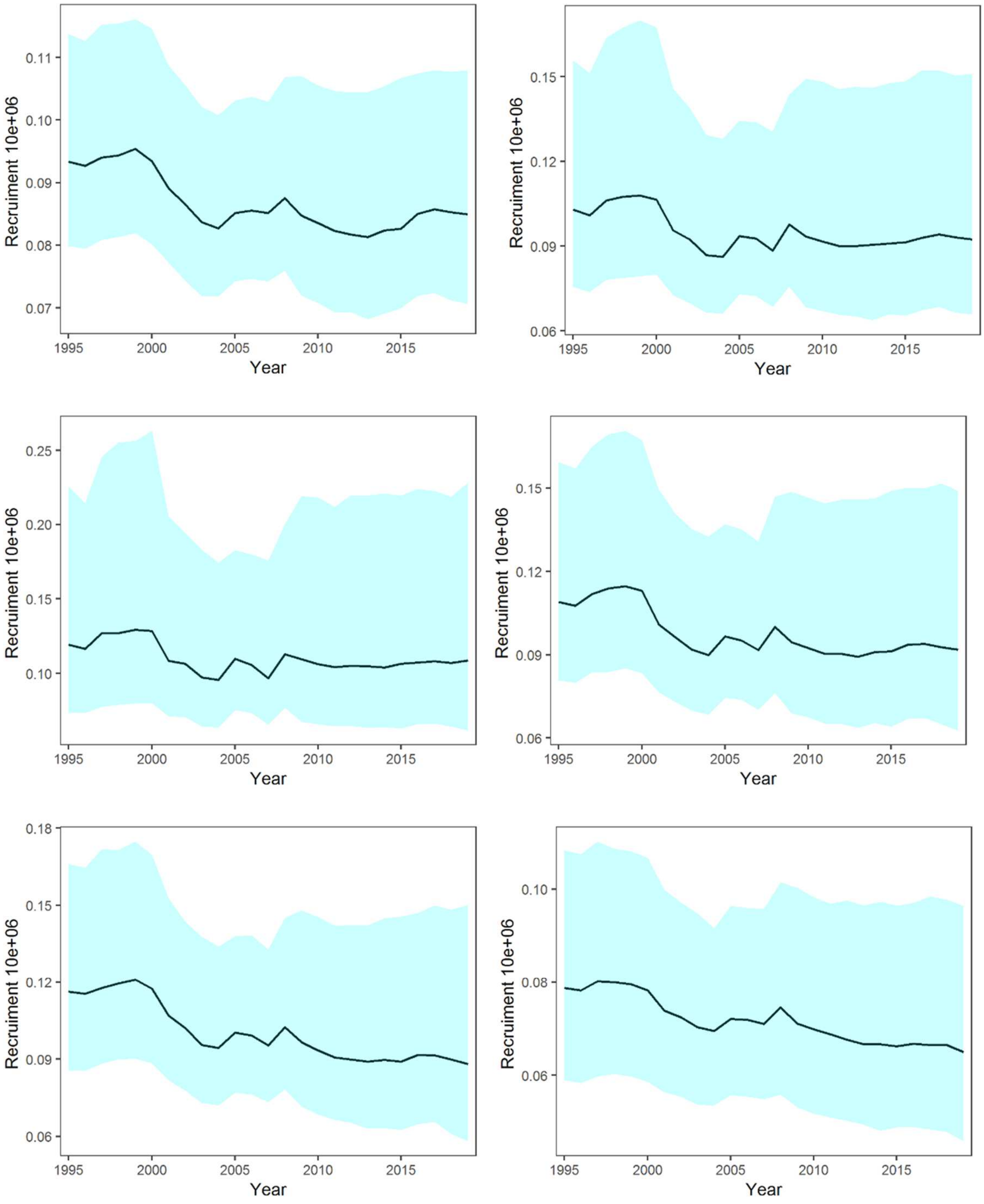

Figure 11- Recruitment trajectories (solid line are the medians and the light shading covers 95% confidence level)) under the different models 1-6, a-f respectively.

3.4. Discussion

In this chapter, we used the Bayesian state-space delay difference model to evaluate the common spiny lobster fishery in Tunisia. The results suggest the stock is depleted and that there is a continuous decrease in the biomass that was similar to the decreasing trend of the biomass for the assessment of this species with CMSY and BSPM observed in the previous chapter. The biomass, depletion, and recruitment trajectories had a decreasing trend which was observed in the methods used in the last chapter; however, a difference between the biomass values was observed between the BSPM and the delay difference model. The predicted CPUE trajectories suggest that the model has fitted well the data and has captured the fluctuations in the observed CPUE, which agrees with Hilborn and Walters (1992) that deduced that the delay-difference model captured better the trends when fitting catch and CPUE data in comparison to the Schaefer model. They also highlighted the lack of the biological reality and the incapability to consider the delay between reproduction and recruitment within the surplus production models, which is problematic, especially for species with a significant delay in this phase. Thus, we investigated the use of the delay-difference model of the stock assessment of the common spiny lobster and included the delay between reproduction and recruitment.

The output of the analysis showed that the model was not sensitive to variation steepness; however, a sensitivity to the natural mortality and to the recruitment deviation was observed. The increase of the recruitment deviation was accompanied by a decrease in the biomass values and a decrease of the stock depletion, which brings attention to the importance of considering the environmental drivers and their effect on the variation of this process and its implication in the population dynamics. On the other hand, the decrease of natural mortality values resulted in the severe depletion of the stock and the steep decline of the biomass. This highlights the importance of sensitivity analysis and the consideration of uncertainties related to this process on the population dynamics and the management of the species.

Chapter IV

4. Management strategy evaluation for the common spiny lobster stock, *Palinurus elephas*, in Tunisia

4.1. Introduction

The common spiny lobster, *Palinurus elephas*, is one of the most valuable species in Tunisia and in the Mediterranean Sea and in general. This species has been exploited by fishing since ancient times in that area, where it has great economic and social importance (Marengo, 2020; Muñoz et al., 2021). In fact, *P.elephas* is sold for high prices and supports an important number of small-scale fisheries vessels in Mediterranean countries. This species has undergone overexploitation, especially after the replacement of the traditional fishing gears, traps by trammel-nets in the 1960s (Goñi & Latrouite, 2005). Consequently, and given the low resilience and the increase of the fishing pressure of the species, a global decline in its landing has been observed in the Mediterranean and led to listing *P.elephas* as a Vulnerable species in the International Union for Conservation of Nature (IUCN) red list (Cau et al., 2019; Raquel Goñi & Latrouite, 2005; Marengo, 2020).

Similar to other Mediterranean countries, the common spiny lobster is in an important resource in Tunisia. Nevertheless, the landings in the Tunisian *P.elephas* fishery also witnessed a decreasing trend starting in the mid-2000s, after a peak of 74t in 1993t (Raquel Goñi & Latrouite, 2005). The decline is believed to have resulted from the fishing pressure that followed the shift in the fishing gear that happened in 1981 and the increase of the number of vessels targeting the species in the 1990s (Rjeibi, 2012). The *P.elephas* fishery in Tunisia is regulated by an annual temporal closure for fishing that (from 15 September to the end of February), a minimum legal size for catch (20 cm total length), and the prohibition of fishing the berried females. Despite these management rules, the common spiny lobster stock is overexploited according to a previous stock assessment of the species (Rjeibi, 2012). The overexploitation of the fishery, in the one hand and the vulnerability of the common spiny lobster to the fishing pressure due to its life-history traits in the other hand, indicates the importance and necessity of effective management to this species.

The regulations applied for the Tunisian *P.elephas* fishery are similar to those applied for the species in other Mediterranean countries (Kampouris et al., 2020). However, other management rules, such as quota management, were proved efficient for the management of lobster fisheries among other species fisheries in other parts of the world. The choice of the appropriate management rules is ensured by the application of the Management Strategy Evaluation (MSE) (Holland, 2010 ; Gardner et al., 2013).

MSE is a simulation-based process that allows to simulate fisheries' system. It is considered as the best practice to develop management procedures (also called management strategies) (Butterworth, 2007) that can achieve management goals and are robust to uncertainties (Kaplan et al., 2021; Punt et al., 2016). This process is based on a set of steps that are necessary for the evaluation of the Management Procedures (MPs) (Punt et al., 2016). The first step is to define the management objectives. These objectives are later quantified by identifying a set of performance measures. Then, uncertainties (i.e., process error, observation error, model error, implementation error...) are identified to test the robustness of the management procedures to these uncertainties (Amar et al., 2008). These uncertainties are integrated into the Operating Models (OMs), which are developed in the next step to simulate the "true" fishing system and to generate the data that will be used by the management procedures. 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) that will be fed back to the operating models. Finally, this closed-loop system is used to extract the performance measures that will be analysed and summarized to advise about the performance of the management procedures and their ability to achieve the management goals (Goethel et al., 2019a).

In this paper, we develop several management procedures to introduce quota management to the common spiny lobster in Tunisia. These management procedures are tested within an MSE framework, where the operating model is conditioned on the state-space delay difference model.

Our main objectives are to (i) develop model-based management procedures to set total allowable catch for *P.elephas* fishery in Tunisia (ii) Test the developed MPs and compare their performance in achieving the management objectives (iii) identify the possible trade-offs between management objectives and which MPs achieve the best balance among them.

4.2.Materials and methods

4.2.1. Overview of the MSE approach

The MSE is a simulation-based process that allows to simulate fisheries' system. It is considered as the best practice to develop management procedures (also called management strategies) that can achieve management goals and are robust to uncertainties. This process is based on seven key steps that are necessary for the evaluation of the management procedures (Punt et al. 2016). The first step is to define the management objectives. These objectives are later quantified by identifying a set of performance measures. Then, uncertainties (i.e. process error, observation error, model error, implementation error...) are identified to test whether the management procedures are robust to it (Amar et al., 2008). These uncertainties are integrated into the operating models, which are developed in the next step to simulate the "true" fishing system and to generate the data used by the management procedures. Alternative management procedures are then developed and are simulated into the future over a management period to set or as total allowable catch (TAC) that will be fed back to the operating models. Finally, the performance measures resulting from the MSE are summarized to advice about the performance of the management procedures and their ability to achieve the management goals.

4.2.2. Construction of the Operating model

The operating model is a fundamental component of the MSE. Ideally, it must consider all the biological component and processes of the population. Given our limited data (absence of age and size data), the state-space delay difference model (Hilborn & Walters 1992; Meyer & Millar 1999) was used as operating model to represent the common spiny lobster population dynamic in Tunisian water. This model is considered an intermediate between surplus production models and more complicated age-structured model. (Hilborn & Walters 1992). Please refer to the previous chapter for deeper explanation about the model population dynamics and estimation methods. The population biomass B_t is in year t obtained from past two years' biomass, survival, growth, and recruitment parameters:

$$B_{t+1} = (1+\rho)S_t B_t - \rho S_t S_{t-1} B_{t-1} - \rho S_t W_{k-1} R_t + W_k R_{t+1} \qquad 4.1$$

where ρ is the Brody growth parameter; S_t is the total survival rate:

$$S_{t=}e^{-M}(1 - H_t) \qquad 4.2$$

R_t is the recruitment at age k; W_k is the weight at recruitment; W_{k-1} is the weight one year before the recruitment; M is the natural mortality and H_t is the harvest rate:

$$H_t = \frac{C_t}{B_t} \qquad 4.3$$

Eight scenarios were considered in the simulations to test alternative MPs. They include the uncertainty in key biological parameters like the steepness and the natural mortality . The specifications of the scenarios are listed in Table 9. They are divided into base case scenarios, where the stock is slightly depleted at the beginning of the management and the values assumed for the natural mortality are those estimated for *p.elephas* in Tunisia, and robustness case scenarios where the stock is severely depleted and lower natural mortality values assumed coinciding with those registered in other common spiny lobster stock in the Mediterranean area. The values assumed for the steepness coincides with those assumed for lobster species in previous studies (Punt et al., 2009; Plagányi et al., 2018).

Table 9- Operating model Scenarios considered in the management strategy evaluation.

	h	M	B_0	θ	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

4.2.3. Development of management procedures

In this study, we considered model-based management procedures that are composed of an assessment model and a harvest control rule. The stock assessment model used was the Schaefer surplus production model, where the biomass is given by:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{k}\right) - C_t \qquad 4.4$$

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.

It used the data generated from the operating model to assess the stock. The results of the assessment are used by the harvest control rule to determine the management action which is setting the TAC in the application of this MSE.

The model was fitted to catch and 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 θ and the fishing mortality at MSY F_{MSY} were estimated using the maximum likelihood function written as follow:

$$I_t \sim \text{lognormal}(\log[qB_t], \sigma_c^2) \qquad 4.5$$

The results of the assessment such as F_{MSY} given by:

$$F_{MSY} = \frac{r}{2} \qquad 4.6$$

and the biomass are used to update the harvest control rules, each year, to determine the TAC as follow:

$$TAC = \begin{cases} 0 & if \quad B_t < B_{lim} \\ F_{MSY} \frac{B_t - B_{lim}}{B_{tar} - B_{lim}} B_t & if \quad B_{lim} < B_t < B_{tar} \\ F_{MSY} Bt & if \quad B_t > B_{tar} \end{cases} \qquad 4.7$$

The harvest control rule is set based on the probability of the biomass dropping below or exceeding certain reference points ($x\%B_0$ 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} (Figure 10). 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 summarized in Table 10. A maximum of 20% permitted inter annual change in the TAC was defined for each harvest strategy.

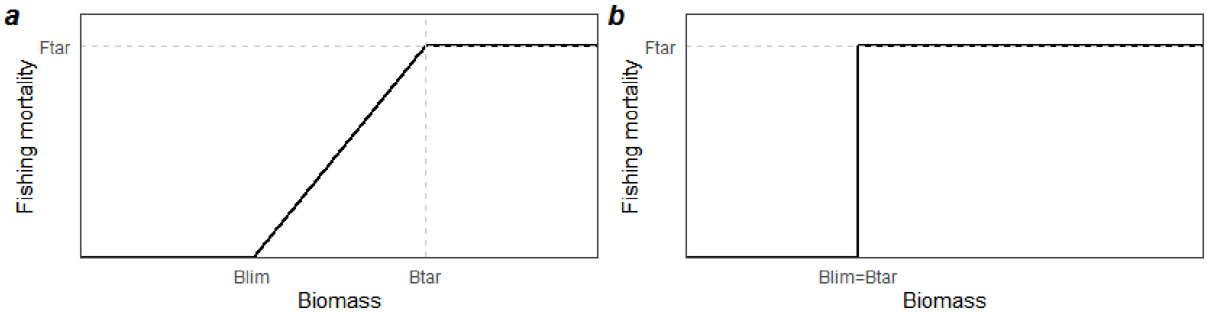

Figure 12- Harvest control rules used for the management of the common spiny lobster. (a) Linear adjustment harvest control rule, (b) threshold harvest control rule.

Table 10- Summary table of the biomass limit (Blim), target biomass (Btarg) and target fishing mortality (Ftarg) set for each management strategy.

Management strategy	B_{lim}	B_{targ}	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	$0.2B_0$	$0.5B_0$	$0.8F_{MSY}$
MP8	$0.2B_0$	$0.4B_0$	$0.8F_{MSY}$
MP9	$0.3B_0$	$0.3B_0$	F_{MSY}
MP10	$0.1B_0$	$0.1B_0$	F_{MSY}

4.2.4. Management objectives and performance measures

The management objective of this MSE are conservation objectives and catch performance objectives. We prioritize the conservation objectives so that the population can recover in the short term, and the overfishing is avoided . This is ensured by maintaining the biomass above 50% of B_0 and preventing the biomass from dropping below 20% of B_0. We also consider catch performance management goals, as we aim to maximize the catch while maintaining its stability over the years.

A variety of performance measures were set to help evaluate the performance of the management procedures and their ability in achieving management goals. The conservation performance was evaluated based on :

- $P(B_{2019\text{-}29}<0.2B_0)$: The median probability frequency of the stock biomass being below 20% of B_0 is equal or smaller than 10% over the projection period.
- $P(B_{2029}>0.5B_0)$: The probability of the stock depletion at the last year of projection being above 50% of 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 10-year projection period.

While the catch performance was evaluated based on:

- $\overline{C}_{2019\text{-}29}$: The medians (over simulations) of the average catches over the projection period.
- AAV: The average annual variation in consecutive catches over 10-year projection period must be equal or smaller to 15%.

$$AAV = \frac{\sum_{y=1}^{10}|C_y - C_{y-1}|}{\sum_{y=1}^{10}|C_{y-1}|} \qquad 4.8$$

Where y refers to the 10 years defining the period of projection and Cy is the catch applied in year y.

4.2.5. Simulations 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. Each simulation the population was projected for 10 years (short-term) and 20 years (long-term) in the future where the estimation model of the management procedures was applied every year and the results were used to update the true 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.
- A table summarizing 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

4.3. Results

4.3.1. Projection results: Biomass, stock depletion and catch trajectories

For base case scenarios, the biomass trajectories have shown an increasing trend at the beginning of the projection period under the different management strategies (Figure 13a, 13b, 13c). Under MP3 which is a relatively conservative management procedure (table 11), 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 (Figure 13a, 13d). The recovery of the stock was followed by an increase in the catch values after a slight decrease at end of the historical period (Figure 13g). Similarly, the biomass reached the target biomass level at the beginning of the projection period and stabilized at that level for the rest of the projection period under MP6 and MP9 that are respectively moderate and less conservative management procedures. The initially set to low allowable catches values were increasing and reaching high values at the end of the projection period allowing for the stock to be at target level (Figure 13h, 13i).

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. The panels a, b, and c in figure 14 shows the increase of the biomass for the scenario S7 under the different management procedures (MP3, MP6 and MP9). The biomass reached the target level at the last year of the management period only under the conservative management procedure MP3 (Figure 14e). 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 (Figure 14h, 14i), reaching the target biomass level requires longer periods under the less conservative strategies (Figure 14e, 14f).

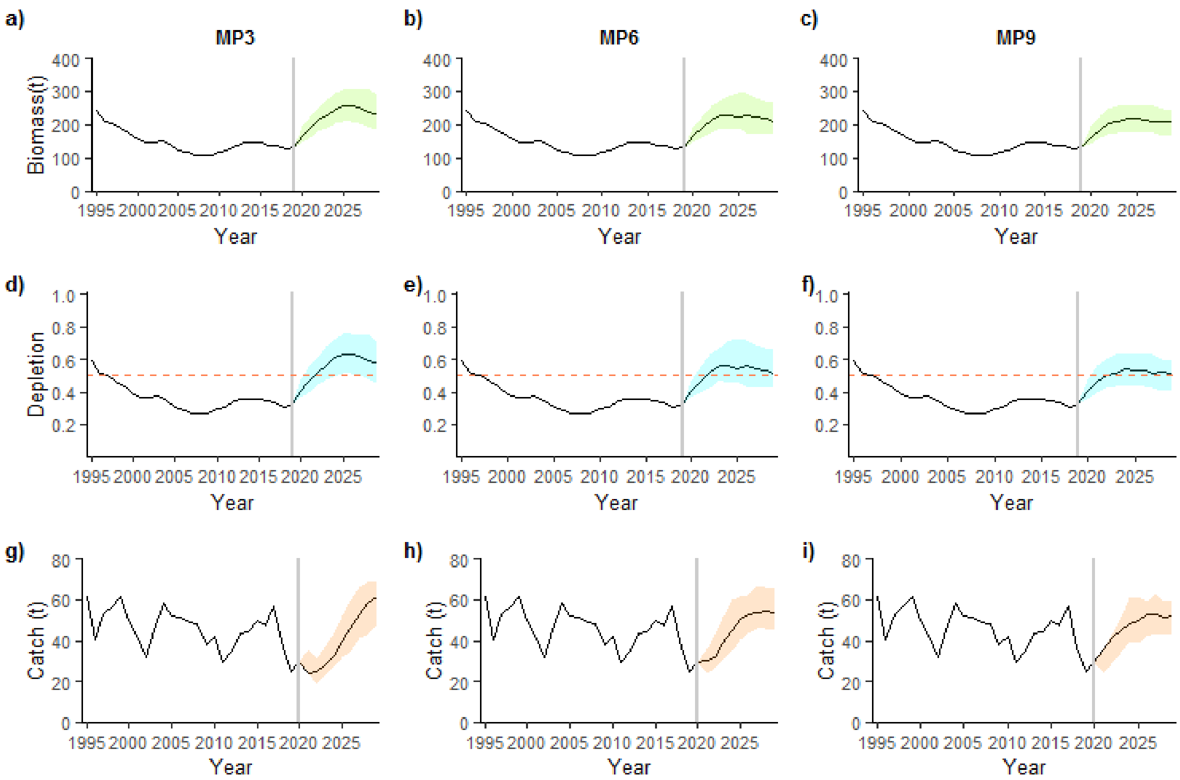

Figure 13 Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected biomass for one of the base case scenarios (S1) and three management strategies (MP3, MP6 and MP9). The grey vertical line shows the start of the start of management period. The horizontal dashed line presents where the stock status is at of 50% of the unfished biomass.

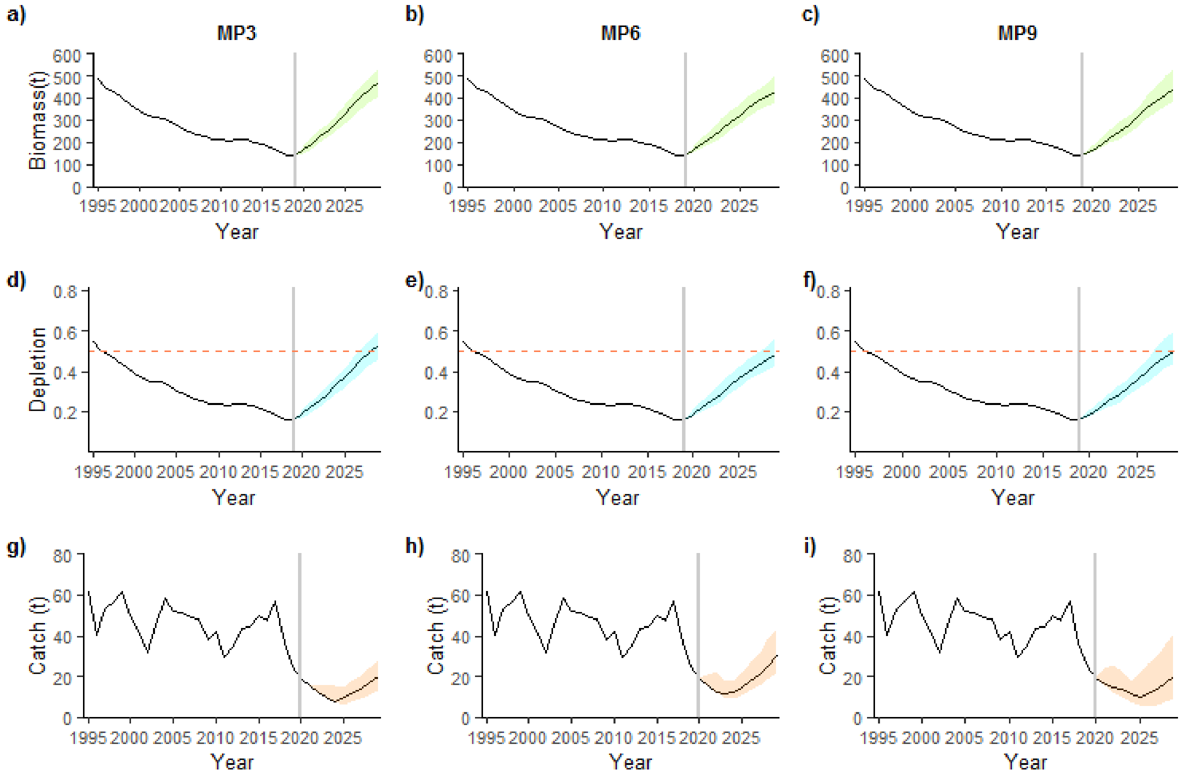

Figure 14 Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected biomass for one of the robustness case scenarios (S7) and three management strategies (MP3, MP6 and M9). The grey vertical line shows the start of the start of management period. The horizontal dashed line presents where the stock status is at of 50% of the unfished biomass.

4.3.2. Performance of the management procedures

Figure 15 shows the performance of each of the management procedures, in term of the biomass in the last year of projection being above 50% of the unfished biomass, for the different base case scenarios. Most of the management procedures seem to perform well with the median of the last year's depletion being above 0.5. MP1, MP2, and MP3 which has the more conservative control points in addition to MP7 and MP8 which has a reduced target fishing mortality met that objective with more than 90% Probability under base case scenario S1 (Table 11).

These management procedures performed similarly under two of the robustness case scenarios S5 and S6 but failed to meet that objective under the more pessimistic scenarios S7 and S8 (Figure 16). Under S7, MP1, MP2 and MP3 has respectively 87%, 85% and 70% probability to keep the last year's biomass above 50% of B_0 (Table 11).

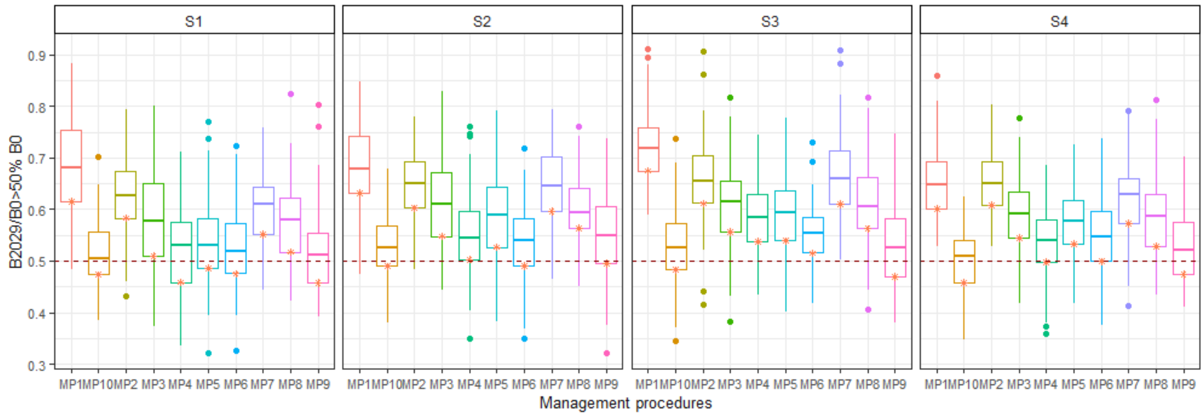

Figure 15- Box plots comparing the management procedures in term of the biomass reaching 50% of the unfished biomass in the last year for each of the base case scenarios. The dark horizontal lines are median values. The bottom and top of the box are respectively the 25th and 75th percentiles.

Less conservative management procedures have lower probabilities to meet 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 11)

None of the management procedures present a risk of the biomass falling below the limit reference point during the projection period (i.e., 20% of B_0) under the base case scenarios; but 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 11).

In term of catch performances, as expected less conservative management procedures performed better in maximizing the catch over the projection period under the base case scenarios (Figure 17). MP9 and MP10 yielded higher average catches, 38.39 T and 43.21 T respectively which is 1.55 and 1.75 times higher than the catch in the last year before the projection period. Even some of the conservative management procedures were able to yield acceptable catch values under S1, as the average catches for MP2 and MP3 were respectively 33.36 and 33.94.

Figure 6 summarizes the average catches during the projection period under the robustness case scenarios. Unsurprisingly, the depleted stock status led to low average catches. Under S7, the lowest average catch values were under MP1, 12.05 T which is around 50% lower than the catch in the last 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, only MP10 met that objective under S7. (Table 11)

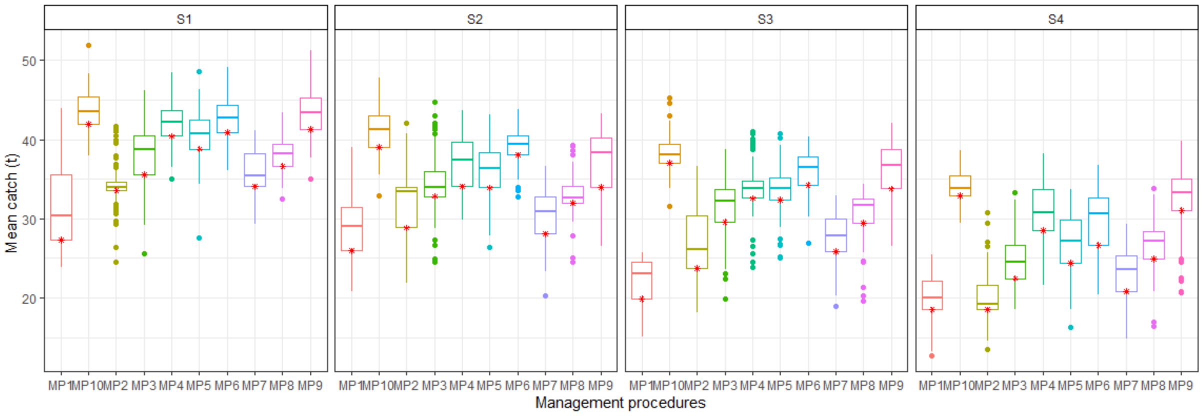

Figure 16- Boxplot comparing the performance of management procedures performance in term mean catch over the projected period for each of the base case scenarios.

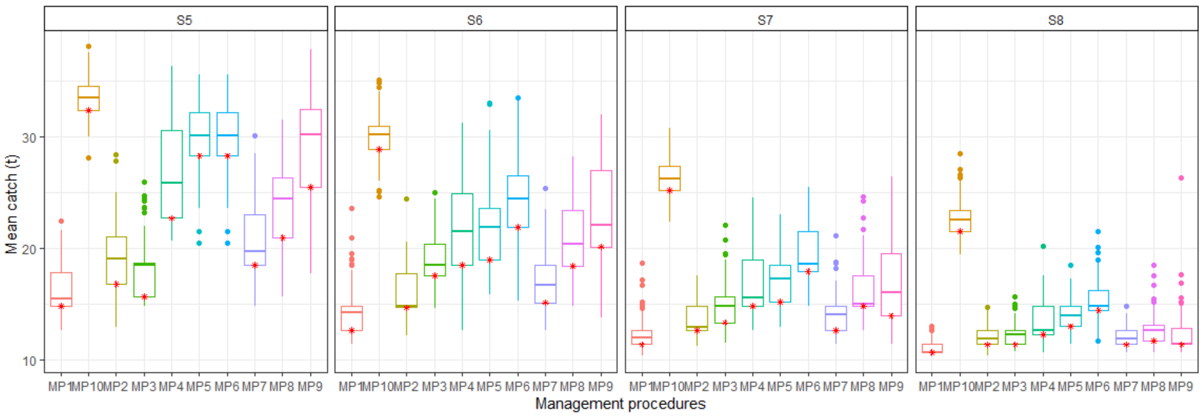

Figure 17- Boxplot comparing the performance of management procedures performance in term mean catch over the projected period for each of the base case scenarios.

Table 11 - summary table of the 10 management procedures under one base case scenario S1 and one robustness case scenario S7. The performance is evaluated based on 5 performance measures.

MP		Conservation objectives			Catch objectives	
S1		$P(B_{2019\text{-}29}<0.2B_0)$	$P(B_{2029}>0.5B_0)$	B_{2029}/B_0	AAV	$\bar{C}_{2019\text{-}29}$
	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	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	19.5	14.99
	MP9	20	48	0.49	20	16.01
	MP10	18	0	0.41	11.75	26.20

4.3.3. Trade-offs between management objectives

None of the management strategies has performed the best in all the objectives which leads to trade-offs between the most conflicting objectives: ensuring the recovery of the stock and maintaining higher catches. Given that the conservation objectives are prioritized for this MSE, we were able to conclude 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 19 illustrates the trade-offs of these five management strategies' abilities in achieving the management objectives. MP1, with the highest target and limit biomass, was in the left side of the plots indicating lower average catches under all the base case scenarios. MP3 and MP8, with the lowest target and limit biomass among these 5 management strategies, has higher catch values which suggests 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 stability in interannual catches and the average catches. Figure 20 shows that higher AAV were associated to the management strategies with higher biomass limits (i.e., MP1 and MP2); and that MP8 ensured the lowest AAV while maintaining high average catches.

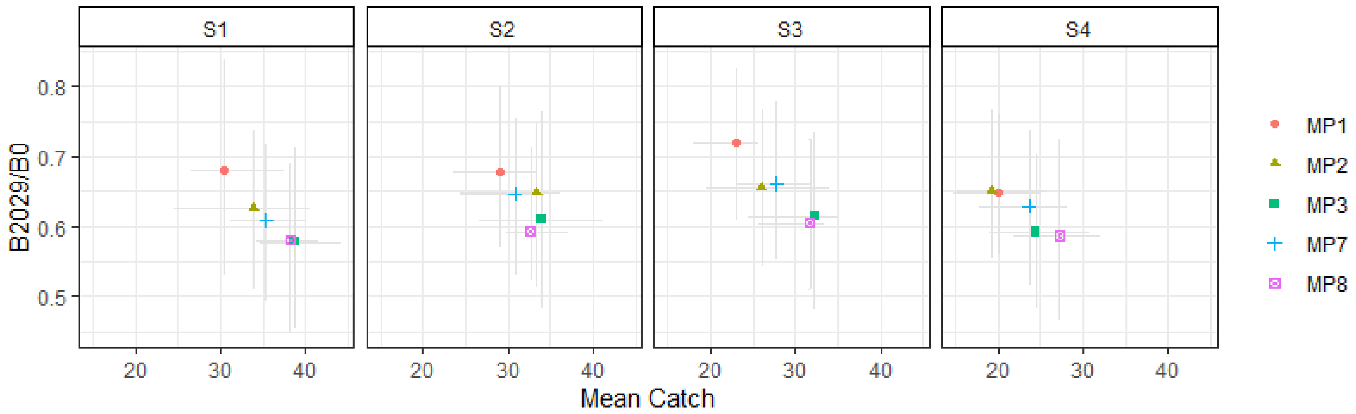

Figure 18- trade off plots illustrating the performance of 5 management strategies in achieving conservation objectives (depletion at the end of 10 years projection) and catch objective (average catch over the projection period) under the base case scenarios. Median values with 90% error bars are plotted.

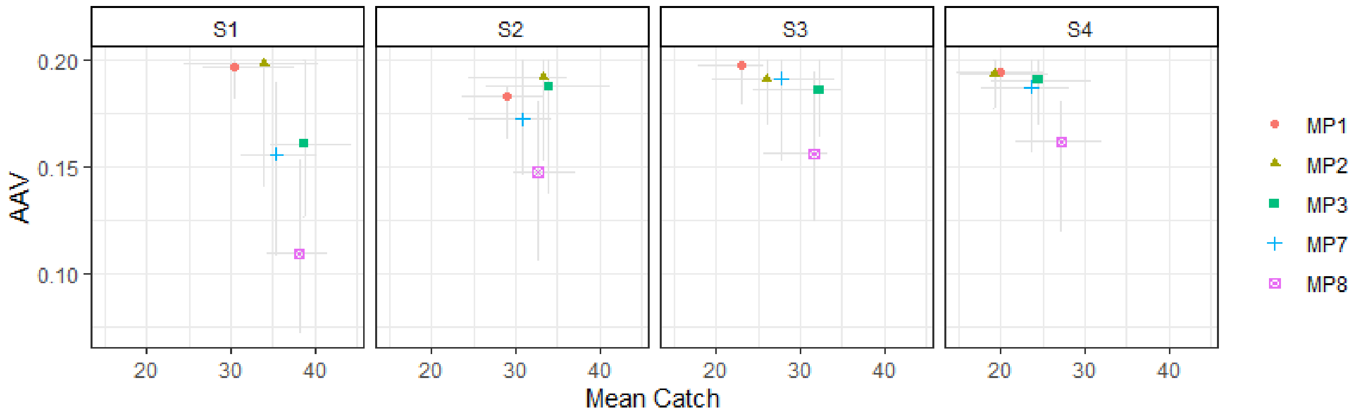

Figure 19- trade off plots illustrating the performance of 5 management strategies in achieving catch objectives: average annual variation in catch and median average catch over the projection period under the base case scenarios.

4.3.4. Projection results for the long-term management: Biomass, stock depletion and catch trajectories

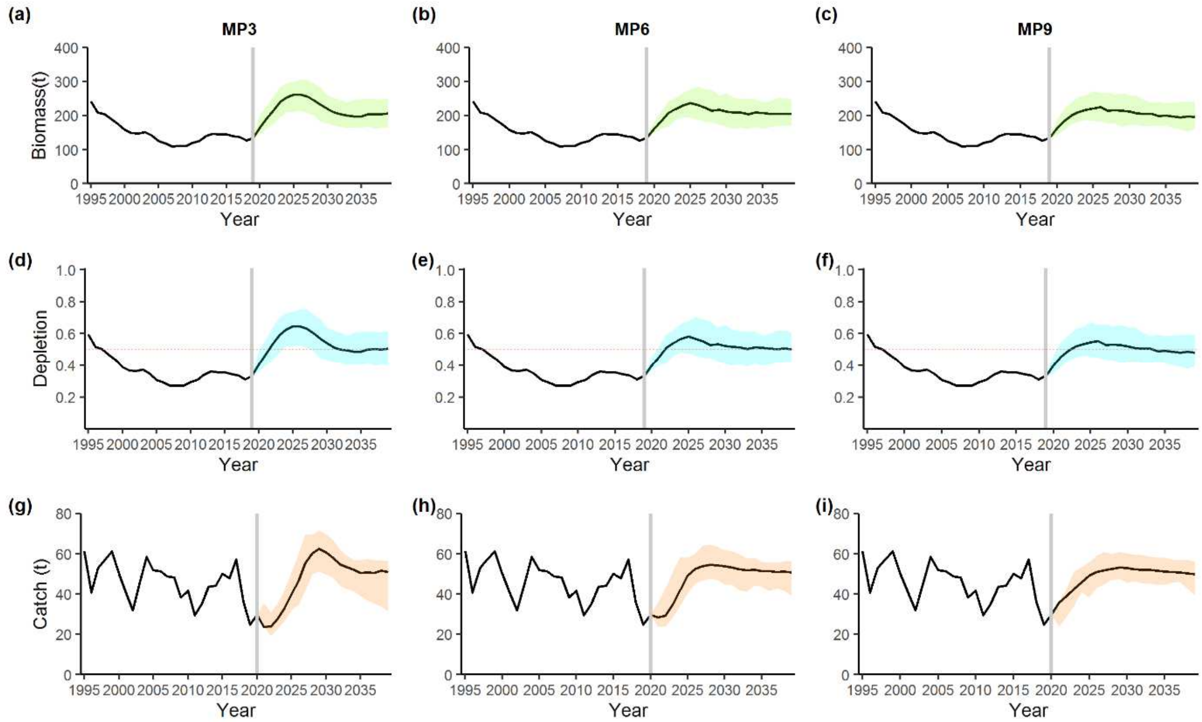

Figure 20- Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected biomass for one of the base case scenarios (S1) and three management strategies (MP3, MP6 and M9). The grey vertical line shows the start of the start of management period. The horizontal dashed line presents where the stock status is at of 50% of the unfished biomass.

For the long-term projections, the increase of the biomass trajectories that occurred on the first 10 years of the projection was followed by a stability in the long-term in under the different management strategies of the base-case scenario (Figure 21a, 21b, 21c). Under MP3, a decrease in the biomass followed the steep increase scenario S1 that peaks to around 50% of B_0 in 2027 to start stabilizing in 2030 around 50 % of B_0 until the end of the projection period. The catches that decreased in the beginning of the projection period, showed a steep increase following the recovery of the stock and then gradually decreased to stabilize at the end of the projection period (Figure 21g). Under MP6 and MP9, the biomass that increased to reach 50 % of B_0 and stabilized in 2030 at that level for the rest of the projection period.

The increasing trend of the projected biomass trajectories observed in the robustness scenario S7, didn't allow for the recovery in the first half of the projection period under MP6 and MP9. Figure 22 shows that after 11 years of management the biomass reaches the target level and stabilizes around it until the end of the management period. The initially low catches values at the beginning of the projection period, increases slightly relatively to the recovery of the biomass.

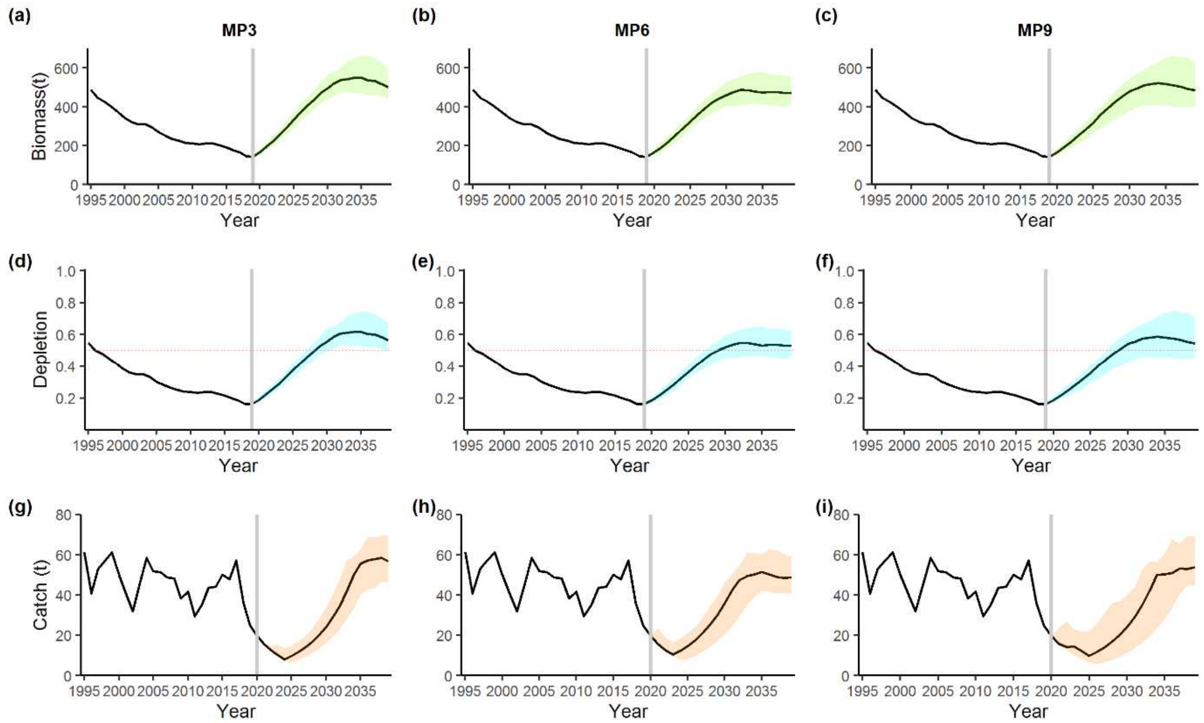

Figure 21-Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected biomass for one of the base case scenarios (S1) and three management strategies (MP3, MP6 and M9) in long-term management period. The grey vertical line shows the start of management period. The horizontal dashed line presents where the stock status is at of 50% of the unfished biomass.

4.3.5. Performance of the management procedures in long-term projection

The management procedures seem to perform more or less similarly in term of management objectives under the base case scenarios for the long-term management period. Figure 22 showed that all the management procedures ensured for the median of the last year's depletion to be above 0.5 which agrees with the biomass trajectories stability around that level under the different base case scenarios (Appendix A). MP1, MP2, MP7 and MP8 had the highest probability (more than 70%) of meeting that objective under the base case scenario S1(Table 11).

Unlike their performances in the short-term projection period, the MPs ensured for the median of the last year's depletion to be above 0.5 in most of the robustness scenarios with the exception of the relaxed management procedures, MP9 and MP10 (Figure 22). The conservative management procedures MP1, MP2 and MP3 had the highest probabilities of meeting that objective (Table 12)

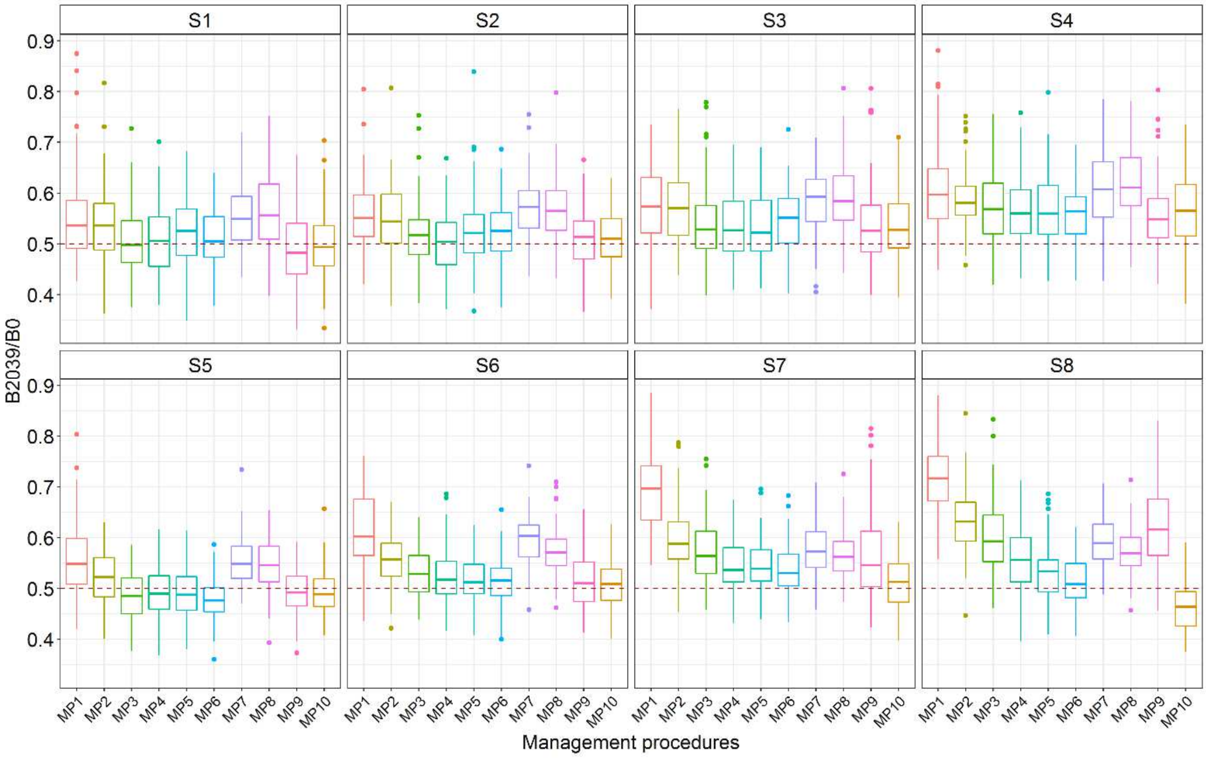

Figure 22- Boxplot comparing the performance of management procedures in term of the reaching 50% of the unfished biomass in the last year for base case (S1-S4) and robustness scenarios (S5-S8).

Similarly to the short-term management period, none of the management procedures present a risk of the biomass falling below the limit reference point during the projection period (i.e., 20% of B_0) under the base case scenarios; but conversely to the previous simulations, this risk of the median biomass dropping below the limit reference point dropped to 10% under all the management procedures (Table 11).

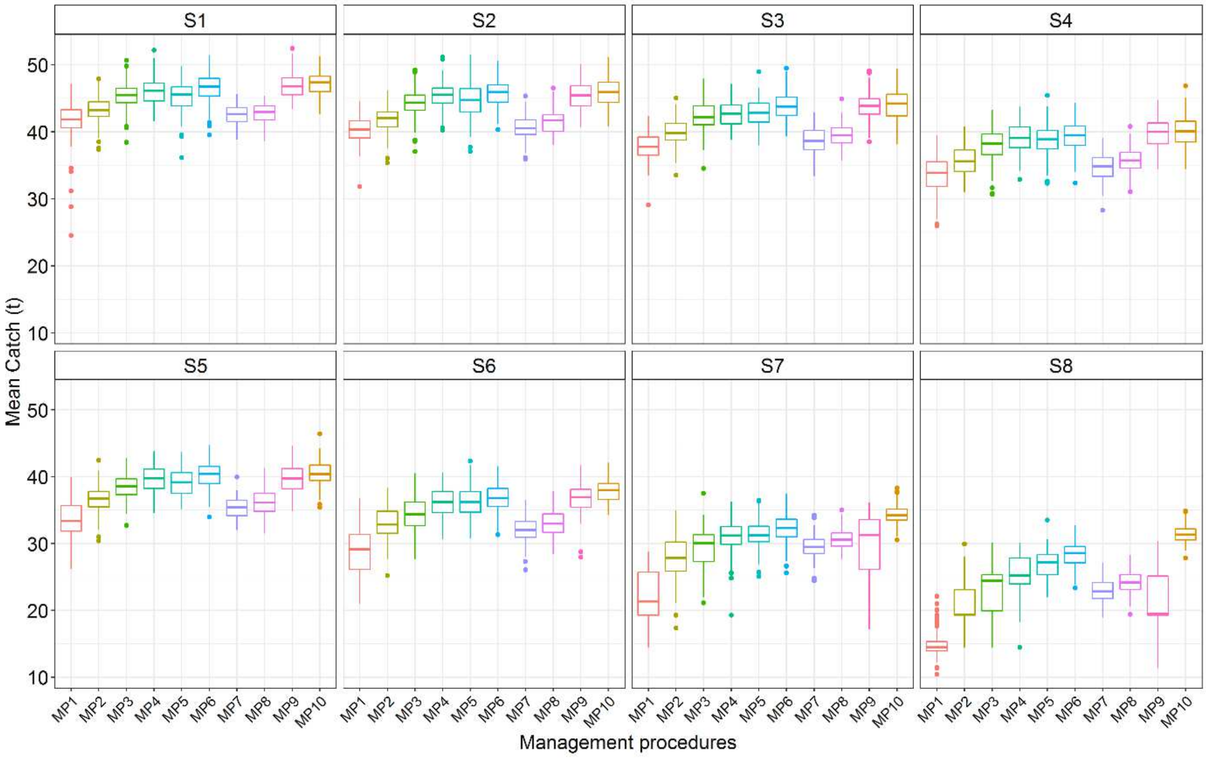

Figure 23- Boxplot comparing the performance of management procedures in term of the reaching 50% of the unfished biomass in the last year for base case (S1-S4) and robustness scenarios (S5-S8).

In term of catch performances, all MPs yielded higher average catches compared to the performance in short-term scenarios . The highest catches were ensured by the less conservative MPs, MP9 and MP10 yielded higher average catches, 47.07 T and 47.27T respectively under S1 (Table 12). Conservative MPs has also yielded in relatively average high catches for the base case scenarios, as the median of average catches over the projection period, of all the MPs was above 40 T (Figure 24)

Under robustness case scenarios, the MPs performed poorly in term of average catches as the depleted stock status led to low average catches. However, they yielded to average catches that are higher than those observed in the short term management with the lowest average catch values were under MP1, 20.80 T, and the highest was under MP10 ,34.21 T for the robustness case scenario S7.

For base case scenarios all the management procedures performed well in term of low AAV values (below 15% of variation), not only under the relaxed management procedures but also moderate ones such as MP7 and MP8 resulted in low variation in annual average catches

4.69% and 3.25% respectively which coincides with the tendency to stabilize at the second half of projected catch trajectories (Appendix A).

Table 12 - summary table of the performance of 10 management procedures in long term projection (20 years) under one base case scenario S1 and one robustness case scenario S7. The performance is evaluated based on 5 performance measures.

MP		Conservation objectives			Catch objectives	
S1		$P(B_{2019\text{-}39}<0.2B_0)$	$P(B_{2039}>0.5B_0)$	B_{2039}/B_0	AAV	$\bar{C}_{2019\text{-}39}$
	MP1	0	73	0.54	11.47	40.54
	MP2	0	76	0.53	10.05	43.52
	MP3	0	55	0.51	7.04	45.72
	MP4	0	54	0.50	5.38	45.93
	MP5	0	62	0.51	6.02	45.87
	MP6	0	54	0.52	3.98	46.27
	MP7	0	78	0.50	4.69	42.69
	MP8	0	77	0.55	3.25	42.59
	MP9	0	45	0.48	3.38	47.07
	MP10	0	49	0.49	3.20	47.24
S7						
	MP1	10	87	0.69	17.69	20.80
	MP2	10	85	0.58	13.78	27.61
	MP3	10	71	0.56	12.02	29.95
	MP4	10	50	0.53	11.09	29.97
	MP5	10	52	0.54	10.61	31.31
	MP6	10	34	0.53	9.27	32.25
	MP7	10	67	0.57	9.10	29.26
	MP8	10	55	0.56	6.05	30.45
	MP9	10	48	0.54	10.56	29.27
	MP10	10	60	0.51	5.06	34.21

4.4. 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.

In fact, 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* and *Palinurus gilchristi* (Johnston & Butterworth 2005) in South Africa; *Jasus* *edwardsii* and *Panulirus ornatus* in Australia (Plagányi et al., 2018; Punt et al., 2013; Punt & Hobday, 2009) and *Jasus edwardsii* in New Zealand (Breen & Starr, 2009). The reference points employed in this research are in general agreement with those employed in the MSE applications mentioned above. The limit reference point is often set at 20 % of B0 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 B0 (Punt and Hobday, 2009; Breen and Starr, 2009) or 50 % of B0 (Johnston and Butterworth, 2005), as proxies for BMSY to ensure rebuilding the stock and its sustainability.

In Tunisia studies undertaking the bio-ecology, socio-economy as well as the assessment of *Palinurus elephas* fishery has been conducted (Rjeibi, 2012; Rjeibi et al., 2011; S. Jaziri, S. Ben Salem, 2014). However, MSE is still not applied for the management of the common spiny lobster fishery in Tunisia nor in any Mediterranean lobster fishery to the best of our knowledge.

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 procedure. Punt et al. (2013) used the latter where he evaluated 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 this 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, MPs based on such models were found to be as useful as more complex model-based MPs for some cases. (Rademeyer et al., 2007).

Although we did not account for the time variability of the key parameters given, we examined the uncertainties related to stock-recruitment steepness and the natural mortality. Our simulations showed that the performance of the management strategies were 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 & Hobday, 2009), where

lower rate of natural mortality led to the worst performance of conservation objectives.

Our simulations indicated that MP1 and MP2, the most conservative management procedures with the highest control points, achieved the conservation management goals, as they maintained the stock above the biomass limit in base case and some of the robustness scenarios; however, they performed poorly and failed to achieve the catch performance management goals resulting in the highest AAV values which are 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 are based on threshold control rules (a constant fishing mortality is allowed below respectively 0.3B0 and 0.1B0) and were considered to take into account potential stakeholder preference to relaxed management procedures. Both MPs performed well in terms of yielding high catches in the best-case scenarios but did not achieve conservation management objectives.

Among the alternative management strategies MP3 (Blim=0.2B0, Btar =0.5B0) and MP8 (Blim=0.2B0, Btar =0.4B0 and Ftar= 0.8FMSY) performed satisfactorily in balancing the trade-off between catch performance and the conservation objectives.

None of the management procedures were 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 the better management of the species. However, in the long-term management period (20 years) the biomass reached the target biomass limits even under the robustness case scenarios, after 12 to 15 years of management depending on the scenario and the applied MP (Appendix A), indicating that the low resilience of the species results in the slower recovery and highlighting the necessity of applying stricter management rules in worst-case scenarios. On the other hand, under the base case scenario, the biomass stabilized around 50% of the unfished biomass during the long-term projection and some of the MPs have high more than 70% of meeting that objective. While these probabilities are not acceptable under the short-term management period as our priority objective is the recovery of the biomass, this condition may be adjusted depending on to the update on stock status and to the decision makers' opinions. Especially that not only 70% probability is acceptable in term of achieving the management objectives once we are sure that the stock status is safe and that the risk of collapse is no longer exists, but also those

MPs has ensured stability in the projected TACs, which is up to more than 5 times lower in some scenarios to those that were considered acceptable in the short-term management.

In this study, we highlight the importance of developing and choosing the appropriate management procedure for the management of the common spiny lobster stock in Tunisian water and the apport of the MSE framework to this process and explore the advantages of the MSE process in establishing a quota management procedure. Future studies should include some major sources of uncertainties that were not addressed in this research, and that would have an impact on the management of lobster fisheries, such as the age at maturity and the survival of the species. There is no certain information regarding the stock-recruitment relationship for the common spiny lobster (Raquel Goñi & Latrouite, 2005), so it is advised to increase the operating model scenarios to include different stock-recruitment relationships. The quota management has been found to increase the economic yield when 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, so it would be beneficial to test both types of MPs within an MSE and, with providing the required data about catch sizes and selectivity, to develop mixed management procedures that include the TAC and the minimum size limit at the same time. Such MP may contribute to a healthiest stock for the common spiny lobster not only in terms of stock size but also in size structure. Testing such MPs within MSE may encourage introducing new management rules for the better management of this species.

Chapter V

5. General discussion

In this chapter, we present the main conclusions about the results of this thesis. Our main objective is to assess the stock of the common spiny lobster in Tunisia and develop management procedures for its fishery and to investigate the outcomes and the performance of data limited ana data-moderate assessment methods in the process.

The second chapter of this thesis concentrates on the application of the data-limited methods, when only catch data are available in the first place and then the application of the Bayesian surplus production model to fit of the catch and abundance index data in assessing the lobster stock. In the third chapter, we focused on the application of the data-moderate assessment method, the state-space delay difference method, and how it may contribute to the stock assessment and management of this species. In the fourth chapter, we explored the results of the application of the management strategy evaluation to the common spiny lobster stock in Tunisia. The delay-difference model explored in the previous chapter was used for the conditioning of the operating model, while the surplus production model was used as an assessment model for the management procedure. We were able to investigate which management procedure can ensure the stock's recovery and maximize the yield while being robust to the different uncertainties.

5.1. Stock assessment for the common spiny lobster fishery in Tunisia using data-limited and data moderate assessment models

The use of the catch-only method CMSY in the second chapter allowed us to assess the stock of the common spiny lobster using the catch data and to estimate stock status and the fisheries reference points. The output of these models indicated that the biomass is decreasing and that the stock is overfished and depleted in most of the scenarios. The estimates of the model parameter were similar to the estimates of the BSPM model for the intrinsic growth rate. Still, they were different for carrying capacity parameter estimates and biomass values. Despite the difference in the biomass values, the biomass trajectory followed the same decreasing trend within the two methods. The difference in the estimates could be explained by the inability of CMSY to capture the variability in abundance and to the underlying observation and process uncertainties considered in the BSPM. The sensitivity analysis of the CMSY method confirmed its sensitivity to change in the prior ranges of the model parameter, notably the final depletion prior range which has been confirmed by several studies for this method. Further sensitivity analysis is needed for the BSPM model.

The Pella-Tomlinson model and M2 with the highest depletion prior ranges had similar results in terms of stocks status as they showed that the stock was highly depleted (32% and 28% of carrying capacity, respectively). The methods also showed similarity in terms of MSY 46t and 45t, respectively, and in terms of fishing mortality relative to FMSY, as their results show that the stock is overfished. This is important given the implication of these reference points in

the management process. However, the methods showed a wide variation in the confidence levels of the estimates which are unsurprising and reflects the limitation of the data.

The use of the CMSY method and the implementation of the BSPM have several advantages for the stock assessment of the common spiny lobster in case of limited data as they can present a temporary solution for to explore the stock status. These advantages include the low complexity of this method and its easy application in addition to the good performance in terms of predicting biomass and fisheries reference points. The non-complexity of the method in one hand ensures its smooth interpretation and easier communication of the outcomes. The easy application in the other hand, allows for the updates regarding the stock status. These methods may be effectively used for the assessment of the common spiny lobster in Tunisia when it comes to the simplicity of the application of these methods and their low requirement in data. However, the prior information about the stock status and the key model parameter may greatly impact the results and the outcome of the model, which highlights the need of previous knowledge of the population and the importance of efficient methods for setting reliable priors.

In the third chapter, the Bayesian delay difference model was used to assess the stock with the aim to assess the stock status; we included biological information about the common spiny lobster in Tunisia and in other areas and considered alternative scenarios to test the model's sensitivity. We were able to deduce that the common spiny lobster is depleted both the biomass and recruitment trajectories had decreasing trend in the alternative scenarios, and the model was sensitive to the variation in the recruitment deviation and natural mortality, which highlights the importance of accounting for these uncertainties in the context of management

Throughout this study, we have tested three different stock assessment methods and sought to use the available data and information in order to get an idea regarding the stock's status. The wide confidence levels in the parameters' estimates reflect the limitation of our data and enhance the importance of employing a management strategy evaluation to test alternative scenarios about the population dynamics but also about the assessment method to use for the common spiny lobster fishery.

5.2.Management strategy evaluation for the common spiny lobster stock, *Palinurus elephas*, in Tunisia

In the fourth chapter, we applied the MSE framework to common spiny lobster stock in Tunisia. We used the delay difference model described in chapter three for the conditioning of the operating model (OM). The harvest control rule was based on the surplus production model that estimates the reference points from the data generated by the OM. Eight scenarios for the operating model were simulated 100 times and projected for ten years in the future to test the performance of ten management strategies in the achievement of management objectives. These scenarios represented the base case scenarios that are likely and supposed to reflect the most the population dynamics and robustness scenarios that are unlikely but still plausible. Depending on the control points used, we developed a range of conservative, moderate, and relaxed management procedures. These MPs were tested within the MSE framework under alternative scenarios that were considered to account for key parameters uncertainty such as the steepness and natural mortality in the short-term (10 years) and in the long-term (20 years). Given that the stock is depleted, its recovery and preventing the collapse of the stock are our priority objectives in the short term. Unsurprisingly the conservative and strict management procedures such as MP1 were able to satisfy the conservation objectives preventing the collapse of the stock by ensuring a high probability of the stock being above 20% of unfished biomass and ensuring the sustainability of the stock and its recovery as the stocks reach 50 % of the unfished biomass. However, they performed poorly in terms of catch performances as they resulted in high average annual variation in catches (e.g., MP1 resulted in 18% of interannual variation in catches) and low average catches. The relaxed management strategies in the other hand failed in meeting the management objectives. The management procedures that succeeded in stabilizing the trade-off between conservation and catch performance objectives and ensured achieving the management objectives were the moderate management procedures MP3 and MP8.

We were able to deduce that, for the short-term period, applying the quota management based on a model-based management procedure may help for the recovery of the common spiny lobster that is overexploited not only in Tunisia but in the Mediterranean Sea where the global trends are in continuous decrease. Although, under some of the robustness (i.e., S7 and S8) case scenarios where the stock was severely depleted none of the management procedures were able to achieve the management objective and the recovery of the biomass to 50% of the unfished biomass was not possible which suggests the need to stricter regulations such as the closure of the fishery to achieve the recovery of the stock in the short term given the low resilience of this species. Projecting the biomass for a longer period (20 years) within the MSE showed that the recovery of the stocks after 11 or 12 years of management even under the worst case of the robustness scenarios such as S7 and S8. This confirms the urgency to apply stricter management rules given the slow recovery of this species which its low resilience could explain. It would be interesting to investigate alternative formulation in the harvest control rules when projecting for the long-term to consider the industry's preference after ensuring the recovery of the stock.

5.3. Conclusions, limitation, and future work

As explained in the previous chapter, our MPs were based on the surplus production model; although it showed good performance, it would be interesting to establish the harvest control rules on alternative assessment models. Given the increasing use of data-limited and catch-only methods such as CMSY for the assessment of data-poor stocks including spiny lobsters such as the *Palinurus mauritanicus* stock in Mauritania (Meissa, 2021) and *Panulirus argus* in Brazil (Cruz, 2021), it would be interesting to test the management procedures with HCR informed by the CMSY method. This would allow for a better understanding for the performance of this method in the assessment of the lobster fishery and in the estimates of fisheries management quantities. Several studies recommend testing the data-limited methods in general within MSE (Carruthers et al., 2014; Punt et al., 2016).

Similarly, regarding the operating models, other sources of uncertainties would have an impact on the management of lobster fisheries, such as the age at maturity and the survival of the species should be addressed. There is no certain information regarding the stock-recruitment relationship for the common spiny lobster (Raquel Goñi & Latrouite, 2005), so it is advised to increase the operating model scenarios to include different stock-recruitment relationships.

Despite the success of this method for other lobster species globally, quota management is not applied for the common spiny lobster in Tunisia and other Mediterranean countries. In this study, we wanted to investigate the feasibility and the performance of this method MSE framework, and with further data availability and the cooperation among the different representative of this fishery (i.e. stakeholders, fishermen, researcher), we may be able to test other management strategies based on the currently applied input control management regulations such as the minimum legal size. The latter regulation is preferred by the decision-makers given it's currently applied and doesn't require more resources as would be the application of new management action. Collecting more data regarding size at the catch and the selectivity would help to test management procedures with different size limits and explore the effect of such management actions on population recovery. Furthermore, the availability of such data would help to test a mixed management strategy based on both input management control rules (e.g., size limit, temporal closure) and output control such as TAC. This management procedure could include the TAC and the size of retention of the species could be based on the current minimum legal size and on different assumptions related to the age and size at maturity for the common spiny lobster. Temporal closures could also be tested within the MSE to ensure the efficiency of the management and that the current fishing campaign overlaps with the female bearing phase that would require good quality data about the weight and length at age, which highlights the importance of undergoing surveys to collect better data. This would allow us to test the efficiency of spatial closures, given that the fishing areas of the common spiny lobster in Tunisia are limited to the northern part of the country and are relatively well known. Defining quota management that is spatially defined by alternating the fishing zones would help the recovery of the species while enabling the fishermen to exert their job. The use of MSE could help to determine more efficient regulation for this species and would encourage the decision-makers to consider investments of resources and time on quota management procedures or alternatively mixed management procedures.

Our discussions with some of the common spiny lobster fishermen is an agreement with such strategies as they feel the danger of the extinction of the species, and they fear the closure of the fishery that represents for some the unique source of revenue. Thus, stricter control and enforcing the management regulations during the fishing operation is necessary currently as it is mentioned that fishing of berried female is sometimes occurring to compensate for the small quantities of landings of, which would contribute to the management and sustainability of the fishery. Additionally, the common spiny lobster has been seen in some private fish markets within the temporal closure season (e.g., January 2022), which, again, highlights the necessity of stricter observation and control and also draws attention to the implication of recreational fishermen in the harvest of the species. This sector remains unfortunately unaccounted for in the management of this species despite the high impact that it presents. Unsustainable practices were observed from the recreational fishermen, such as using destructive gears for the habitat of the spiny lobster by using unauthorized gears to weigh the nest in order to reach the species in

important depth. This also indicates that introducing a quota management procedure could be an efficient alternative to rebuild the stock and to facilitate the control of the fishery.

Considering environmental and abiotic factors is gaining more importance, especially under the current context of climate change, which can have direct or indirect effects on populations and marine ecosystems (Harley et al., 2006; Brander, 2010). The common spiny lobster is highly vulnerable to variation in abiotic factors such as temperature. These factors influence the growth of the species, the maturity, and breeding and have a high impact on larval survival (Whomersley et al., 2018; Goñi & Latrouite, 2005). This highlights the necessity of taking into account the climate change impact on this species and in its management. MSE would provide a useful tool to assess the performance of management strategies in response to the climate change effect.

The success of the MSE process depends on the trust between the fisheries' actors, including scientists, managers, and stakeholders (Miller et al., 2019). Therefore, increased collaboration between scientists and fishermen could facilitate the collection of data but also would allow for better communication and less defiance from the fishermen. The inclusion of the social sciences in the processes of rendering management advice, and the inclusion of fishermen in the decision-making processes, would make it possible to attenuate the tensions often present between the different fishing actors and would have significant importance on the process of the management strategy evaluation for the common spiny lobster in Tunisia. This highlights the importance of including the socio-economic component of the fishery in the management.

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Appendix A

Supplementary information for Chapter 4

1- **MSE projection results for short-term management period: biomass and catch trajectories for four base-case scenarios under all the management procedures**

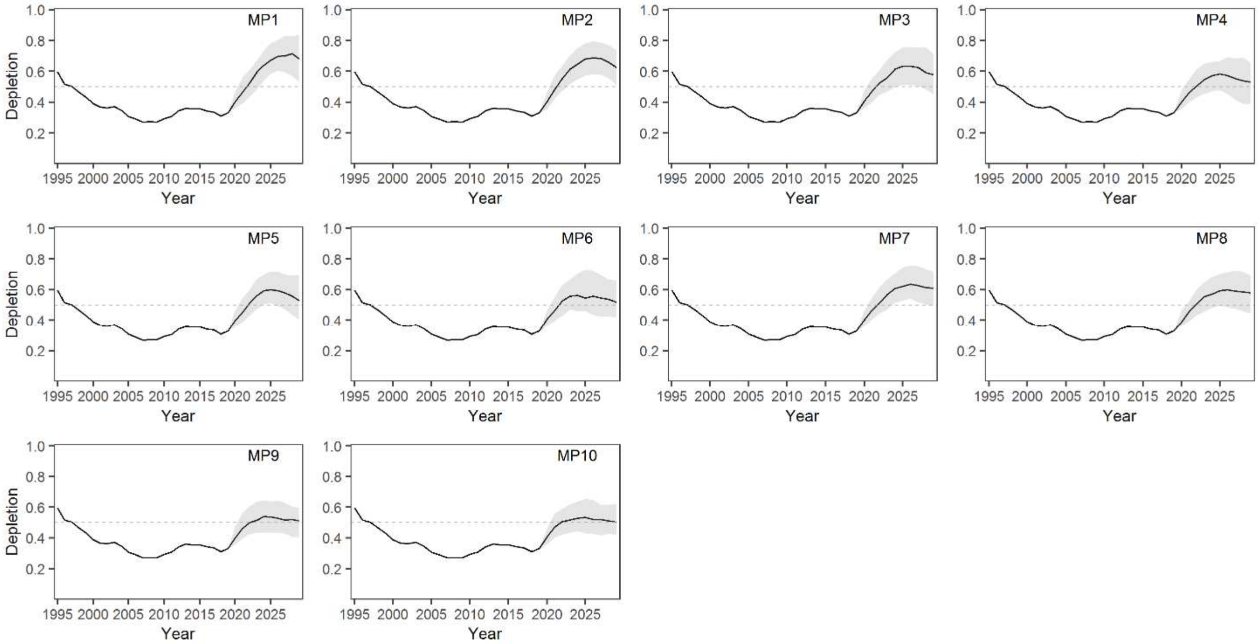

Figure A 1- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the base-case scenarios (S1) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

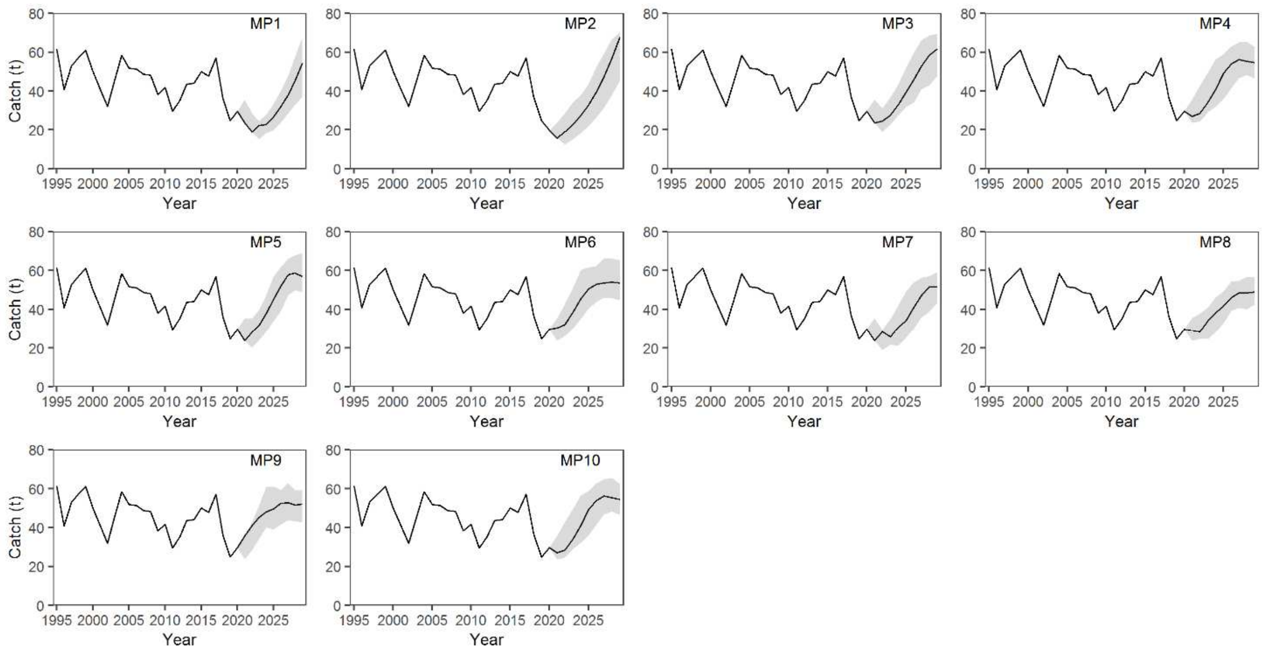

Figure A 2-trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the base-case scenarios (S1) under 10 management strategies.

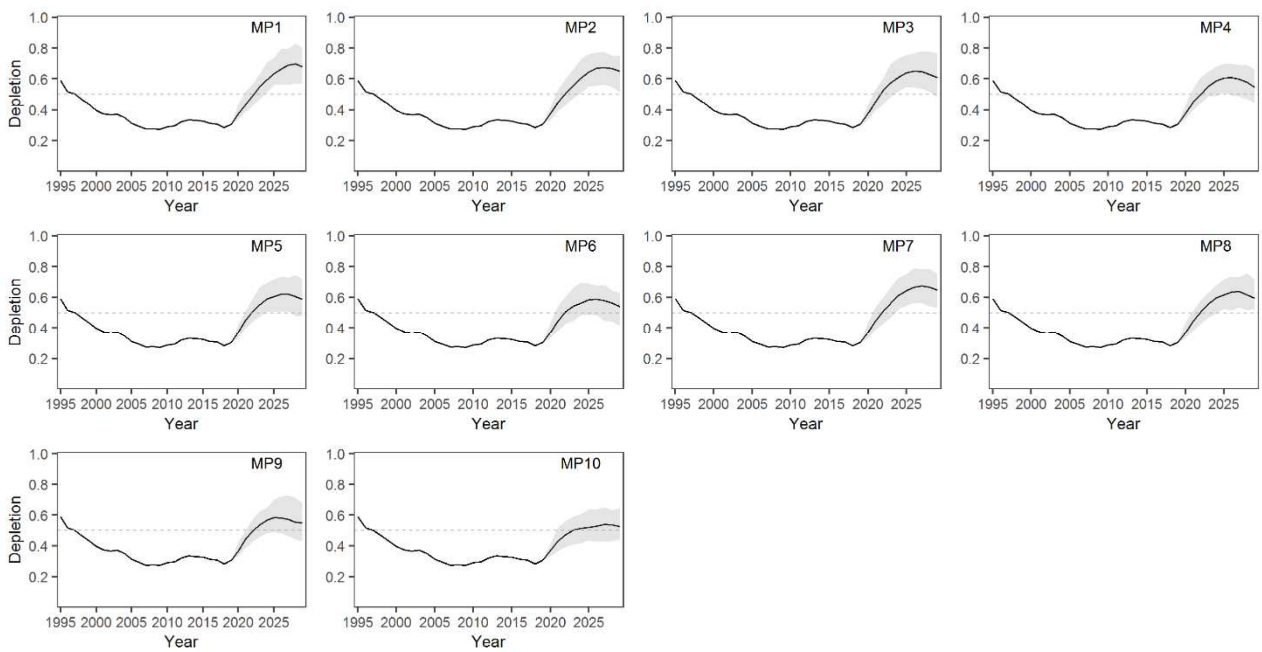

Figure A 3- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the base-case scenarios (S2) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

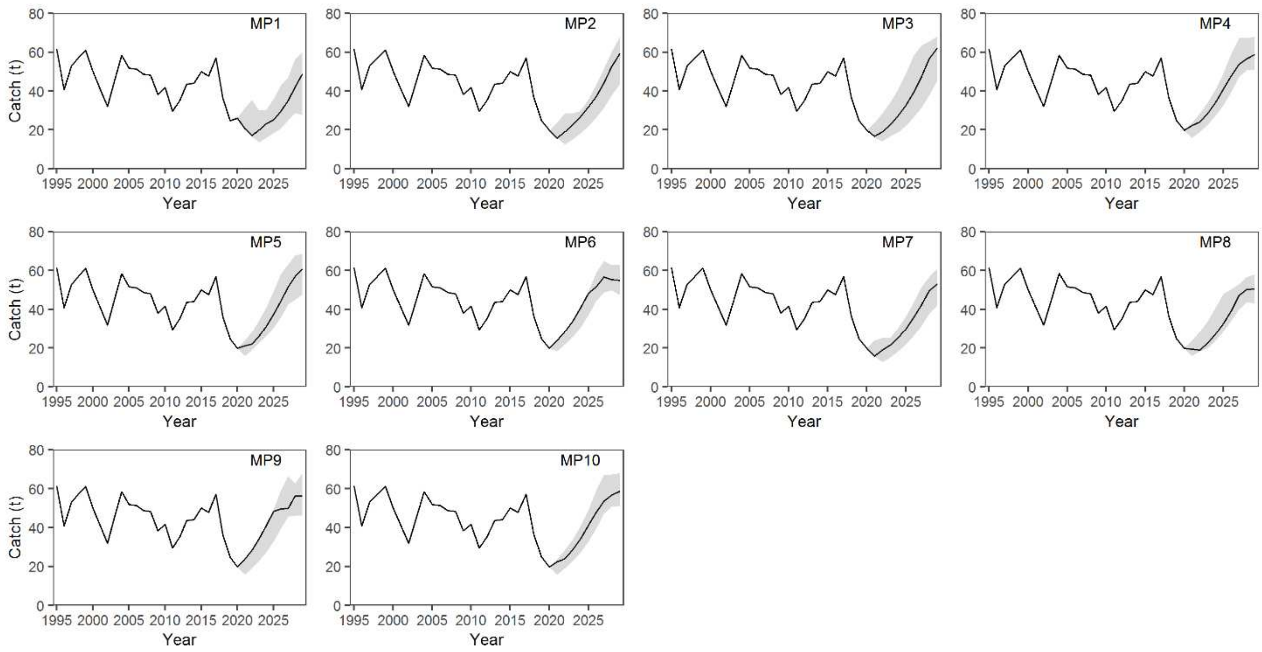

Figure A 4- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the base-case scenarios (S2) under 10 management strategies.

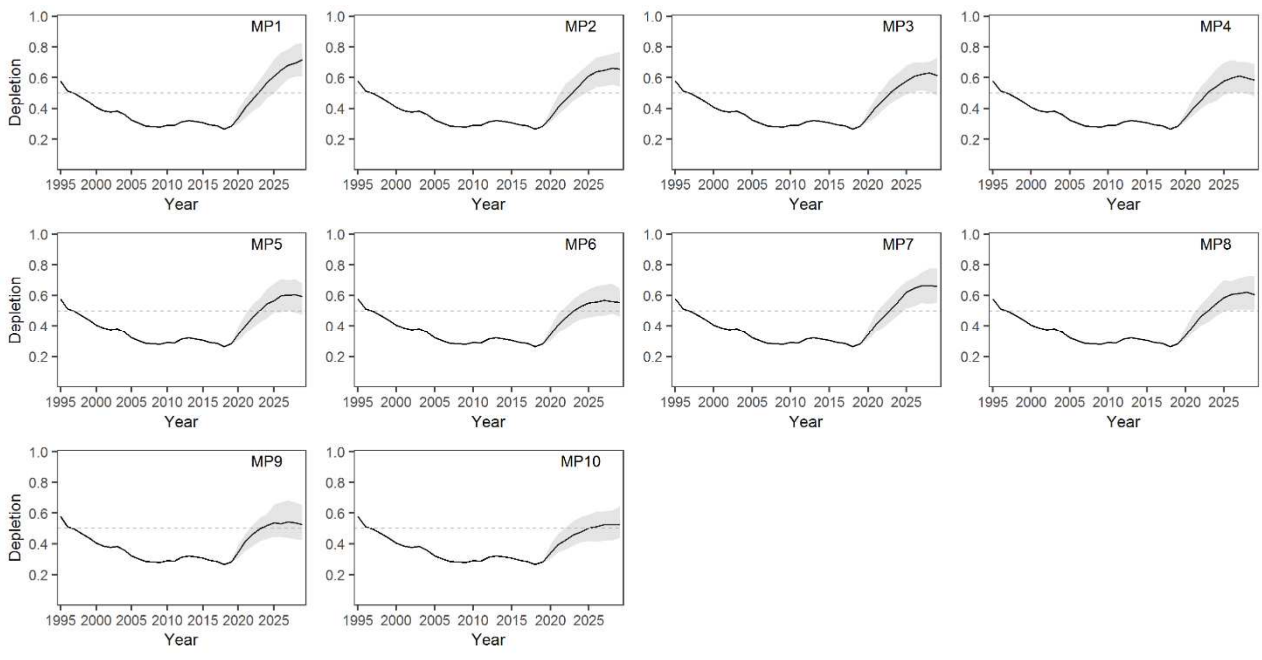

Figure A 5- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the base-case scenarios (S3) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

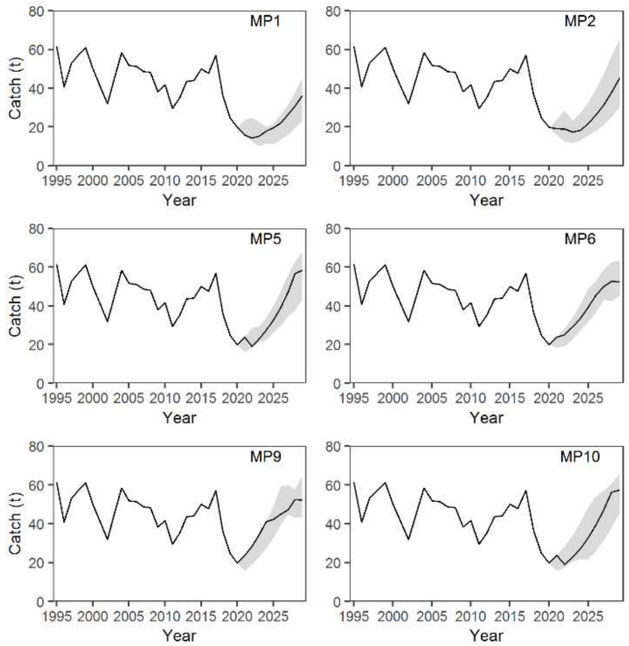

Figure A 6- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the base-case scenarios (S3) under 10 management strategies.

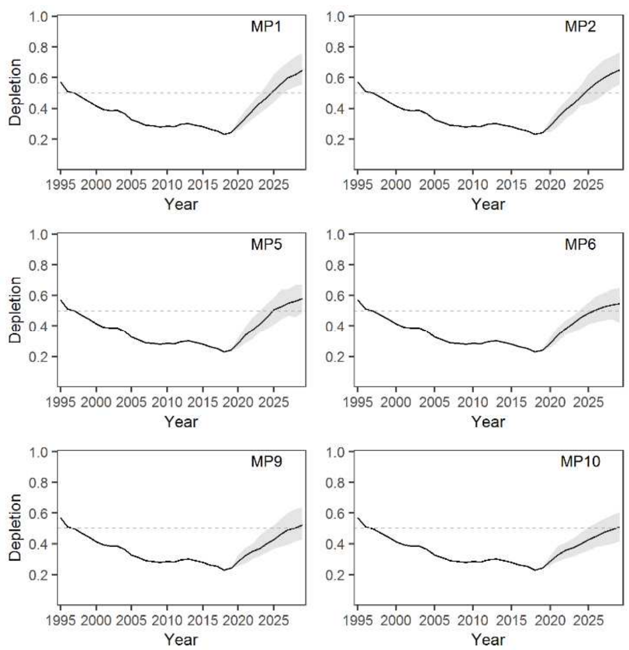

Figure A 7- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the base-case scenarios (S4) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

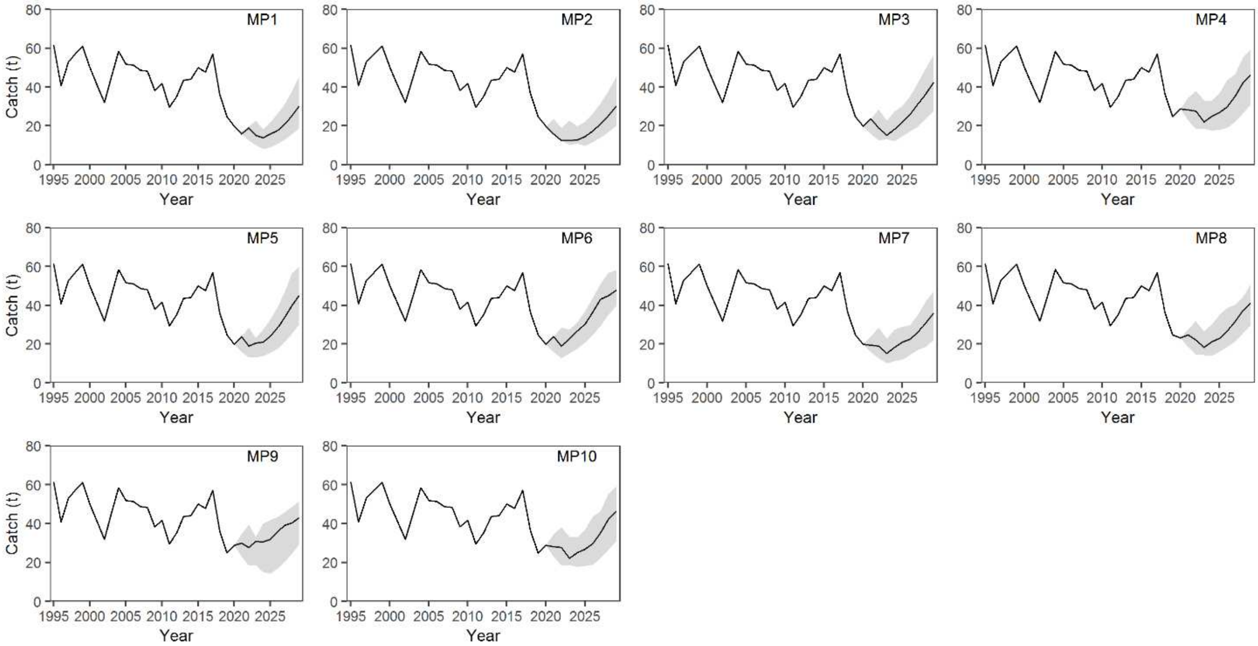

Figure A 8- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the base-case scenarios (S4) under 10 management strategies.

2- MSE projection results for short-term management period: biomass and catch trajectories for four robustness-case scenarios under all the management procedures

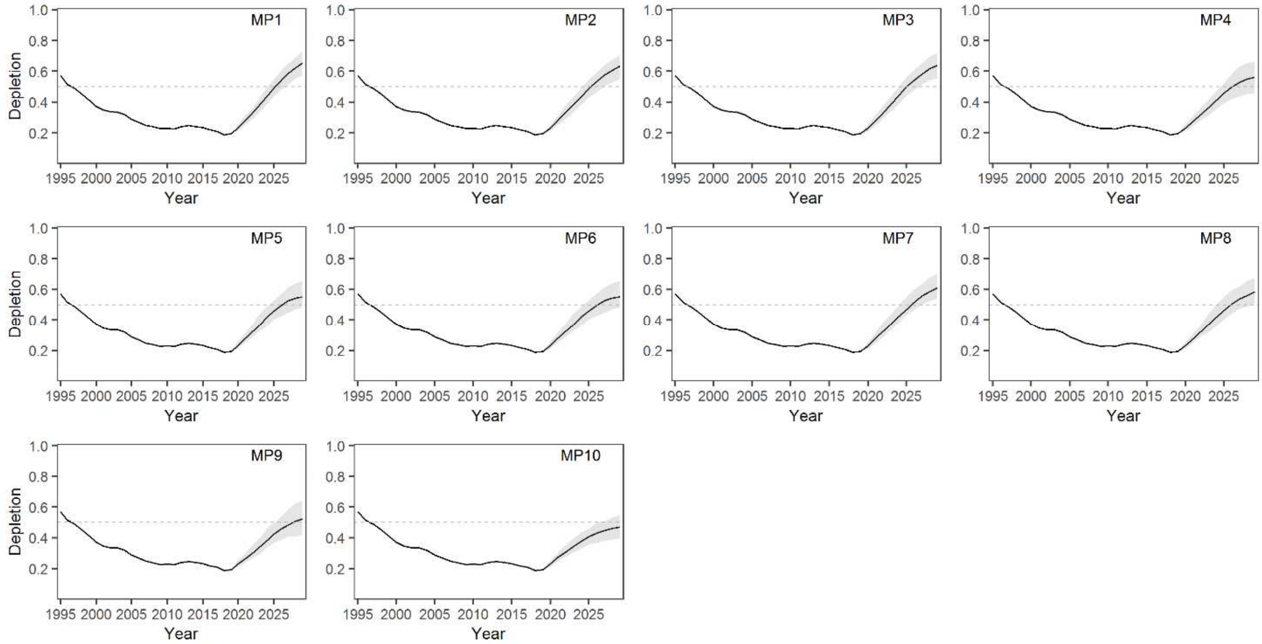

Figure A 9 Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the robustness case scenarios (S5) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

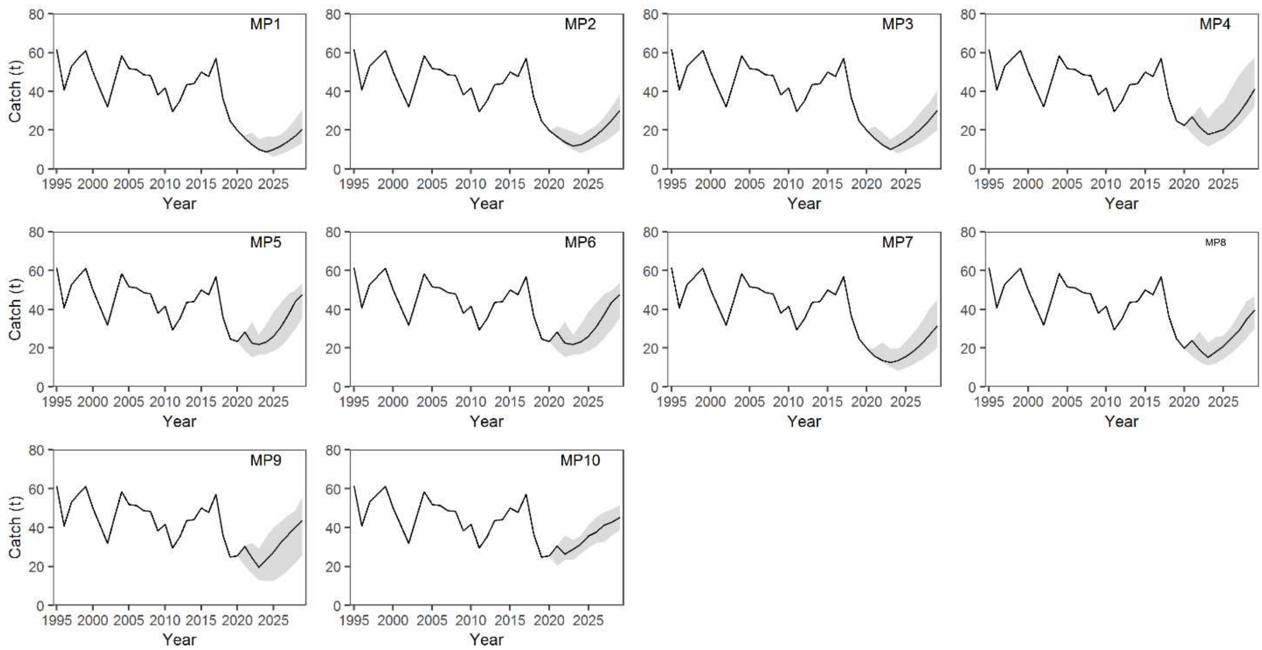

Figure A 10- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the robustness case scenarios (S5) under 10 management strategies.

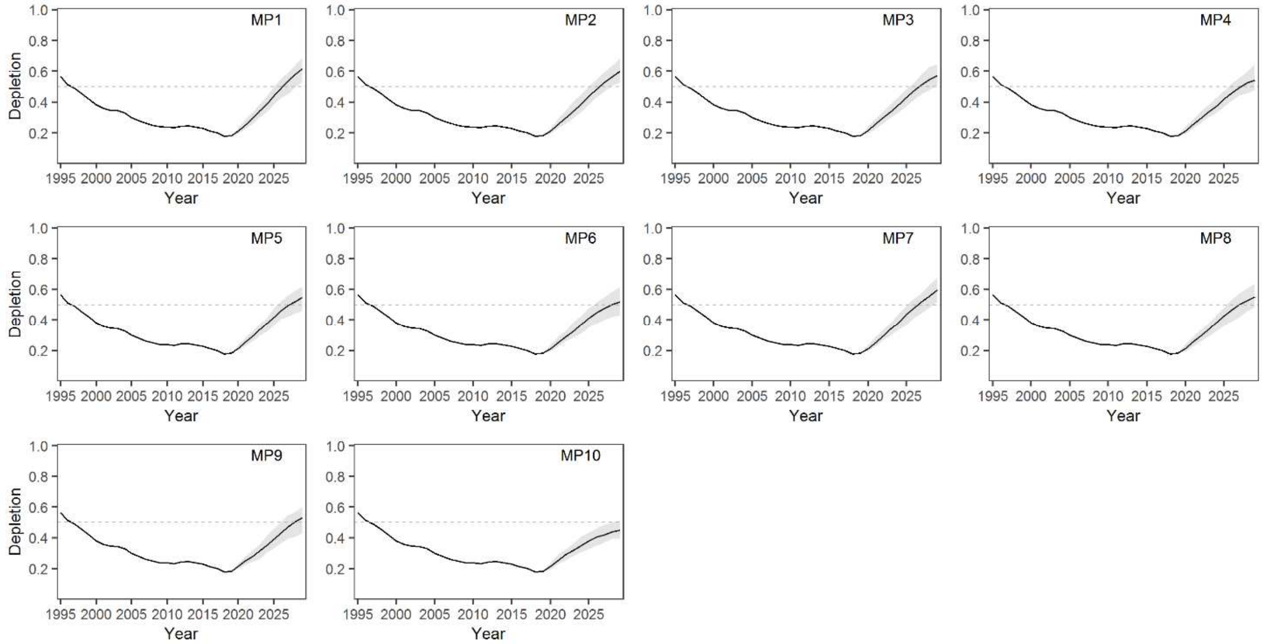

Figure A 11- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the robustness case scenarios (S6) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

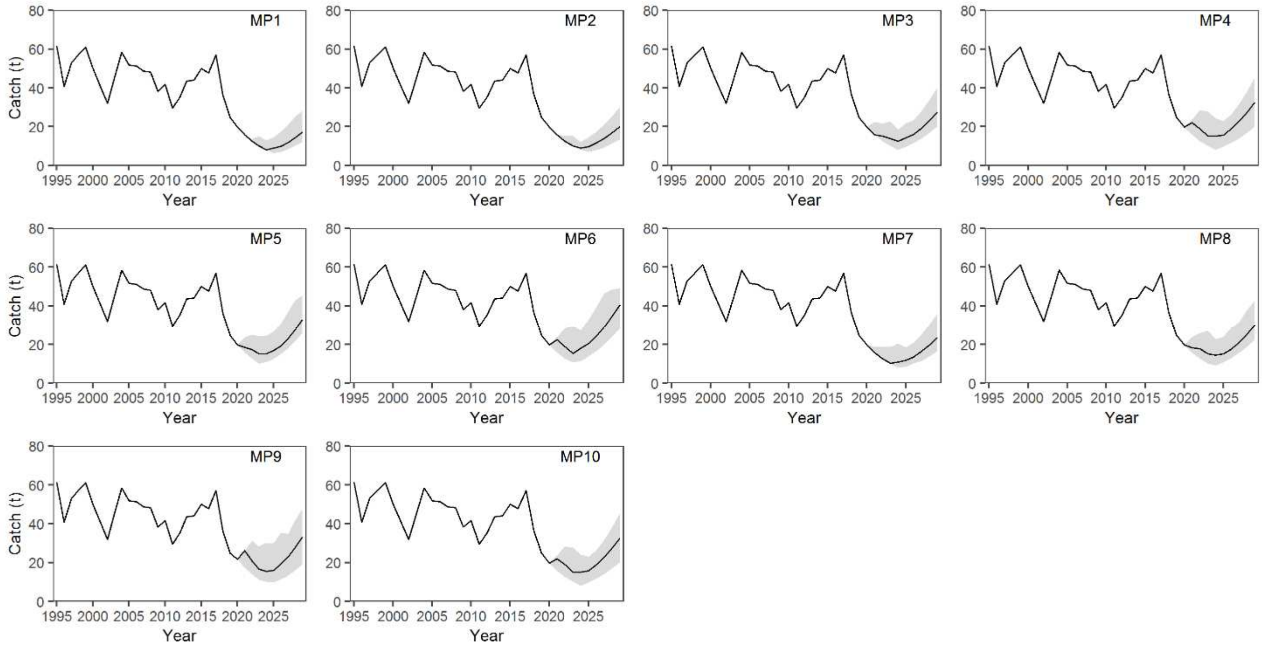

Figure A12- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the robustness case scenarios (S6) under 10 management strategies.

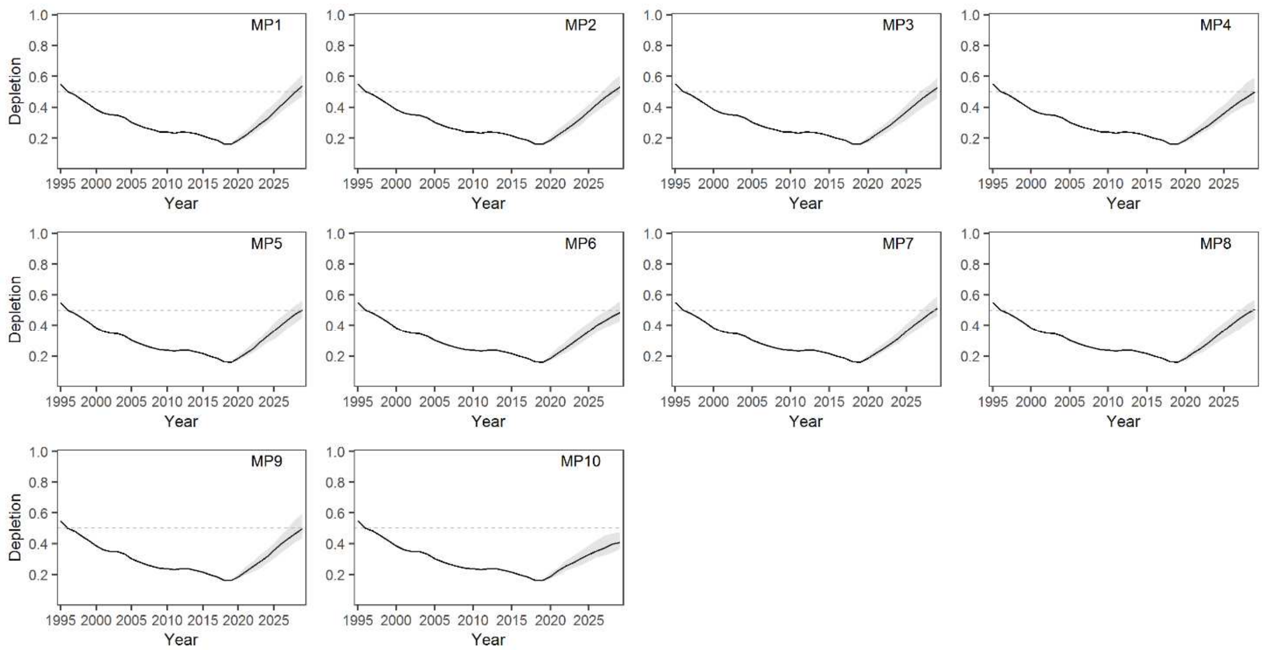

Figure A 13- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the robustness case scenarios (S7) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

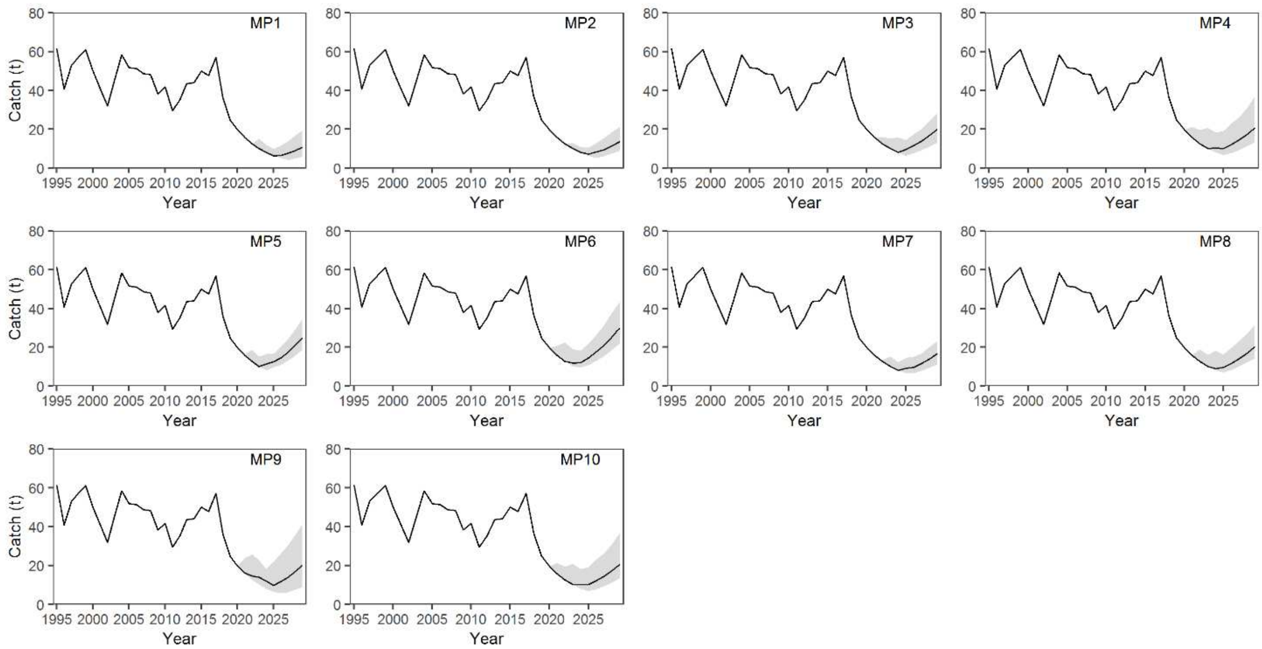

Figure A 14- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the robustness case scenarios (S7) under 10 management strategies.

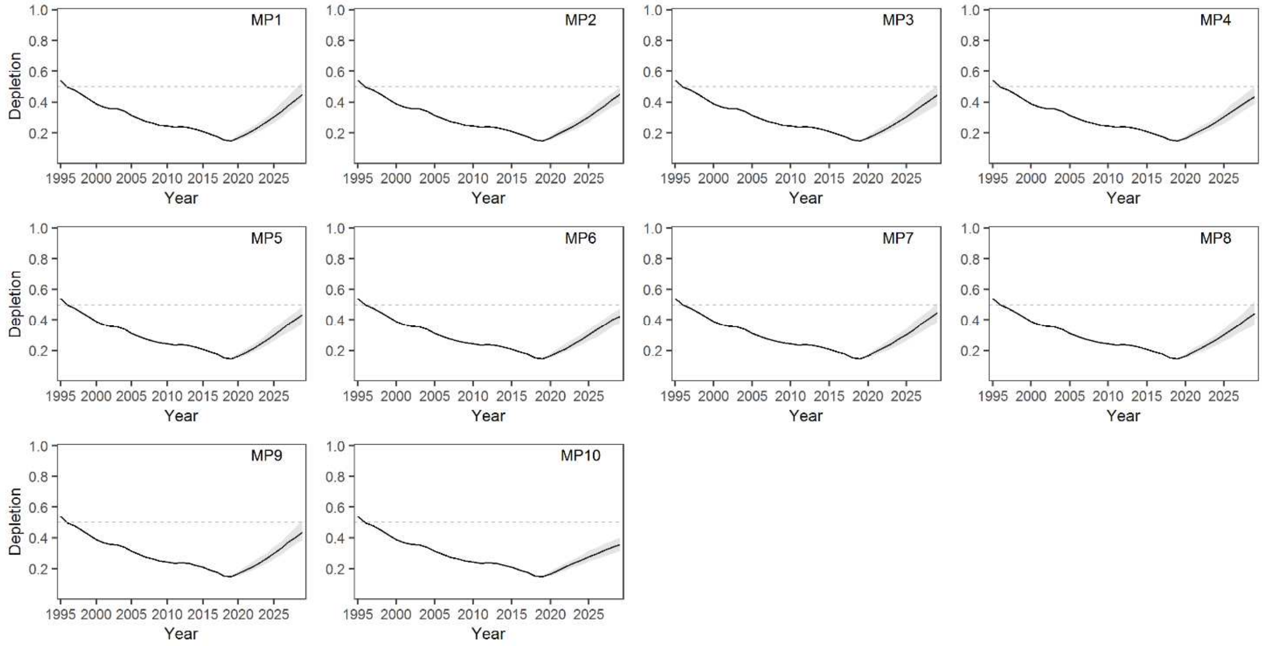

Figure A15- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and projected stock depletion for one of the robustness case scenarios (S8) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

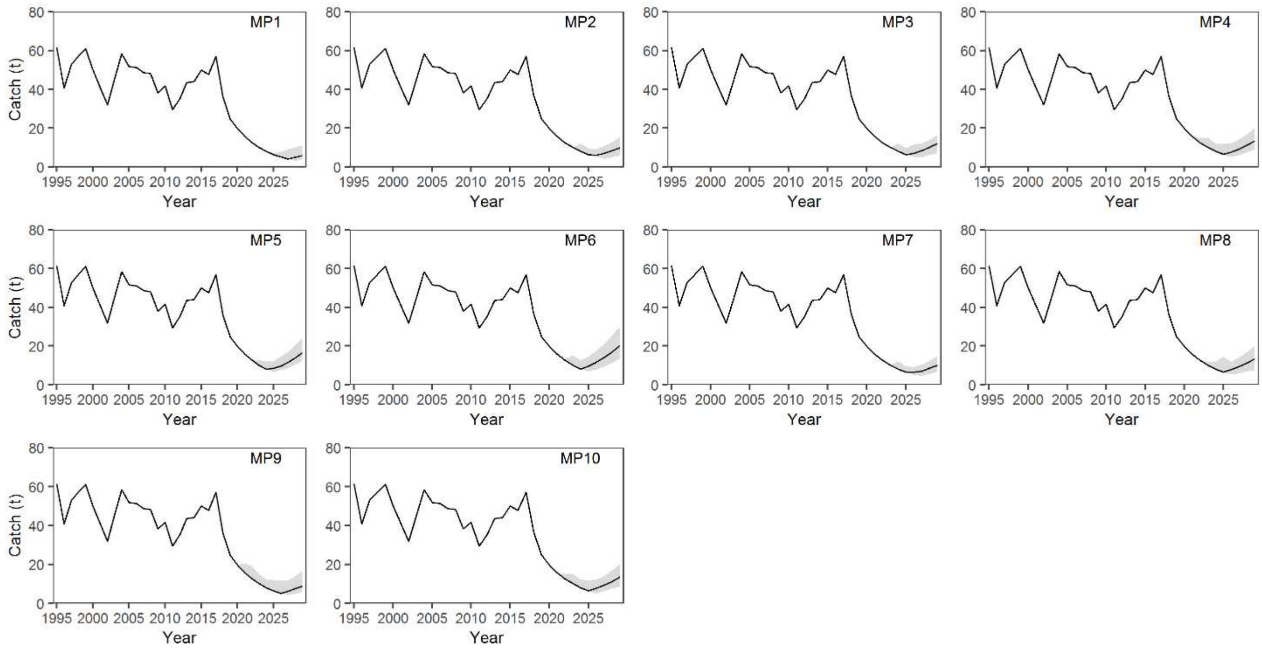

Figure A 16- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and projected catches for one of the robustness case scenarios (S8) under 10 management strategies.

3- MSE projection results for long-term management period: biomass and catch trajectories for four base-case scenarios under all the management procedures

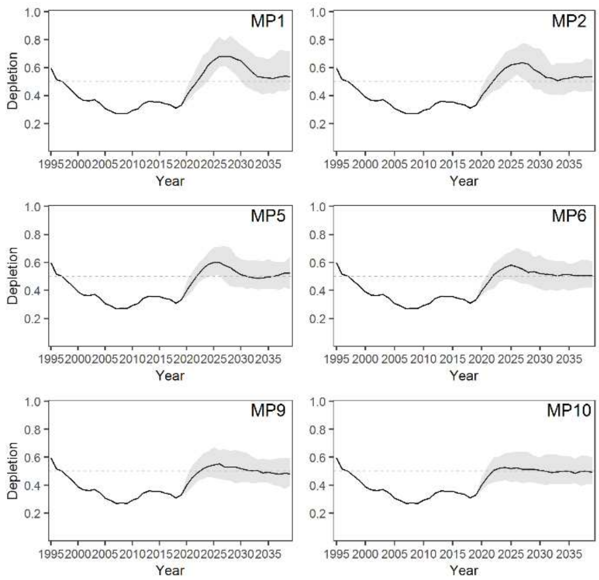

Figure A17- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the base case scenarios (S1) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

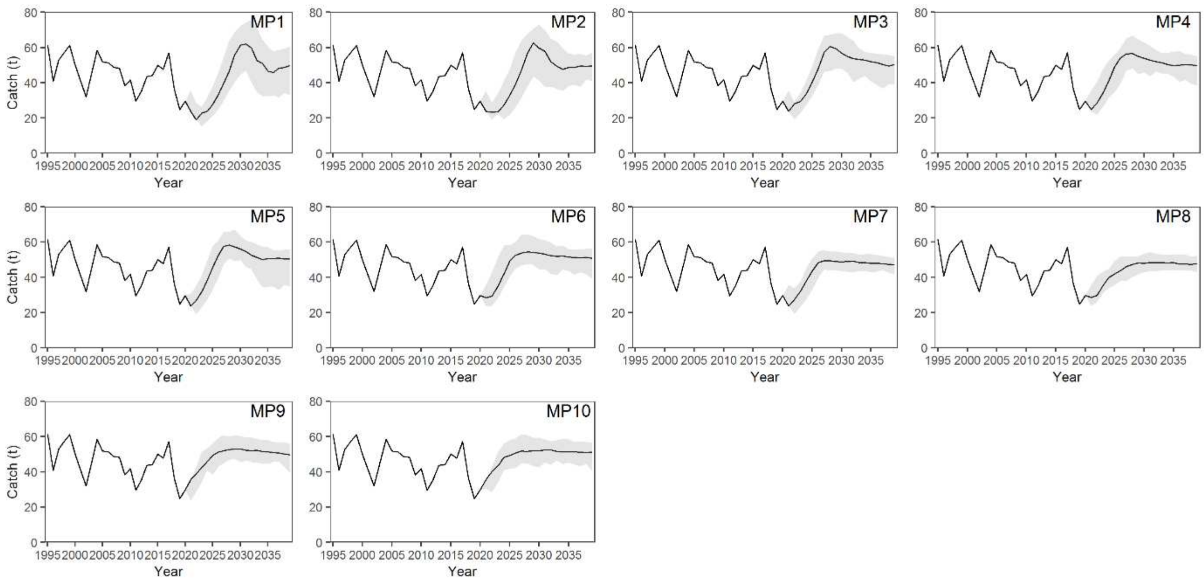

Figure A 18- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the base case scenarios (S1) under 10 management strategies.

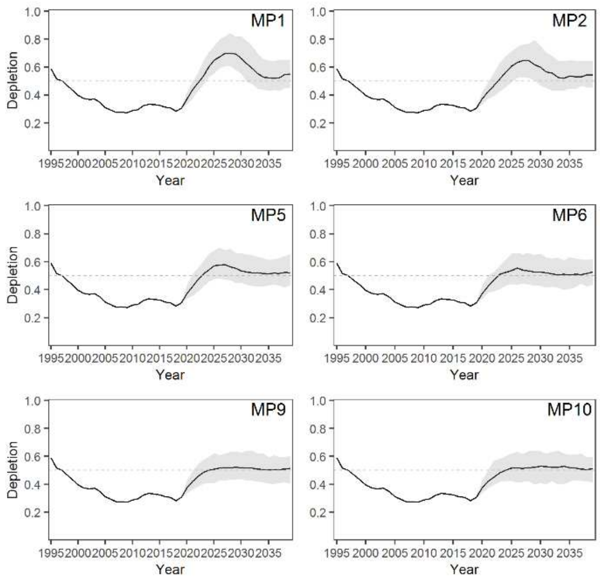

Figure A19- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the base case scenarios (S2) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

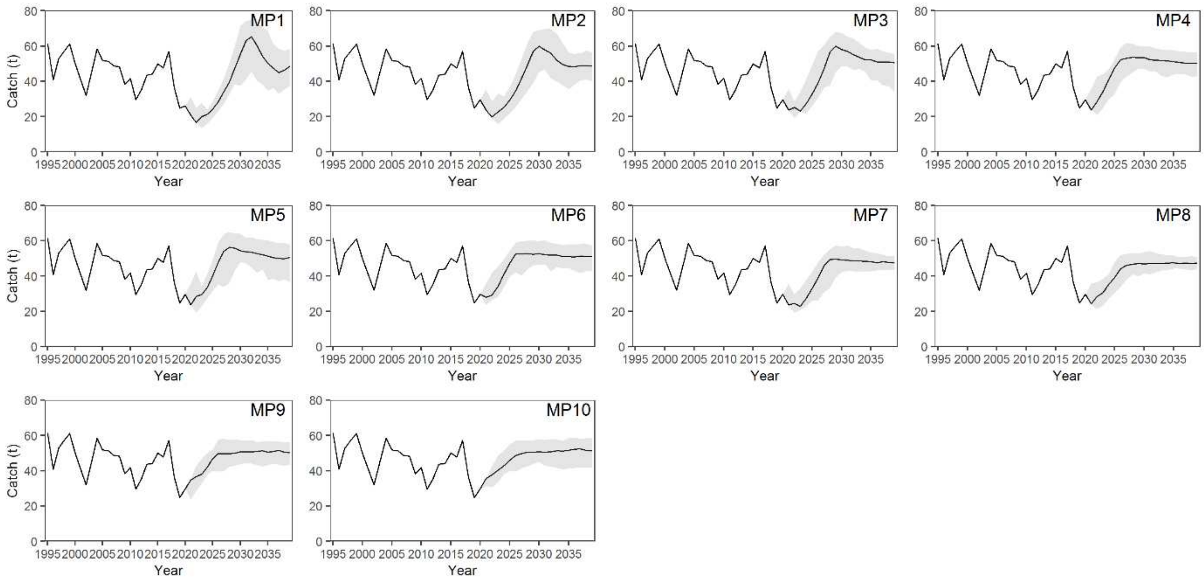

Figure A 20- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the base case scenarios (S2) under 10 management strategies.

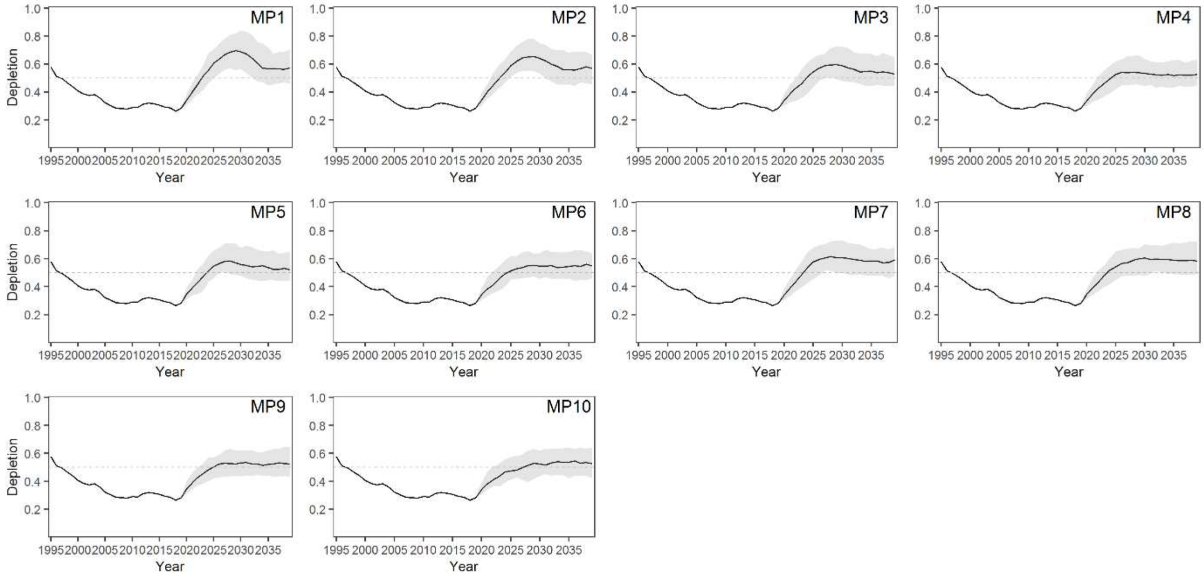

Figure A21- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the base case scenarios (S3) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

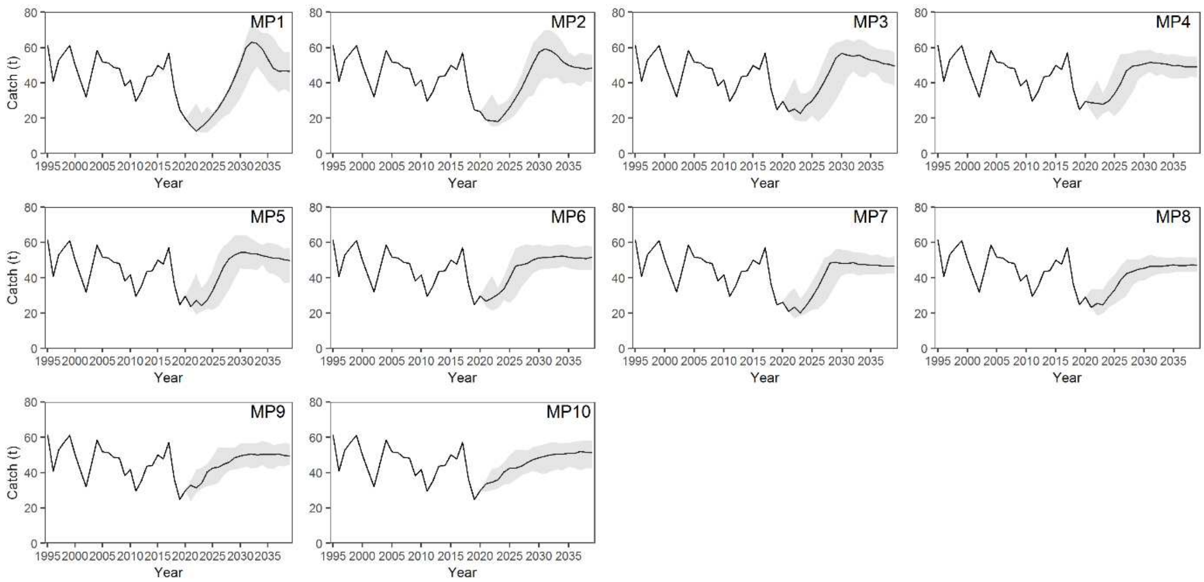

Figure A 22- trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the base case scenarios (S3) under 10 management strategies.

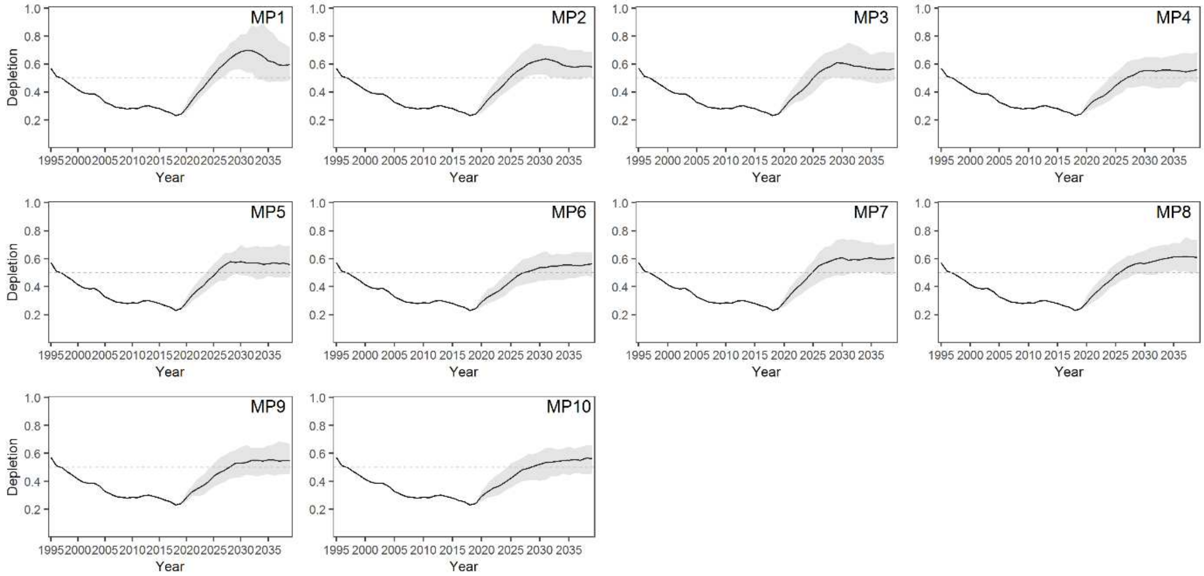

Figure A23- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the base case scenarios (S4) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

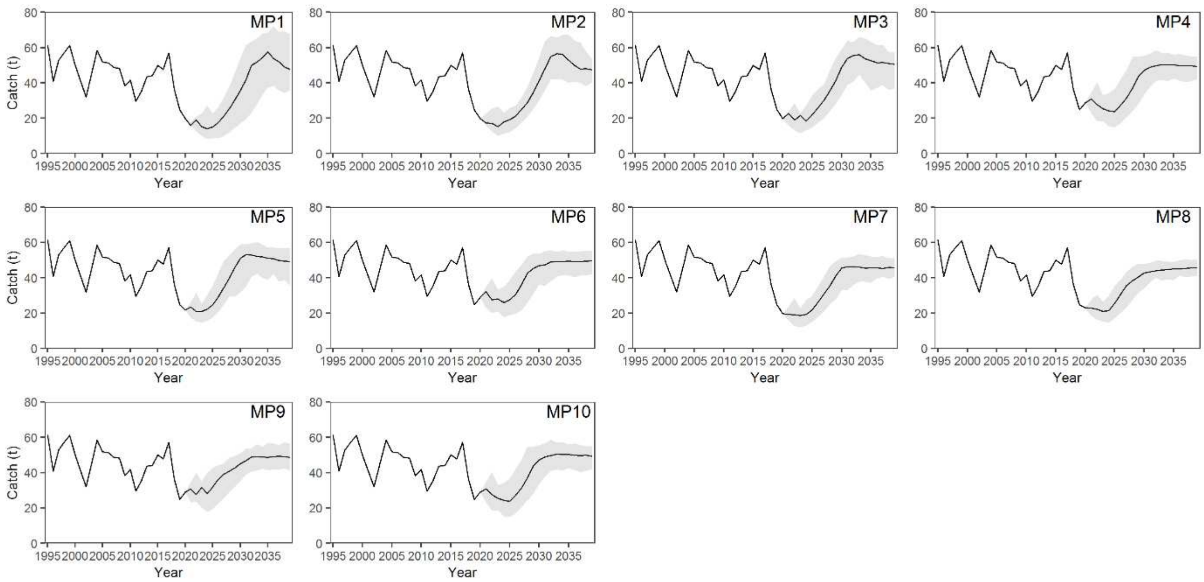

Figure A 24 - Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the base case scenarios (S4) under 10 management strategies.

4- MSE projection results for long-term management period: biomass and catch trajectories for four robustness case scenarios under all the management procedures

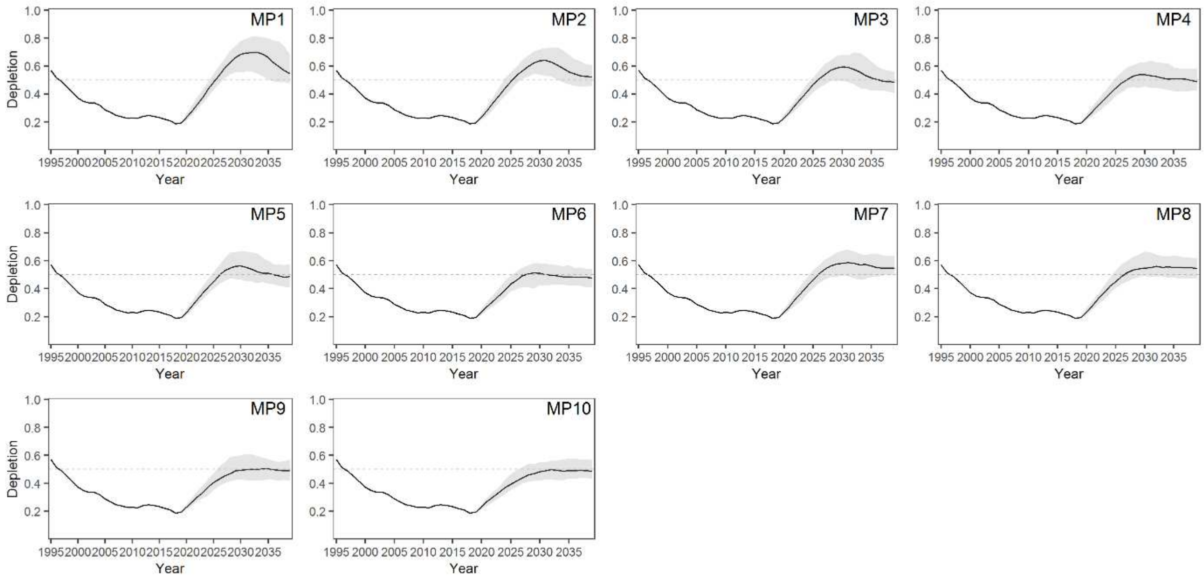

Figure A25- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the robustness scenarios (S5) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

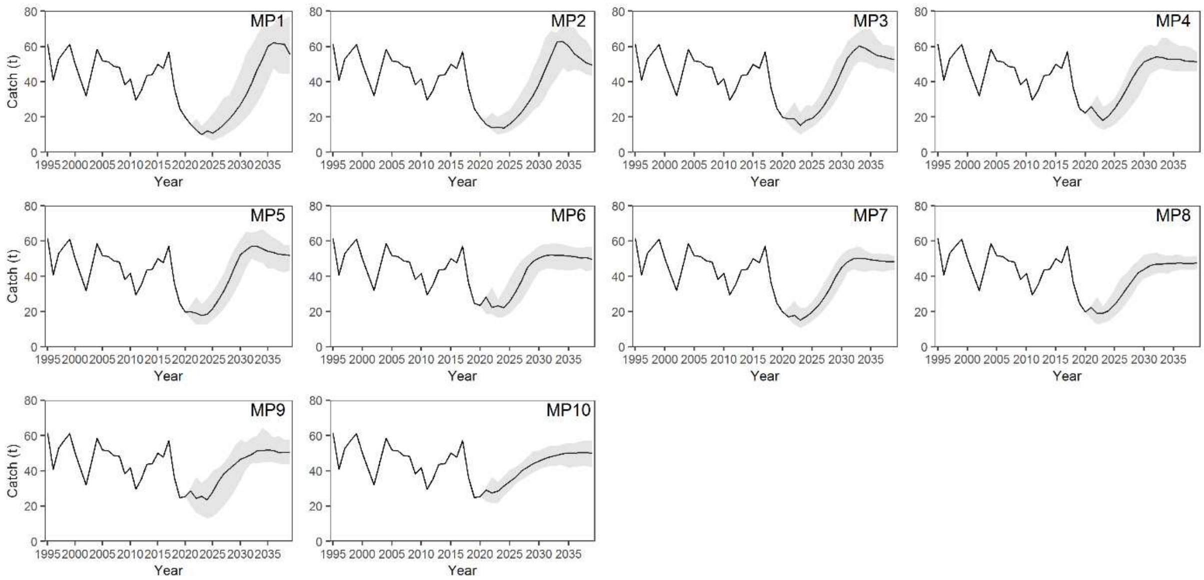

Figure A 26- Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the robustness scenarios (S5) under 10 management strategies.

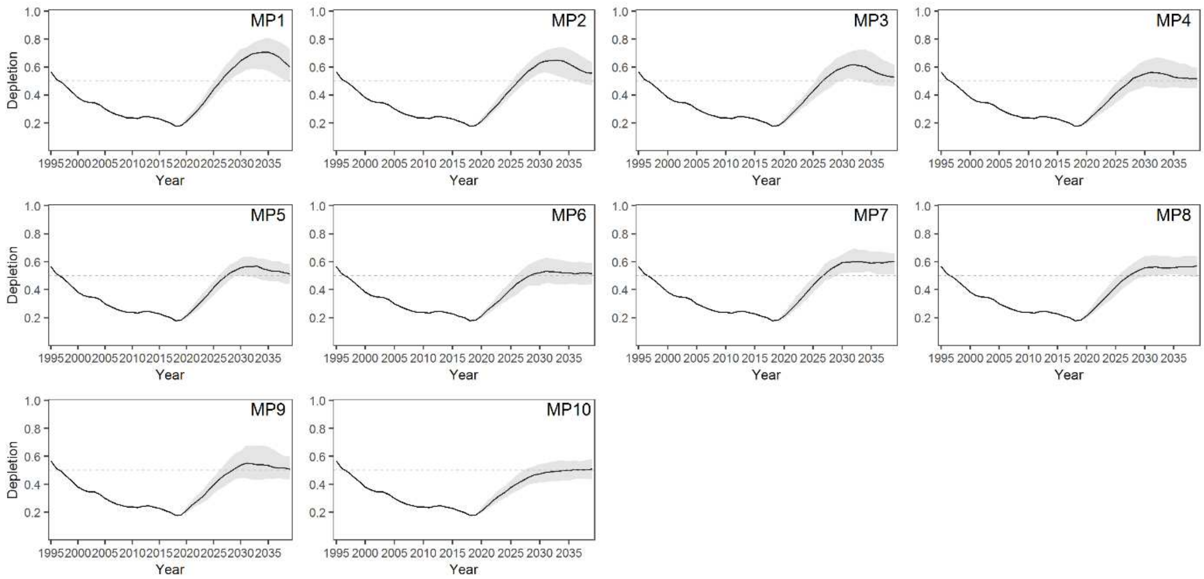

Figure A27- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the robustness scenarios (S6) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

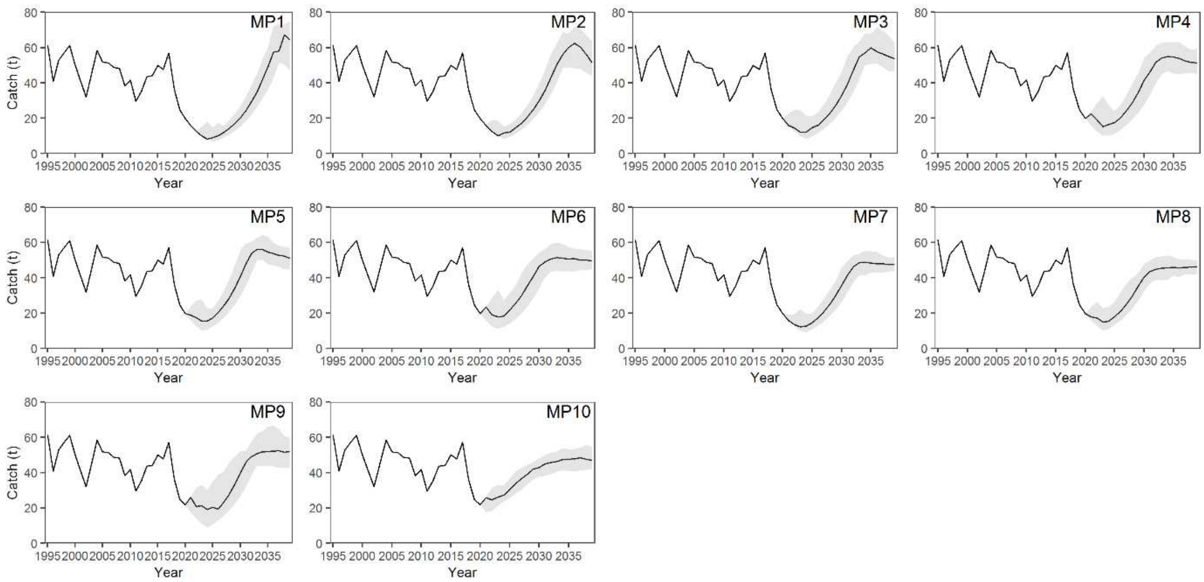

Figure A 28- Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the robustness scenarios (S6) under 10 management strategies.

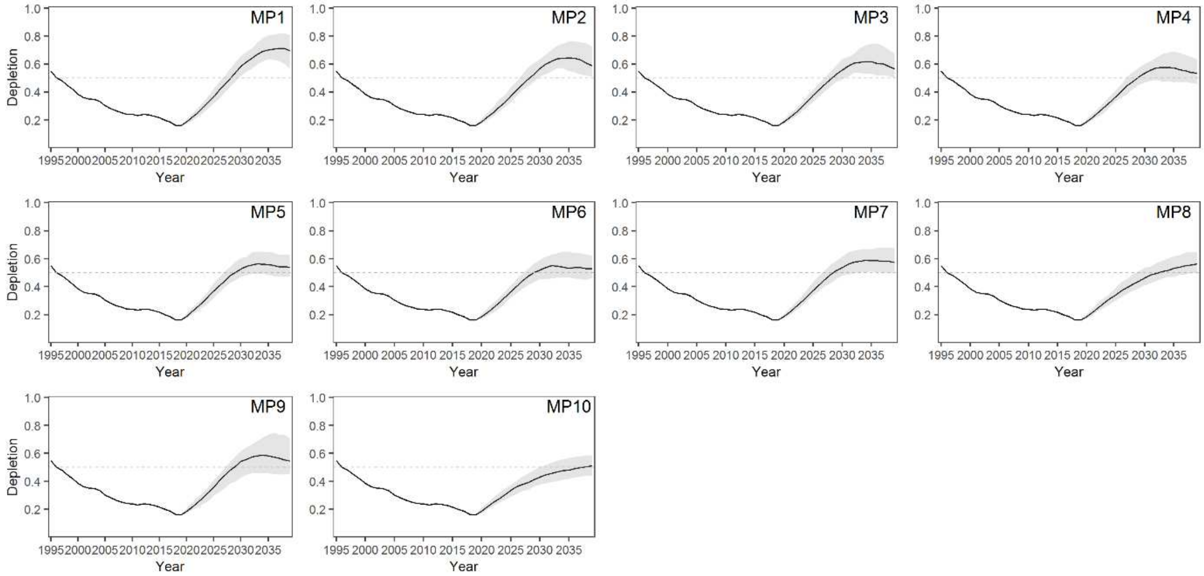

Figure A29- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the robustness scenarios (S7) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

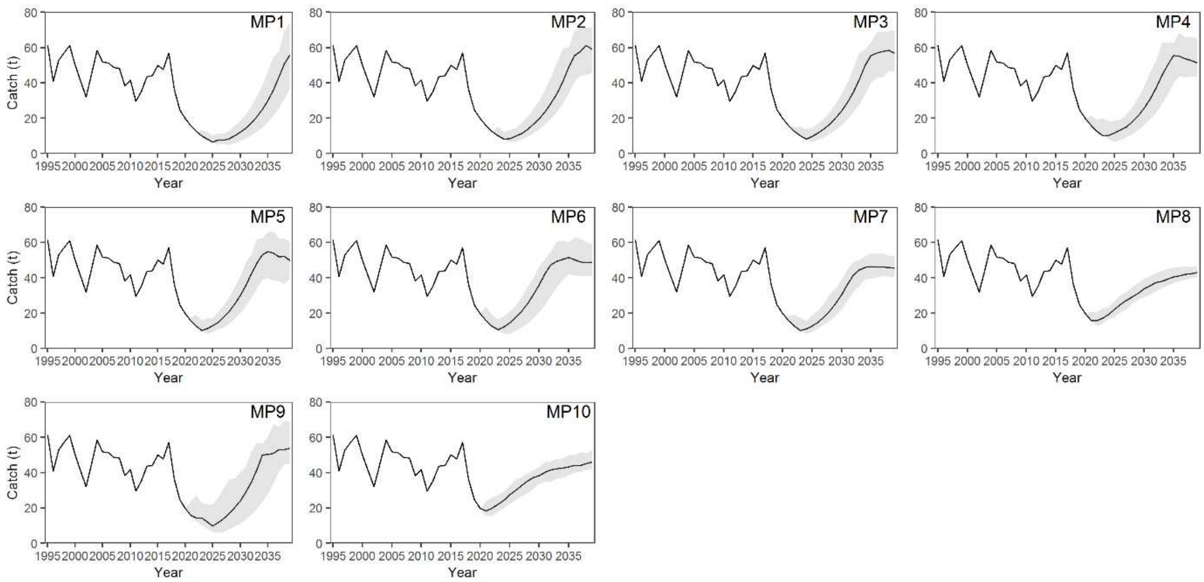

Figure A 30- Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the robustness scenarios (S7) under 10 management strategies.

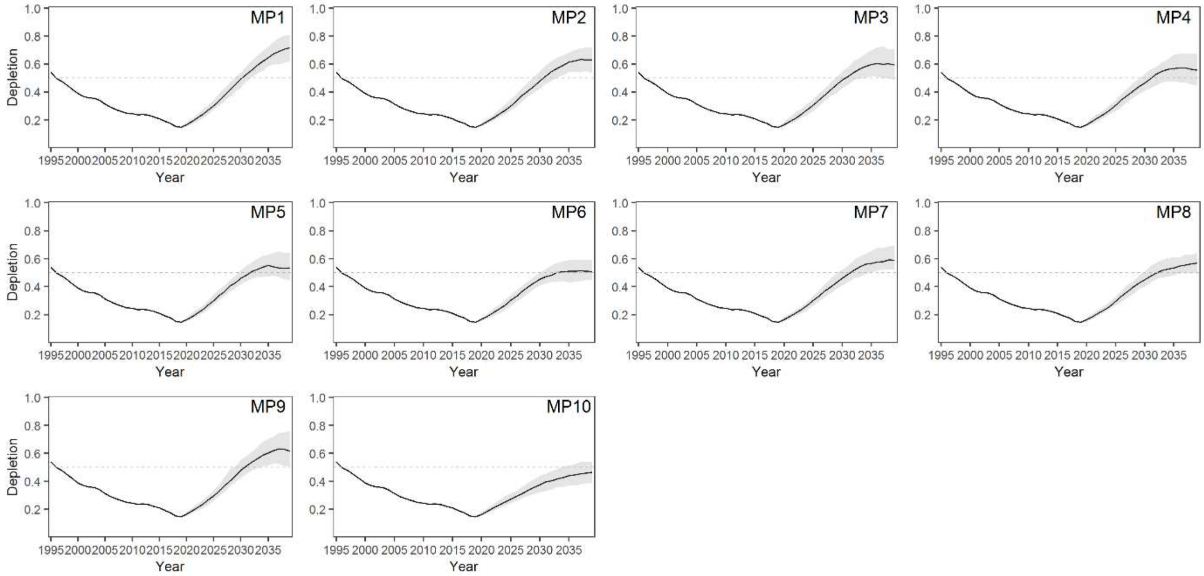

Figure A31- Trajectories of (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected stock depletion for one of the robustness scenarios (S8) under 10 management strategies. The horizontal dashed line indicates where the stock status is at of 50% of the unfished biomass.

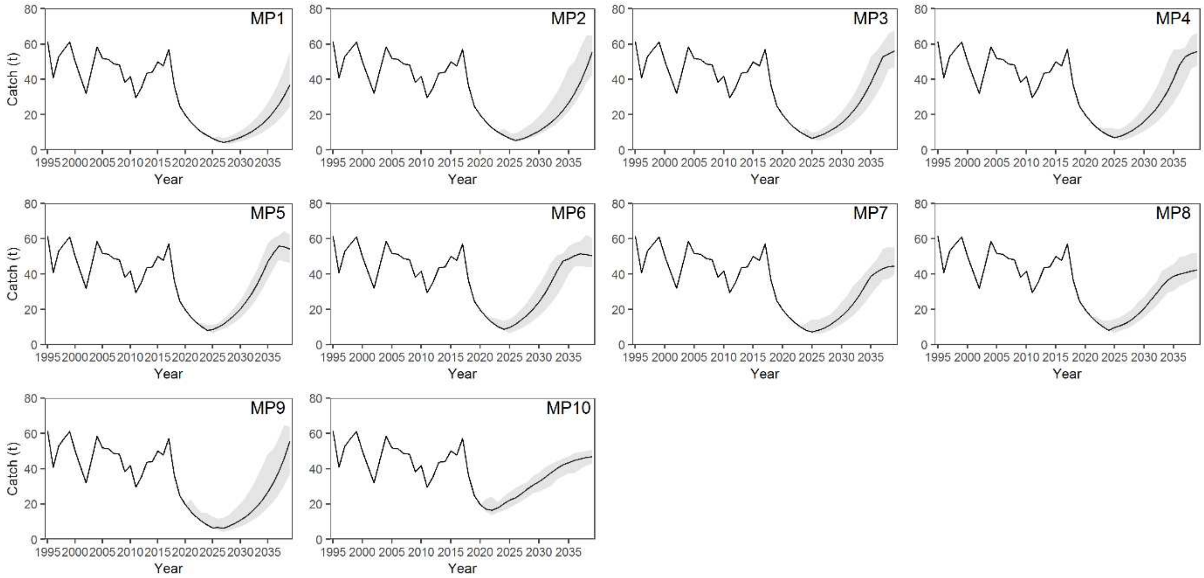

Figure A 32- Trajectories (dark lines are medians; light shading covers the 90% intervals) of historical and 20 years projected catches for one of the robustness scenarios (S8) under 10 management strategies.