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The impact of natural mortality variations on the performance of management procedures for Spanish mackerel (*Scomberomorus niphonius*) in the Yellow Sea, China

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Abstract

Natural mortality rate (M) is one of the essential parameters in fishery stock assessment, however, the estimation of M is commonly rough and the changes of M due to natural and anthropogenic impacts have long been ignored. The simplification of M estimation and the influence of M variations on the assessment and management of fisheries stocks have been less well understood. This study evaluated the impacts of the changes in natural mortality of Spanish mackerel (*Scomberomorus niphonius*) on their management strategies with data-limited methods. We tested the performances of a variety of management procedures (MPs) with the variations of M in mackerel stock using diverse estimation methods. The results of management strategies evaluation showed that four management procedures DCAC, SPMSY, curE75 and minlenLopt1 were more robust to the changes of M than others; however, their performance were substantially influenced by the significant decrease of M from the 1970s to 2017. Relative population biomass (measure as the probability of B>$0.5B_{\mathrm{MSY}}$) increased significantly with the decrease of M, whereas the possibility of overfishing showed remarkable variations across MPs. The decrease of M had minor effects on the long-term yield of curE75 and minlenLopt1, and reduced the fluctuation of yield (measure as the probability of AAVY<15%) for DCAC, SPMSY. In general, the different methods for M estimation showed minor effects on the performance of MPs, whereas the temporal changes of M showed substantial influences. Considering the fishery status of Spanish mackerel in China, we recommended that curE75 has the best trade-off between fishery resources exploitation and conservation, and we also proposed the potentials and issues in their implementations.

Key words: fishery management, uncertainty, management strategy evaluation (MSE), data limited method, DLMtool

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1 Introduction

Natural mortality rate (M) is one of the most important parameters in fishery stock assessment. The magnitude of natural mortality relate directly to stock productivity, sustainable yields, optimal exploitation rates, and management reference points (Brodziak et al., 2011). Meanwhile, it is also one of the parameters that difficult to quantify (Lee et al., 2011), and most estimation methods make certain compromise due to the limitation of available data. For example, integrated assessment models may provide relatively precious estimation of M but have a high requirement for the time series of data (Brodziak et al., 2011), which make it unfeasible or imprecise for less-well studied stocks. On the other hand, methods that do not rely on time series data, such as Pauly and other empirical formula may be useful for data-limited stocks and are actually commonly used for estimating natural mortality rate when other methods are unavailability; however, their reliability and applicability are not systematically tested (Kenchington, 2014). Other specific methods also show their limitation in use, e.g., the catch curve analysis method is applicable to the undeveloped population and unsuitable for the highly exploited fish populations (Windsland, 2015). Despite of the limit of estimation methods, most stock assessment assume constant M for the whole population (Deroba and Schueller, 2013), whereas in fact M is age-specific and generally decreases with body size (Power, 2014). In addition, many environmental and anthropogenic factors can influence natural mortality rates, such as the climate change, marine currents, and biotic interactions (Hamel, 2015). In general, we concluded that the estimation of natural mortality has substantial uncertainties in fishery stock assessment, resulting from data quality, estimated methods and time-variation, etc. These uncertainties will affect the results of stock assessment by biasing the estimate for fishing and total mortality, blurring the interspecific relationships and predation (Suda et al., 2005.), and reducing/increasing

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the estimate of total population production (Dutil and Lambert, 2000). Therefore, the variation and uncertainty of M should be explicitly considered in stock assessment and management (Whitlock et al., 2012), and in this study, we mainly studied the impact of two sources: data sources and estimated methods.

The uncertainty of fish natural mortality has been evaluated in many studies. For instance, Quiroz et al. (2010) used two sources of uncertainty including error in the life history traits estimates and variability of the equations coefficients to incorporate error on M estimates, and they suggested that Pauly's method is the most appropriate one in terms of trade-off between parameter needed and CV of M estimates incorporating all sources of uncertainty. Gaertner (2015) estimated M based on life history parameters with different estimators for the entire population and by length size classes, respectively, suggesting that the estimation of natural mortality was associated with considerable uncertainty. However, the impact of M uncertainty on the assessment and management of fisheries stock have been less well understood. Furthermore, most existing fisheries lack survey data and formal assessments (Costello et al., 2012), which makes such evaluations unfeasible. In particular, the situation is prevalent in China where most fisheries are not well assessed due to the lack of historical documents, imposing significant challenges for the sustainable restoration and management.

The recent development of data-limited methods (DLM) shows the potential to provide reasonable management advices with scarce data. The reliability of those methods should be extensively evaluated before the actual implementation to fisheries management (Kokkalis et al., 2017). Regarding the significant importance and large uncertainty of natural mortality, the sensitivity of DLM to this parameter should be evaluated with priority. In this study, we used Spanish mackerel (*Scomberomorus Niphonius*) in China's seas as an example to evaluate the robustness of a range of management procedures (MPs) on the uncertainty of natural mortality. Spanish mackerel is a long-lived pelagic fish with high commercial values. The annual commercial and recreational catch for Spanish mackerel in China is about 45 000 t, contributing significantly to regional economy (Cheng and Wei, 1987). In recent years, this species is subject to increasing fishing effort, diverse fishing gears, and expanded fishing grounds, all of which implied a high risk of overexploitation, although the fishery status have not been formally assessed in literature. Remarkable changes have been observed in the life history traits of Spanish mackerel, such as higher growth rate, earlier maturation, and changes of population structure (Qiu and Ye, 1996). A preliminary analysis using Beverton-Holt life history invariants method (Prince et al., 2015) suggested that the natural mortality rate of this species decreased significantly in last decades, i.e., from 0.80 in the 1970s (Liu et al., 1982) to 0.59 in 2001–2013 (You, 2014).

The aim of this study is to take into account the uncertainty of natural mortality in the management of Spanish mackerel fishery to achieve sustainability improvement. In this study, we estimated the changes in natural mortality of Spanish mackerel in recent years, and attributed the uncertainty of natural mortality into temporal and methodological variations. We compared the performances of a range of management procedures for Spanish mackerel fisheries using an approach of management strategy evaluation, and evaluated the effect of the uncertainty and variation of natural mortality on stock management. In addition, we proposed the potentials and issues in the practical application of those MPs in China to improve the effective fishery management of Spanish mackerel.

2 Materials and methods

2.1 *Data-limited methods (DLM)*

In the present study, we adopted a DLMtool method to simulate the dynamics of mackerel fishery and test the performance of a variety of management procedures. The DLMtool (Data-limited methods Toolkit) is an R package (R Development Core Team, 2016) developed by the University of British Columbia's Institute for Oceans and Fisheries and the Natural Resources Defense Council (Carruthers et al., 2015). The implementation of DLMtool can be divided into four steps as other data-limited methods (Honey et al., 2010): (1) determining data richness of specified fishery, (2) selecting the appropriate assessment methods, (3) assessing stock status, and (4) management strategy evaluation (MSE). The core process of DLMtool, i.e., the MSE step is generally introduced bellow.

MSE is a fisheries management paradigm that evaluates the performance of management procedures and the trade-off among different management objectives as the basis for management decisions (Butterworth and Punt, 1999; Butterworth, 2007). MSE predict the status of fish stocks in terms of specific management objectives and provide management recommendations with explicit consideration of the uncertainty and sensitivity of management strategies. MSE involves three components of DLMtool, operating model, management procedure and performance criteria (Fromentin el al., 2014).

(1) Operating model (OM) is used to simulate the dynamics of fishery stocks and fleets, and includes the error processes of monitoring and observation. An OM is composed of three submodels in DLMtool, including Stock, Fleet and Observation, in which the Stock model contains biological parameters of the population; Fleet model includes gear selectivity and fishing effort; and Observation model contains parameters of observation error and bias.

(2) Management procedure (MP) is a general approach to fisheries management, including both input and output control methods. It provides management advices in the form of TAC or limit gear size and fishing effort. MPs of Output control provide TAC as a management suggestion while MPs of input control adjust the catchable size and the relative fishing effort in management. DLMtool now includes 89 MPs and the new method is still being added. Depending on data availability, there are 22 MPs in DLMtool that can be applied on Spanish mackerel fishery. They were 11 output control MPs including AvC, CC1, CC4, DD, DD4010, GB_slope, SPmod, SPMSY, NFref, DCAC and Fratio, and 11 input control MPs including curE, curE75, DDe, DDe75, EtargetLopt, matlenlim, matlenlim2, minlenLopt1, MRnoreal, MRreal and slotlim (Table 1).

(3) Performance criteria are used for evaluating the performance of MPs. The evaluation criteria for MSE in DLMtool include relative spawning population biomass, long and short term yield, probability of overfishing and so on. We used the following six criteria for the evaluation of MPs considering the necessary trade-off among management objectives: (i) Median yield (last 5 years) relative to current; (ii) Median biomass (last 5 years) relative to current; (iii) B50%: likelihood of biomass dropping below 50 percent B_{MSY}; (iv) PNOF: probability of not overfishing; (v) LTY: fraction of simulations getting over half F_{MSY} yield in the last ten years of the projection; (vi) AAVY: fraction of simulations where average annual variability in yield is less than 10 percent.

2.2 *Fishery data*

The samples of Spanish mackerel were collected from five

Table 1. The description of MPs in this study, including 11 output control MPs and 11 input control MPs

Type	MPs	Description	Reference
Output control	DCAC	depletion-corrected average catch, which calculated as the sum of catches divided by the sum of the number of years; relevant formulas are W=0.5B_0, $\frac{W}{Y_{\rm pot}}=\frac{1}{M}$, where W is Harvest ratio, B_0 is unfished biomass, $Y_{\rm pot}$ is potential yield, and M is natural mortality.	Maccall (2009)
	NFref	TAC=0	Carruthers and Hordyk (2016)
	SPMSY	an MP for estimating MSY to determine the OFL (optimal fishing limit); OFL=D×(1–D)×r×$K_{\rm c}$×2, where $K_{\rm c}$ is the carrying capacity, r is the maximum rate of population increase, and D is depletion.	Martell and Froese (2013)
	AvC	TAC=average catch	
	CC1	TAC=recent catch level	Geromont and Butterworth (2015)
	CC4	TAC=70% of recent catch level	
	Fratio	TAC=fixed ration of nature mortality rate × current absolute stock biomass	Gulland (1971), Martell and Froese (2013)
	DD	a delay difference stock assessment	Carruthers et al. (2012), Carruthers and Hordyk (2016)
	DD4010	a delay difference stock assessment with a 40–10 harvest control rule superimposed	
	SPmod	$TAC_y\begin{cases}\frac{4}{5}C_y, \Delta B<\frac{4}{5}\\ \frac{6}{5}S_{y-1}, \Delta B>\frac{6}{5}\\ TAC_{y-1}, \frac{4}{5}<\Delta B<\frac{6}{5}\end{cases}, \Delta B=\frac{B_y}{B_{y-1}}, S_y=B_y-B_{y-1}+C_{y-1},$ $TAC_1=C_1$, where C_y is the slope in surplus production at the y year, B is biomass, B_y is biomass at the y year and S is biomass over the last 10 years.	Carruthers and Hordyk (2016), Maunder (2014)
	GB_slope	the incremental changes of TAC made to maintain a constant relative abundance index	Geromont and Butterworth (2015)
Input control	EtargetLopt	adjust effort up/down if mean length above/below $L_{\rm target}$	
	curE	using the fishing effort of the final year in historical simulations as the management target	
	curE75	using 75 percent of the fishing effort of the final year in historical simulations as the management target	
	Mrnoreal	a spatial control, requiring no fishing in Area 1 and not reallocating this fishing effort to Area 2	
	MRreal	a spatial control, requiring no fishing in Area 1 and reallocating this fishing effort to Area 2	
	minlenLopt1	rebuilding the stock biomass towards the optimal length by restricting the catch of small fish; $L_{\rm opt}$=b/(M/K+b), where b is length-weight parameter beta, approximately equal to 3, M is natural mortality rate, K is von Bertalanffy growth rate, M/K is Beverton-Holt life-history invariant, and M and K should come from the same research time and sea area	Hordyk et al. (2015)
	matlenlim	selectivity-at-length set equivalent to maturity-at-length	Carruthers and Hordyk (2016)
	matlenlim2	selectivity-at-length set slightly higher than the maturity-at-length	Carruthers and Hordyk (2016)
	slotlim	selectivity-at-length set using a slot limit. The maximum limit is the 75th percentile between the new minimum legal length and the estimated asymptotic length.	Carruthers and Hordyk (2016)
	DDe	a delay-difference assessment, using a time-series of catches and a relative abundance index to estimate and recommend FMSY	method based on equations of Carl Walters
	DDe75	a delay-difference assessment, using a time-series of catches and a relative abundance index to estimate and recommend 75 percent FMSY	

docks around the Yellow Sea from 2016 to 2017, including Yantai, Weihai, Qingdao, Nantong in China and Jeju in Korea (Fig. 1a). A range of biological parameters such as weight-length relationship and von-Bertalanffy growth rate were estimated from the samples using ELEFAN method (Gayanilo, 1988). The parameters that cannot be precisely estimated from the survey were obtained from relevant studies (reference values in Table 2). In addition, annual averaged CPUE data was collected by the East China Sea Fisheries Research Institute (unpublished data), and annual catch data was obtained from Chinese Fisheries Statistical yearbook (the Ministry of Agriculture Fishery and Fishery Administration, 2016) (Fig. 1b). The parameters were used to simulate the dynamics and the associated uncertainty of mackerel stock.

We evaluated M with a variety of estimation methods and from different periods of time. Four empirical methods were used in this study considering data availability, including M/K invariants, Hoenig, Pauly and Then's empirical formula.

(1) M/K (Prince et al., 2015): the method is based on Beverton-Holt life history invariants, M/K=1.5, where K is the von Bertalanffy growth rate.

(2) Hoenig empirical formula (Hoenig, 1983): ln$M$=1.48–1.01ln$t_{\rm max}$, where $t_{\rm max}$ is the maximum age. We use the maximum age of 30 according to the of growth equation.

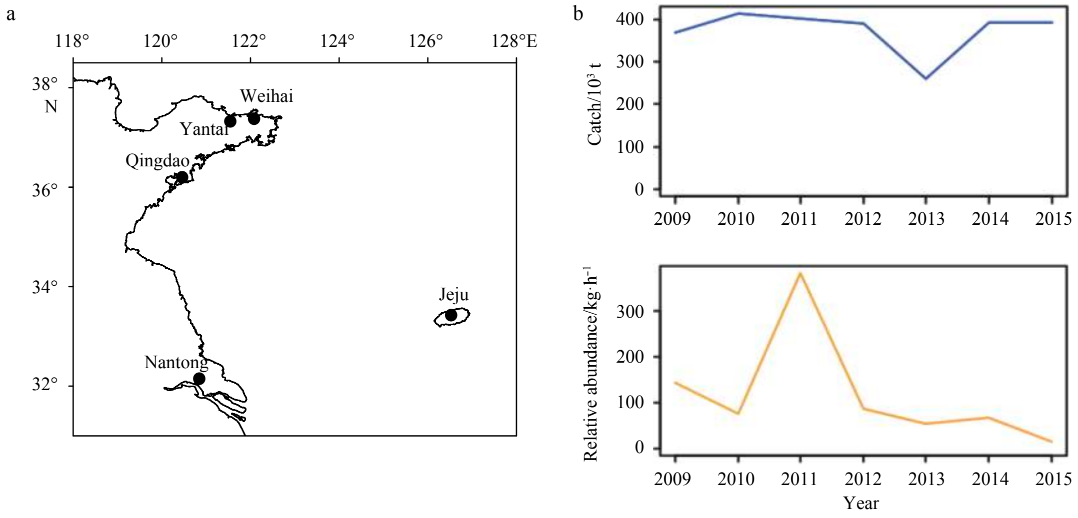

Fig. 1. Survey stations and fishery data of Spanish mackerel. a. The black dots represent five cities that we collected Spanish mackerel during 2016–2017; b. the blue line represents the catches of Spanish mackerel in China from 2009 to 2015 and the orange line the annual averaged CPUE (unpublished data) in China from 2009 to 2015.

Table 2. Biological parameters of Spanish mackerel in DLMtool (the estimated values were derived from the survey during 2016–2017 and the reference values were collected from relevant literature)

Parameter	Comment	Estimate value	Reference value	Reference
a	weight-length parameter	1.5×10^{-5}	1.00×10^{-4}–2.30×10^{-5}	Liu et al. (1982)
b	weight-length parameter	2.89	2.4–2.94	Liu et al. (1982)
K	von Bertalanffy growth rate	0.1	0.39, 0.46, 0.53	Liu et al. (1982), Sun (2009), You (2014)
Linf	maximum length	746 mm	777–983 mm	Sun (2009)
t_0	theoretical age at length zero	−0.733	−1.06 to −0.7	Liu et al. (1982)
maxage	the maximum age	30	–	
R_0	the magnitude of unfished recruitment	–	10^8	Sun (2009)
Vmaxlen	the vulnerability of the longest (oldest) fish	–	7.5×10^{-3}	Sun (2009)
L_{50}	length at 50% maturity	–	380	

(3) Pauly empirical formula (Pauly, 1980): $\ln M=-0.015\,2-0.279\ln_{\infty}+0.654\,3\ln K+0.463\,4\ln T$, where L_{∞} is maximum length, K is von Bertalanffy growth rate, and T is annual average temperature. The average annual water temperature was 14°C according to the average temperature of the Yellow Sea and Bohai Sea (Sun, 2009).

(4) Then empirical formula (Then et al., 2015): $M=4.889t_{\max}{}^{-0.916}$ and $M=4.118K^{0.73}L_{\infty}{}^{-0.33}$.

It should be noted that the accuracy of these methods have not been explicitly examined for Spanish mackerel, however, as the aim of this study is to evaluate the uncertainty of M and its effect on fisheries management, a wide range of M in simulation scenarios could relieve the requirement of accurate estimation. In addition, the changes of M in four different periods from 1974 to 2017 were estimated using M/K, Pauly and Then's empirical approach (Table 3). A remarkable decline of M was illustrated from all the three methods, and we used the result of Pauly's equation in the following simulation study. We assume the changes of M following $M_y=M_0(1+r)^y$, and fitted a linear regression analysis between $\ln M$ and survey time to estimate the declining rate (r) and annual variation of M (Msd). The variation, declining rate ($r=-0.019$) and annual variation ($Msd=0.19$) of M was used in the simulation of DLMtool (Carruthers and Hordyk, 2016).

We first tested the robustness of available MPs on the uncertainty of M as well as other biological parameters that cannot be estimated accurately using MSE approach, in which OM was specified with a range of possible parameter values (Carruthers and Hordyk, 2016), and the specific parameter settings of our simulations can be seen in Table 4. The values of M were drawn from the preassigned uniform distribution in each simulation run. The scenarios were repeated for 1 000 times for each MP, and the MSE processes were repeated for 100 times. The number of years used for implementing MPs was set to 20 years and the interval of stock assessment was every 2 years in MSE. The performance of different MPs was compared using a range of criteria to select suitable MPs for the mackerel fishery. In addition, we distinguished the influence of M variation on fishery management resulting from two sources of uncertainty, for which the performance of the selected MPs was compared across different time periods and estimation methods.

3 Results

3.1 *MP selection*

Management strategy evaluation (MSE) showed that 22 MPs had different trade-offs with respect to fishery yield, population biomass and the risk of overfishing, whereas none of these MPs could simultaneously optimize all the demanding properties. AvC, MRreal could maintain the level of production but lead to

Table 3. The variation of nature mortality estimated from different methods and time periods (four time periods were chose and four empirical methods were used to estimate the natural mortality rate of Spanish mackerel)

	Time period			
	2016–2017	2006–2008	2001–2013	1974–1978
M/K	0.15	0.69	0.59	0.8
Hoenig (1983) — Joint Equation	0.15			
Hoenig (1983) — Fish Equation	0.14			
Pauly (1980) — Length Equation	0.11	0.32	0.28	0.35
Then et al. (2015) — tmax	0.22			
Then et al. (2015) — growth	0.1	0.26	0.23	0.3
Sampling size	465	800	2 041	6 522
Data source	this study	Sun (2009)	You (2014)	Liu et al. (1982)

Table 4. The description of Operating model (OM)

Sub-model	Slot names	Value 1	Value 2	Comment
Stock	Name	*Scomberomorus niphonius*		the name of the Stock object
	maxage	30		the maximum age of individuals that is simulated
	R_0	100 000 000		the magnitude of unfished recruitment
	M	0.1	0.22	natural mortality rate (uniform distribution)
	Msd	0.18	0.2	inter-annual variability in natural mortality rate expressed as a coefficient of variation (uniform distribution)
	Mgrad	–0.02	–0.02	mean temporal trend in natural mortality rate, expressed as a percentage change in M per year (uniform distribution)
	h	0.3	0.8	steepness of the stock recruit relationship (uniform distribution)
	SRrel	1		type of stock-recruit relationship: (1) Beverton-Holt; (2) Ricker
	Linf	777	983	maximum length (uniform distribution)
	K	0.08	0.1	von Bertalanffy growth rate K (uniform distribution)
	t_0	–1.6	–0.7	von Bertalanffy theoretical age at length zero (uniform distribution)
	Ksd	0	0.05	inter-annual variability in growth parameter K (uniform distribution)
	Kgrad	–0.25	0.25	mean temporal trend in growth parameter K, expressed as a percentage change in K per year (uniform distribution)
	Linfsd	0	0.05	inter-annual variability in maximum length-uniform distribution
	Linfgrad	–0.25	0.25	mean temporal trend in maximum length, expressed as a percentage change in Linf per year (uniform distribution)
	recgrad	–10	10	mean temporal trend in log-normal recruitment deviations (uniform distribution)
	a	0.000 023	0.000 1	length-weight parameter alpha (uniform distribution)
	b	2.4	2.94	length-weight parameter beta (uniform distribution)
	L_{50}	357	403	length-at-50 percent maturity (uniform distribution)
	AC	0.1	0.9	autocorrelation in recruitment deviations $\mathrm{rec}(t)=AC\times\mathrm{rec}(t-1)+(1-AC)\times\mathrm{sigma}\,(t)$ (uniform distribution)
	D	0.05	0.6	current level of stock depletion (Bcurrent/Bunfished) (uniform distribution)
	L_{50_95}	30	50	length increment from 50 percent to 95 percent maturity
	Period	NA	NA	period for cyclical recruitment pattern in years (uniform distribution)
	Perr	0.15	0.25	process error, the CV of lognormal recruitment deviations (uniform distribution)
	Size_area_1	0.095	0.105	the size of Area 1 relative to Area 2 (uniform distribution)
	Frac_area_1	0.095	0.105	the fraction of the unfished biomass in Stock 1 (uniform distribution)
	Prob_staying	0.8	0.9	the probability of invividuals in Area 1 remaining in Area 1 over the course of one year
	Source	None		a reference to a website or article form which parameters were taken to define the operating model
Fleet	Name	myFleet		name of the Fleet object
	nyears	37		the number of years for the historical simulation
	Spat_targ	1	1	distribution of fishing in relation to spatial biomass: F is proportional to B^Spat_targ (uniform distribution)
	Fsd	0	0.4	inter-annual variability in fishing mortality rate
	L5	43	45	shortest length corresponding ot 5 percent vulnerability (uniform distribution)
	LFS	400	450	shortest length that is fully vulnerable to fishing (uniform distribution)
	EffYears	0	0.3	years at which to simulate varying relative effort
	EffLower	0.4	0.4	lower bound on relative effort corresponding to EffYears (uniform distribution)
	EffUpper	0.6	0.6	Upper bound on relative effort corresponding to EffYears (uniform distribution)
	Vmaxlen	0	1	the vulnerability of the longest (oldest) fish (uniform distribution)
	qinc	–2	2	average percentage change in fishing efficiency (uniform distribution)

to be continued

Continued from Table 4

Sub-model	Slot names	Value 1	Value 2	Comment
	qcv	0.1	0.3	inter-annual variability in fishing efficiency (uniform distribution)
	isRel	FALSE		Are the selectivity parameters relative to size-of-maturity? TRUE or FALSE
Observation	Name	myObservation		the name of the observation model object
	Cobs	0.75	1.33	log-normal catch observation error expressed as a coefficient of variation (uniform distribution)
	Cbiascv	0.4		a coefficient of variation controlling the sampling of bias in catch observations for each simulation (uniform distribution)
	CAA_nsamp	50	100	number of catch-at-age observation per time step (uniform distribution)
	CAA_ESS	10	20	effective sample size (independent age draws) of the multinomial catch-at-age observation error model (uniform distribution)
	CAL_nsamp	50	100	number of catch-at-length observation per time step (uniform distribution)
	CAL_ESS	10	20	effective sample size (independent length draws) of the multinomial catch-at-length observation error model (uniform distribution)
	CALcv	0.1	0.15	lognormal, variability in the length at age (uniform distribution)
	Iobs	0.2	0.6	observation error in the relative abundance indices expressed as a coefficient of variation (uniform distribution)
	beta	0.333	3	a parameter controlling hyperstability/hyperdepletion.
	Dcv	0.05	0.2	imprecision in the prescription of stock depletion among years, expressed as a coefficient of variation (uniform distribution)
	Btcv	0.2	0.5	persistent bias in the prescription of current stock biomass sampled from a uniform-log distribution with range (Btbias) (uniform distribution)
	Fcurcv	0.5	1	persistent bias in the prescription of current fishing mortality rate sampled from a log-normal distribution with coefficient of variation (Fcurcv) (uniform distribution)
	Reccv	0.1	0.3	bias in the knowledge of recent recruitment strength (uniform distribution)
	Btbias	0.2	5	persistent bias in the prescription of current stock biomass sampled from a uniform-log distribution with range (Btbias) (uniform distribution)

Note: OM is composed of three sub-models in DLMtool, including Stock, Fleet and Observation, in which the Stock model contains biological parameters of the population; Fleet model includes gear selectivity and fishing effort; and Observation model contains parameters of observation error and bias. Here are the specific parameter settings of our simulations.

declined biomass. EtargetLopt, minlenLopt1, curE, matlenlim, matlenlim2, DD, DCAC, Fratio, SPMSY, slotlim, CC4 and GB_slope had satisfactory performances on keeping biomass, but yield relatively low catch. CurE75 and MRnoreal showed better performance on balancing production and biomass. DDe, DDe75, DD4010, CC1 and SPmod failed to maintain either yield or population biomass (Fig. 2a).

We then evaluated the trade-off between long-term yield (LTY) and the risk of overfishing (Fig. 2b). CC4, SPMSY, GB_slope, DCAC and curE75 were the most effective MPs to avoid overfishing. In particular, the possibilities of not-overfishing using CC4 and SPMSY were 75.5% and 70.6% respectively. MinlenLopt1 provided the highest yield with LTY>80% MSY, followed by curE, MRnoreal. Regarding the trade-off between population biomass and the variation of yield, DCAC and SPMSY were able to reduce yield fluctuation effectively and maintain population biomass.

The MSE results suggested that curE75, DCAC, minlenLopt1 and SPMSY were more robust to the parameter uncertainty than others for the management of Spanish mackerel. Specifically, minlenLopt1 and DCAC performed best in terms of providing yield and reducing yield fluctuation, and curE75 and SPMSY had a balanced performance in the aspects of population status. It should be noted that the four methods covered both output control (DCAC and SPMSY) and input control (curE75 and minlenLopt1) methods. Their responses to the variation of M were further evaluated in the following section.

3.2 *Effect of M variation*

The dots size represent four different time periods from 1974

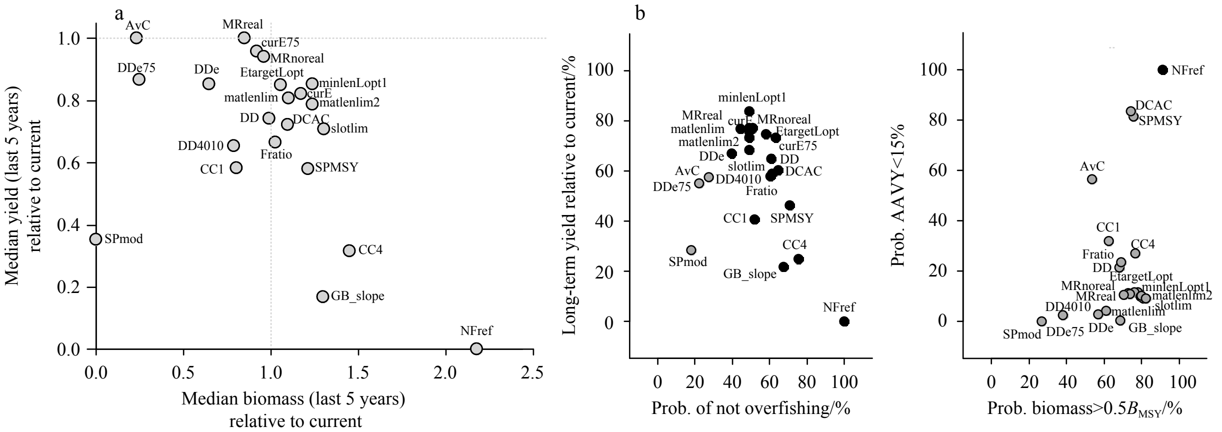

Fig. 2. Performance of 22 different management procedures for Spanish mackerel. a. The short-term trade-off for fisheries management, and b. the long-term trade-off for fisheries management.

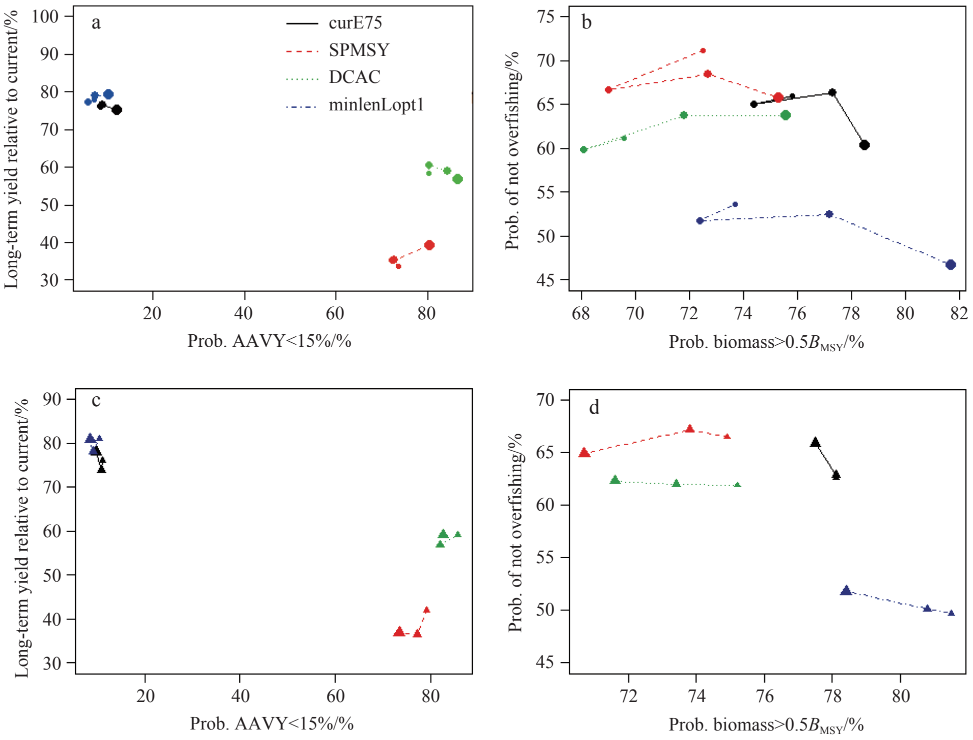

Fig. 3. The management performance of different MPs with respect to the variation of natural morality for Spanish mackerel. The dots size represent four different time periods from 1974 to 2017 in the upper panels; the size of triangles denote the relative M values estimated from different methods, ranging from 0.1 to 0.22. a and c. The long-term yield and the fluctuation of yield trade-off for fisheries management; b and d. the trends in the risk of overfishing and the relative population biomass trade-off for fisheries management.

to 2017 in the upper panels in Fig. 3, and regarding the different temporal periods (Table 3), the performance of each MP showed minor responses to the variation of M. MinlenLopt1 and curE75 could keep relatively stable yield, for which both long-term yield and the fluctuation of yield (AAVY<15%) showed limited response and the changes in the fluctuation of yield less than 5%. The long-term yield of DCAC and SPMSY also showed minor variations, whereas the fluctuation of yield changed substantially which was more than 5%, indicating unstable status of mackerel fishery (Fig. 3a). Regarding population status, the relative population biomass (measure as the probability of $B>0.5B_{\rm MSY}$) of mackerel increased significantly with the decrease of M from 1970s to 2017 using all MPs. The trends in the risk of overfishing of DCAC were different between other three MPs. DCAC showed a slight increase, while the other methods showed a downward trend (Fig. 3b).

The size of triangles denote the relative M values estimated from different methods, ranging from 0.1 to 0.22, and the variation of M from four estimation methods showed different effects on the performance of MPs with respect to the yield and population status. The changes of overfishing possibility and the relative population biomass showed minor responses to different estimation methods, with less than 5% value changes, whereas the long-term yield and the fluctuation of yield of Spanish mackerel fishery showed remarkable differences in all MPs, especially for SPMSY (Fig. 3c). In particular, the possibility of overfishing under the management of curE75 tended to increase with the decreasing M (Fig. 3d).

The management advices were derived from the MPs of Spanish mackerel fishery on the basis of our survey data. Among the most robust MPs, SPMSY suggested a total yield of 601.77 thousand tons; minlenLopt1 required the current fishing effort unchanged while the catchable size limited to 46.61 cm. Otherwise, the fishing effort could be reduced to 75% of current level to ensure stock biomass as suggested by curE75.

4 Discussion

The natural mortality rate of Spanish mackerel is determined by its ecological niches in marine ecosystems and its relationship with related species, thus that may fluctuate with the alteration of the marine ecosystem structure. In the data-limited situation, the estimation methods may impose additional uncertainty to M. We evaluated the performance of a variety of MPs and showed that the uncertainty and variation of M has substantial effects on both input control and output control MPs, although the influences varied among different aspects of the fishery. Specifically, M uncertainty had minor effects on the production of input control MPs but great influence on the production of output control MPs. The same uncertainty had large effects on population biomass and overfishing possibility for all MPs. From a mechanistic prospect, the uncertainty of M may influence MPs in two approaches, by affecting control rules directly or affecting operating model indirectly. For example, the changes of M will affects the recommended harvest relative to potential yield for DCAC $\left(\frac{W}{Y_{\rm pot}}=\frac{1}{M}\right)$ (MacCall, 2009), and the lower value of M leads to the overestimated biomass level. For minlenLopt1, M influences the optimal trap length, and the lower M lead to the underestimated risk of overfishing (Hordyk et al., 2015). We emphasize the importance of improving the precision of M estimation for stock assessment and fisheries management.

MSE revealed that none of the management procedures could provide satisfactory population biomass, yield, overfishing possibility and fluctuation of yield simultaneously. The choice of MP should thusly take into account practical management objectives and trade-off, such as maintaining production, long-term restoration and short-term production. The general conclusion is consistent with the results of Carruther et al. (2015). Additionally, some results of this study may be useful in the application of many MPs when M is in large uncertainty. For instance, when the range of M changed from 0.35 to 0.11 in this study, the changes in the risk of overfishing was the most obvious for some common methods such as curE75. This implied that risk of overfishing should be taken with priory with a large uncertainty of M. The population biomass may also be significantly affected by M for some MPs, e.g., the probability of B>$0.5B_{\mathrm{MSY}}$ increased by 8% as natural mortality declined using MinlenLopt1, suggesting a strong effect of population conservation. According to fisheries statistics, the production of Spanish mackerel fishery in China is in a relatively stable state in recent years, with the catch stabilizing at 450 000 t per year (Zheng et al., 2014). We therefore suggest that it is a superior challenge to sustain the population biomass and avoid overfishing rather than pursuing high yields for Spanish mackerel fishery, for which conservative MPs such as SPMSY are more desirable. However, it should be noticed that the result of MSE can be affected by not only M, but also other biological parameters such as length composition, growth rate, recruitment and depletion. In particular, the quality of data is pivotal for parameter estimation thus more critical for fisheries management, indicating that time-series survey observations is needed and the simulation should be revisited periodically according the gradually accumulated data (Uriarte et al., 2016). In addition, there are some limitation of DLMtools which need to be needs further research and development. For example, although the operating model can simulate the temporal trend in natural mortality rate, it only represents the overall trend of change and currently simulation assumes constant M with age. OM also using a Beverton-Holt stock recruitment model, in which all stocks are assumed to have density-dependent recruitment that does not decrease with increasing stock size, however, not all of the recruitment pattern in the fish community are this one. Besides, the observation model used in DLMtool is unrealistically well-behaved, and it simulates catch-composition data from the true simulated catch composition data via a multinomial distribution and some effective sample size, which will favor the simulation (Carruthers and Hordyk, 2016).

When the uncertainty of natural mortality comes mainly from data sources, curE75 can provide satisfactory yields while maintaining the stock biomass and reducing the risk of overfishing (Fig. 3). Therefore, our results promoted this MP for the management of Spanish mackerel fishery in data-limited situation. However, it is important to note that accurate data of historical fishing effort are needed in the application of curE75 to actual Spanish mackerel fishery (Carruthers and Hordyk, 2016). Due to the current challenge of the large number of fishing vessels, complicated practitioners of fisheries, decentralized production and the fisheries management system in China (Sun and Lu, 2016), the control of current fishing effort in management is surely difficult. On the contrary, if the uncertainty of natural mortality comes mainly from different methods, SPMSY can keep the biomass at a satisfactory level while reducing the fluctuation of production and the possibility of overfishing. This MP requires accurate estimation of the maximum age of the population, individual size at 50% sexual maturity, growth parameter K and catch data. It should also be noted that SPMSY is based on the maximum sustainable yield (MSY) to determine overfishing limits (OFL) (Martell and Froese, 2013), so the uncertainty of catch data has a great impact on this MP. At present, due to the large uncertainty of catch data in China, it is actually challenging to apply SPMSY to the Spanish mackerel fishery without more detailed data.

Generally, the estimation of natural mortality is challenging, and the estimation of M based on empirical equations could not ensure the accuracy of M estimation for Spanish mackerel; however, there is a wide acknowledge of the decrease in mackerel natural mortality (Sun, 2009; You, 2014; Liu et al., 1982). The decrease of M could be attributed to a variety of biological changes in China's seas. Specifically, the predator species of mackerel, such as dolphins, whales and catshark have been decreasing along with the high fishing intensity in China since 1980. The relief of predation mortality could be one of the major factors that reduce the total natural morality. Secondly, many other species of similar feeding habitat are enduring high fishing pressure in this area, such as small yellow croaker (Yan et al., 2014). It has been widely reported that the intensive fishing in China's coast caused the reduction of population size and simplification of the age structure in fish population, such as yellow snout sea bass (Lin et al., 2016). As Spanish mackerel is carnivorous since early life stage, such changes of size composition in marine ecosystems might suppress the competition between juvenile mackerel and other predatory species thus benefit their survival. However, as the M has not been accurately evaluated for this species, further studies would be needed to validate this assumption. In addition, the early development of Spanish mackerel was significantly affected by changes in water temperature and salinity (Song et al., 2016), thus the habitat quality will also affect the survival rate of Spanish mackerel. It is reported that when water temperature increases from 15 to 21°C, the development rate of embryonic mackerel will gradually accelerate (Jiang et al., 2016). This study explicitly simulated the changes of M value in different time periods; however, the future changes of M due to climate changes are less well understood. In addition, we assumed that M was fixed in each simulation but M is actually size-dependent and age-dependent in the life history (Johnson et al., 2015). These aspects are also needed to be taken into account in further study.

In summary, the changes of natural mortality rate of Spanish mackerel should be particularly concerned in the management of Spanish mackerel fisheries. Particularly, in order to improve the utilization of marine resources, China has adopted a series of “double control” actions to fishing vessel system in recent years (Zheng et al., 2014), and evaluating the uncertainty of different management strategies would be helpful for Chinese fisheries, especially in a data-limited situation. However, although some MPs showed satisfactory performances in our evaluation, the implementation of them would remain to be challenging in practice. Most output control methods provide an advice of TAC, however, it is difficult to assign the total TAC to the different marine regions as the mackerel is wide-distributed in China's seas and there is no traditional quota. Moreover, as this species has a wide range of migration and long life history (Shui et al., 2009), the country-wise cooperation for managing Spanish mackerel would be necessary, which, to the best of our knowledge, is far from routine. More research efforts of natural mortality are needed to build a solid foundation for the fisheries management in China, and the uncertainty of fishery statistics and other biological parameters should also be taken into account in stock assessment and management.

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