Operating model development for Peruvian fisheries

of the Pacific common eel, *Ophichthus remiger*

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Executive summary

The Pacific common eel, *Ophichthus remiger*, is an important fishery species in Peru, especially within the northern region. An MSC pre-assessment has also recently been conducted for the Northern fishery. This report describes a technical basis for population dynamics modeling of Pacific common eel. Population dynamics modeling is developed with the aim supporting subsequent evaluation of a sustainable harvest strategy, also known as a management procedure (MP). A synthesis of common eel biology and its fisheries is provided, followed by translation of this information into a mathematical model of population dynamics. This model is referred to as an operating model (OM) and forms the basis for evaluating the performance of alternative MPs using an approach known as management strategy evaluation (MSE). While this report emphasizes OM development, a preliminary set of MPs is examined to demonstrate the potential for MSE to support design and critical evaluation of an MP for the eel fishery. The evaluation of preliminary MPs also highlights the need for communication with stakeholders in defining fishery objectives, the need for pragmatism in addressing the realities of achieving those objectives, and ultimately, the potential for MSE to support identification of an MP that is palatable to stakeholders and decision-makers.

This report is also intended to serve as a resource to support on-going capacity building for design and evaluation of MPs for the Peruvian common eel fishery. Thus, in addition to the technical work that is presented, a proposal for a series of workshops is included. These workshops emphasize capacity building with respect to conducting MSE. These workshops are aimed at supporting biologists, fishery scientists, modelers, and decision-makers who are motivated to become more familiar with the methods reported herein and to carry out additional analyses. This proposed series of workshops will require a collaborative approach to prioritizing topics for discussion, conducting data analysis to strengthen modeling assumptions, and designing and testing MPs.

Additional resources

All materials presented in this report can be accessed through a GitHub repository:
https://github.com/natureanalytics-ca/eel_data_limited_OM

Additional useful resources related to the simulation modeling framework are also available

openMSE:
https://openmse.com/

SAMtool:
https://samtool.openmse.com/

DLMtool:
https://dlmtool.openmse.com/

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INTRODUCTION

Peruvian fisheries targeting common eel, *Ophichthus remiger*, began as an experimental program in 1990. Since 2000, this fishery has produced annual landings from 1,000 to 11,000 metric tons (SAI 2020). The eel population is estimated to be above its target biomass reference point, with sustainability attributed to fishery management measures implemented in 2011, including limited tolerance to harvesting below the 42 cm minimum size limit (SAI 2021). This fishery has been subject to stock assessment and to an MSC pre-assessment to assist with planning for a full evaluation and to identify obstacles to achieving certification (IMARPE 2020; SAI 2021).

This report develops a technical basis for population dynamics modeling of Pacific common eel. The need for population dynamics modeling aligns with interests in fishery science capacity building within organizations engaged in management of Peruvian fisheries as well as the need for analytical tools to support evaluations in accordance with MSC Fisheries Standard Principle 1, sustainable fish stocks. Thus, population dynamics modeling is developed with the aim supporting subsequent evaluation of sustainable harvest strategies. A model that is specified to simulate fish population dynamics and fishery operations is often referred to as an operating model (OM). The OM forms a key modeling component of management strategy evaluation (MSE). Management Strategy Evaluation (MSE), facilitates rigorous examination of the effect of uncertainties on the performance of a harvest strategy, also known as a management procedure (MP). MSE is used to simulate the interactions between the parts of an MP, which consists of data collection, data analysis, and a decision rule for fishery regulation. MSE is accordingly used to highlight how well these interacting parts can be expected to result in the achievement of fishery management objectives (Punt et al. 2016).

The goal of this report is to support TNC Peru and the TNC FishPath team in providing capacity building for Peruvian fisheries. A synthesis of common eel biology and its fisheries is provided, followed by translation of this information into an OM. Given emphasis on capacity building, OM development and a preliminary MSE are developed using the well-documented and open- source MSE framework known as openMSE (https://openmse.com/). While this report emphasizes OM development, a preliminary set of MPs is examined to demonstrate the potential for MSE to support design and critical evaluation of an MP for the eel fishery. This report is also intended to serve as a resource to support capacity building for design, refinement, and evaluation of MPs for the Peruvian common eel fishery. Thus, in addition to the technical work that is presented, a proposal for a series of workshops is included. These workshops are aimed at supporting biologists, fishery scientists, modelers, and decision-makers who are motivated to become more familiar with the methods reported herein and to carry out additional analyses. This proposed series of workshops will require a collaborative approach to prioritizing topics for discussion, refining presentation materials, conducting data analysis to strengthen modeling assumptions, and designing and testing MPs.

PART A. FISHERY BACKGROUND

A literature search was conducted for records pertaining to the eastern Pacific punctuated snake-eel (or common eel), *Ophichthus remiger*. Relevant information on geographical range, life history, reproductive characteristics, and fishery locations was summarized. The survey encompassed academic theses, governmental technical reports, peer-reviewed journal articles, and public news articles (Table A1).

Geography & stock structure

O. remiger's geographical range stretches the Pacfic coast of South America, from Nicaragua (12°N) to central Chile (Valdivia, 38°4'S) (Arancibia et al. 2000). Although distinct fishery stocks and genetic populations have not been distinguished for this demersal species, it is hypothesized that multiple populations of *O. remiger* may inhabit these coastal waters (Chicaiza 2016). Chicaiza (2016) reports the variability in total length and length at first maturity, stating the following:

> "From the analysis, it is clearly observed the differences in the population structure in terms of Lt and L50% for other latitudes compared to those reported in this study, it is highlighted that the range of sizes and the maturity size for the specimens captured in the Gulf of Guayaquil are higher than those reported by other authors in the region. In analytical prospecting, this is limited to several aspects: ***1)*** That there could be two or three different stocks corresponding to each country (Ecuador, Peru and Chile), Ecuador (Gulf of Guayaquil) being where the stock represented by larger specimens is found. , ***2)*** There is the same population between Peru and Ecuador, being the area of the Gulf of Guayaquil an important

spawning area where males and females of larger sizes (mature) migrate to spawn and ***3)*** There is a single population between Ecuador and Peru and, the fraction present in the Gulf of Guayaquil registers the largest sizes compared to the other countries, because it has not been subjected to strong fishing pressure. This is important to consider for fisheries management purposes both locally and regionally."

Chicaiza (2016). As the Master's thesis of Chicaiza (2016) is written in a nonnative language (Spanish) to the reviewer, the "translate document" tool available in Google Docs was utilized for the above quoted statement.

Further, *O. remiger* are known to segregate according to size classes and undertake diel bathymetric migrations (PROPEX- IMARPE 2003). Migrations also occur to higher latitudes during an El Niño event (Castillo 1991, PROPEX- IMARPE 2003), which collectively complicate delineation of stock structure.

Life history parameters

von Bertalanffy growth equation

The von Bertalanffy growth equation was utilized to estimate *O. remiger* growth parameters in studies conducted in Peru and Chile, using both FISAT II length-at-frequency (cm) and the relationship between otolith radius (mm) and total length (TL; cm) (Table A2). The growth parameters reported include: asymptotic length, L_∞, the body growth coefficient, K, and theoretical age of the fish at length 0 cm, t_0.

Length-weight relationship

Parameters of total length (TL; cm) to weight (g) conversion were established utilizing two similar methods. The first method is the length-weight relationship equation $W = a\ Lb$; where W is the total weight (g), a the intercept, L the total length (cm), and b the weight-length exponent (Vera 2004, Chicaiza 2013 & 2016, España 2015). Additionally, IMARPE (2012) utilized a second method: the von Bertalanffy growth curve for weight, $Wt = W\infty\ (1 - e\ {-K}\ (t{-}t0))^{b}$, which is a combination of the length-weight relationship and von Bertalanffy growth equation ($Lt = L\infty\ (1{-}e({-K}\ (t + t0))$). The parameters of this method include: Wt the weight at age, $W\infty$ the asymptotic weight, K the body growth coefficient, t the age of the fish, t_0 is the theoretical age of the fish at length 0 cm, and b the weight-length exponent. The weight-length exponent, b, has a standard value of 3.0 and is a key component for deciphering isometric or allometric growth of a fish species. When b is equal to 3.0, the body grows isometrically, i.e., weight and length are contant (Pauly 1983). However, a value of $b > 3.0$ indicates positive allometric growth (gaining weight faster than length) and $b < 3.0$ is indicative of negative allometric growth (gaining length faster than weight) (Weatherley and Gill, 1987). Negative allometric growth ($b = 2.886$) was only described in the Gulf of Guayaquil (España 2015), while Chicaiza (2013, 2016) reported positive allometric findings ($b = 3.339$) for the same region. Furthermore, all remaining study locations reported positive allometric growth ($b = 3.025 - 3.339$) for O. remiger (Table A3).

Sexual maturity

Average total lengths (TL; cm), TL catch range, average TL at 50% sexual maturity (L50%), and average TL at 95% sexual maturity (L95%) are listed for multiple study locations in Ecuador and Peru (Table A4). It is worth noting the trend between latitude and TL, with the largest punctuated snake-eel appearing in the northern most region (Gulf of Guayaquil; 1°00S) and the smallest TL recorded in the southernmost region (Lambayeque; 6°35S - 7°S) (IMARPE 2007).

Sexual dimorphism and sex ratio

Sexual dimorphism occurs as the mean TL between sexes, revealed higher average TL lengths for female *O. remiger* in all study regions. Moreover, sex ratio statistics range from 0.74 M :1 F (España 2015) to 1 M : 30 F (Vera 2004), supporting larger average TL for female punctuated snake-eel (Tables A5 & A6).

Fecundity and spawning

Fecundity data for *O. remgier* is deficient, however a single study (Vera (2004) measured fecundity in 29 female punctuated snake-eels utilizing the gravimetric method (Kjesbu & Holm 1994). Absolute fertility fluctuated between 31,337 - 190,977 oocytes and correlated with both length and weight of mature female punctuated snake-eels. The spawning season of *O. remiger* was determined by the utilization of the gonadosomatic index (G_{SI}) formula: GSI = Gonad weight / body weight ×100, an indicator for the state of gonadal development. *O. remiger* shows synchronism in maturity between males and females, as well as fractional or partial spawning events (Chicaiza 2013 & 2016, España 2015, PROPEX- IMARPE 2003, Vera 2004 & 2006) in the autumn season (Castillo *et al*. 2000, IMARPE 2012, Vera 2004 & 2006).

Natural mortality

Longevity and natural mortality estimates are reported by SAI (2021) (Table A7).

Fisheries

Peru

Fishing for *O. remiger* in Peru began in February 1990, through an experimental program, resulting from an agreement between the Paita Fisheries Training Center (Centro de Entrenamiento Pesquero de Paita, CEP-Paita) and the fishing company PESCA ANDINA (now SAKANA S.A.). Although eel fishing is permitted within Peru's entire maritime zone, the area the eel fleet fishes is Tumbes (from Zorritos to the south of Punta Sal) and Piura (north and south of Talara and from north of Paita to the south of Punta La Negra). Fishing effort is concentrated especially in the district of Sechura within Piura.

The fishery is regulated with a minimum size limit of 42 cm, a maximum tolerance of 20% of specimens in the catch being below the size limit, annual quotas, and a limit on the number of traps by vessel size. Fisheries management regulations specific to *O. remiger*, el Reglamento de Ordenamiento Pesquero de recurso anguila, were adopted in 2011. According to these regulations, only Peruvian flag vessels that qualify as smaller-scale vessels can participate. Vessels that participate in this fishery must be equipped with satellite tracking devices and are permanently monitored with respect to their geographic satellite position by the Ministry of Production and the maritime authority. Fishing logs and daily landings reports are also required.

The only gear used in the fishery is the eel trap, made of PVC pipes that are capped on either end. The caps have an opening of 5 mm, are white to attract attention, and are baited with anchovies, mackerel, and Peruvian puffer (Figs A1 & A2). Between 500 and 1000 traps, depending on the size of the boat, are left on the seafloor at depths from 50 m to 500 m for 3 hours before being collected. Each trap is connected to a weighted mother line which sits on the seafloor.

Fishing trips typically lasts 5-6 hours with ~3 lines of traps fished per trip, although this varies depending on how many eels are captured. Fishing trips are typically one day in summer and two days in winter, although this depends upon the time of year, especially the temperature. The main fishing times are night, sunrise, and sunset and only occasionally during the day. The target capture size is between 30 and 80 cm, taking into account the minimum size limit of 42 cm and tolerance regulations. The common eel increases in size and decreases in abundance with increasing depth. The size of eels is also smaller in the south. Therefore, fishers try to avoid fishing too deep or too far south to avoid non-desirable sizes.

The capacity of each boat varies considerably, but they generally have two tanks, 2-4 tons each. Vessels dedicated to fishing eel cannot have hold capacity greater than 32.6 m3 nor be longer than 17 meters. The fleet dedicated to the eel fishery is composed of approximately 20 vessels ranging in length from 5.18m to 16.72 m. The vessels are owned by three companies – Sakana Perú S.A.C., ILLARI S.A.C., Perú Pez S.A.C. The main export market is Asia, in particular South Korea, Japan, and Vietnam. Exports were valued at over $18 million USD in 2019. Average price of frozen eel fillets (USD/Kg) from 2014 to 2018 fluctuated between $5.56 and $8.98. In 2019 landings were over 4,300 tons. The Total Allowable Catch of common eel in Peru in 2019 was 5,400 tons. According to monthly data on landings from 1990-2019, the colder months of the year (April-July) produce slightly higher landings.

Ecuador

Artisanal fishing in Ecuador consists of ~16,000 registered vessels, with a predicted 4,000 additional non-registered vessels and 153 artisanal fishing ports. As of 2013, average catch was estimated at 30,000 - 70,000 tonnes, with 18% of the catch consisting of “other species" (*O. remiger* is included in the 18% of other species) (FAO 2013). Artisanal eel catches are recorded per the Instituto Nacional de Pesca “Program: Monitoring of Artisanal Fishing Landings of

Demersal Fish in the Main Ports of Ecuador" however specifications on genus or species are not reported (INP 2021).

In 2004, the fishery managing body, Undersecretariat of Fisheries Resources, authorized 10 industrial long lines vessels to use traps (nets) to seasonally harvest O. remiger (INP 2018). This authorization (Ministerial Agreement 202 (INP 2018) includes two closed periods every year, July 1-31 and October 1-31, however Chicaiza 2016 states there is lack of catch monitoring.

O. remiger is subject to bycatch by the artisanal and industrial hake fleets (Merluccius gayi), a similarly demersal species (INP 2018). Additionally, while Ecuador has an exclusive economic zone of 200 nautical miles offshore, there remains persistent fishing pressure from foreign commercial fishing vessels (Rust 2021) and increased exportation to Asian markets (Chicaiza 2005).

Chile

Artisanal fishing efforts in Chile consist of approximately 12,700 vessels and an estimated 254 industrial vessels as of 2013 (FAO 2014). Data related to eel species was unavailable at the time of this literature review.

Columbia

There is a data deficiency for fisheries information in Colombia, with the only available information being the total number of registered industrial fleet vessels in 2017 was 1,174. There is no information on artisanal fisheries fleet numbers, ports, or catch reports (FAO 2019). Consequently, no information on *O. remiger* was publicly available at the time of this literature review.

Tables and Figures

Table A1. Study locations providing *Ophichthus remiger* data.

Country Reporting	Study Location	Geographic Coordinates	Reference
Chile	Central Chile		Arancibia et al. 2000
Ecuador	Posorja, Esmeraldas, Puerto Lopez		Chicaiza 2005
Ecuador	Gulf of Guayaquil		Chicaiza 2013, 2016
Ecuador	Gulf of Guayaquil	1°00S, 80°41W	España 2015
Peru			Castillo *et al.* 2000
Peru	Lambayeque, Isla lobos de afuera		IMARPE 2007
Peru	Tumbes - Paita	3°27S – 5°S	IMARPE 2012
Peru			PROPEX- IMARPE 2003
Peru	Paita	5°S	Schuhbauer 2006
Peru	Lambayeque	6°35S - 7°S	Vera 2004
Peru	Tumbes Region	03°24S to 03°58S	Vera 2006

Table A2. Reported growth parameters for *Ophichthus remiger.* Length is total length in cm.

L_∞ (cm)	K	t_0 (years)	Method	Reference
B = 136.5 F = 136.5 M = 114	B = 0.129 F = 0.132 M = 0.159	B = 0.105 F = 0.105 M = 0.105	Otoliths	IMARPE 2012
B = 76.65 F = 76.65 M = 51.45	B = 0.1 F = 0.25 M = 0.27	B = -8.25 F = -1.23 M = -1.46	FISAT II	Vera 2004
B = 97.95	B = 0.11167	B = -2.555	Otoliths	Schuhbauer 2006
B = 90.8	B = 0.115	B = -1.108	FISAT II	Arancibia *et al.* 2000

F = Female; M = Male; B = Both sexes; L_∞ = asymptotic length; K = body growth coefficient; t^0 = theoretical age of the fish at length 0 cm; cm = centimeters

Table A3. Parameters of the length-weight relationship of *Ophichthus remiger*. Length is total length in cm, weight is total weight in g.

W_∞ (g)	K	t_0 (years)	*a*	*b*	Reference
			B = 0.003 F = 0.004 M = 0.003	B = 3.339 F = 3.281 M = 3.328	Chicaiza 2013, 2016
				B = 2.8886 F = 3.2118 M = 2.5992	España 2015
			B = 0.0007 F = 0.0007 M = 0.0008	B = 3.0802 F = 3.0828 M = 3.0764	IMARPE 2007
B = 3456.2 F = 3562.4 M = 2004.28	B = 0.129 F = 0.132 M = 0.159	B = 0.105 F = 0.105 M = 0.105		B = 3.025 F = 3.000 M = 3.064	IMARPE 2012
				B = 3.1979 F = 3.167 M = 2.854	Vera 2004

F = Female; M = Male; B = Both sexes; W_∞ = asymptotic weigh; K = body growth coefficient, t_0 = theoretical age of the fish at length 0 cm; *a* = intercept; *b* = weight-length exponent

Table A4. *Ophichthus remiger* mean length in the catch (cm), average total length (cm), average total length at 50% maturity (L50%) and average total length at 95% sexual maturity (L95%).

Range (cm, TL)	Mean length in catch (cm, TL)	L50%	L95%	Reference
F = 55.0 - 60.9 M = 51.0 - 56.8				Castillo *et al.* 2000
F = 41 - 119 M = 41-95	F = 71 M = 62	F = 75 M = 62		Chicaiza 2005
F = 36 - 106 M = 36 - 88	F = 64.6 M = 60.4	F = 63.7* M = 65.3*		Chicaiza 2013
F = 23 - 138 M = 27 - 117	F = 61.8 M = 58.1			Chicaiza 2016
B = 25 - 103.5 F = 31 - 103.5 M = 25 - 93.8	B = 63.7 F = 65.78 M = 61.08	F = 75.3 M = 72.12		España 2015
B = 22-61 F = 23 - 61 M = 22 - 54	B = 36.47 F = 36.7 M = 35.8	F = 39 M = 40	F = 62 M = 56	IMARPE 2007
B = 27 - 73 F = 28 - 73 M = 27 - 49	B = 39.9 F = 46 M = 37	F = 48 M = 44	F = 73 M = 49	Vera 2004
F = 31 - 128 M = 27 - 103	F = 76.6 M = 43.2	F = 57.3	F = 67	Vera 2006

F = Female; M = Male; B = Both sexes; TL = total length in centimeters; cm = centimeters.
*reported L50% appear to be inconsistent or erroneously calculated, based on parameters of the logistic function used in estimating these quantities.

Table 5. Sex ratio values of *Ophichthus remiger*.

Overall Sex Ratio	Minimum Sex Ratio	Maximum Sex Ratio	Reference
	1 M : 1 F	1 M : 5.9 F	Castillo *et al*. 2000
1 M : 2 F			Chicaiza 2005
1 M : 1.8 F			Chicaiza 2013, 2016
0.74 M : 1 F			España 2015
	1 M : 1:41 F	1 M : 1.89 F	IMARPE 2007
1 M : 1.02 F			PROPEX- IMARPE 2003
	1 M : 1 F	1 M : 30 F	Vera 2004

F = Female, M = Male

Table A6. Seasonal sex ratio values of *Ophichthus remiger*.

Spring	Summer	Autumn	Winter	Reference
1 M : 1 F	1 M : 1.08 F	1 M : 1.08 F	1 M : 1.10 F	PROPEX- IMARPE 2003
1 M : 3.75 F	1 M : 3.75 F	1 M : 3.75 F	1 M : 1.15 F	Vera 2004

F = Female, M = Male

Table A7. Estimated natural mortality values for the common eel. Table reproduced from SAI Global (2021).

Authors	Locality	Method	L∞ (cm)	K (year-1)	t0 (years)	ϕ (phi)	M	Lmax	Age Max
Goicochea *et al.* (2014)	Tumbes-Paita Peru	Otolitos ♀♂	136.5	0.129	0.105	3.38		124	14
		Otolitos♀	136.5	0.12	0.105	3.35			
		Otolitos ♂	114	0.159	0.105	3.32			
IMARPE (2008)	Tumbes-Paita Peru	Otolitos ♀♂	110	0.14	0.375	3.23	0.20		14
Schuhbauer (2006)	Paita Peru	otoliths♀♂	97.95	0.12	2.555	3.06	0.211		7
Vera (2004)	Lambayaque Peru	FISAT II ♀♂	76.5	0.10		2.77			
		FISATII♀	76.5	0.25		3.17		73	7
		FISAT II♂	51.45	0.27		2.85		51	3
Cubillos *et al.* (1999)	Chile	Powell Wetherall♀♂	90.8	0.115	1.108	2.98	0.3	92	

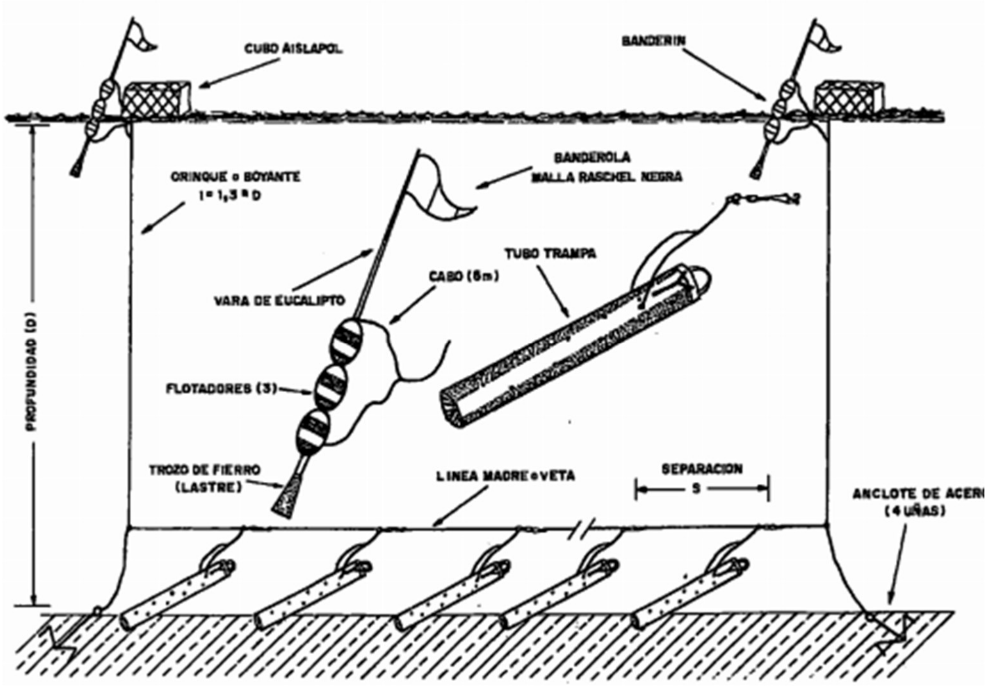

Figure A1. Design of the fishing line with a set of traps to catch eel (Arancibia et al. 2000).

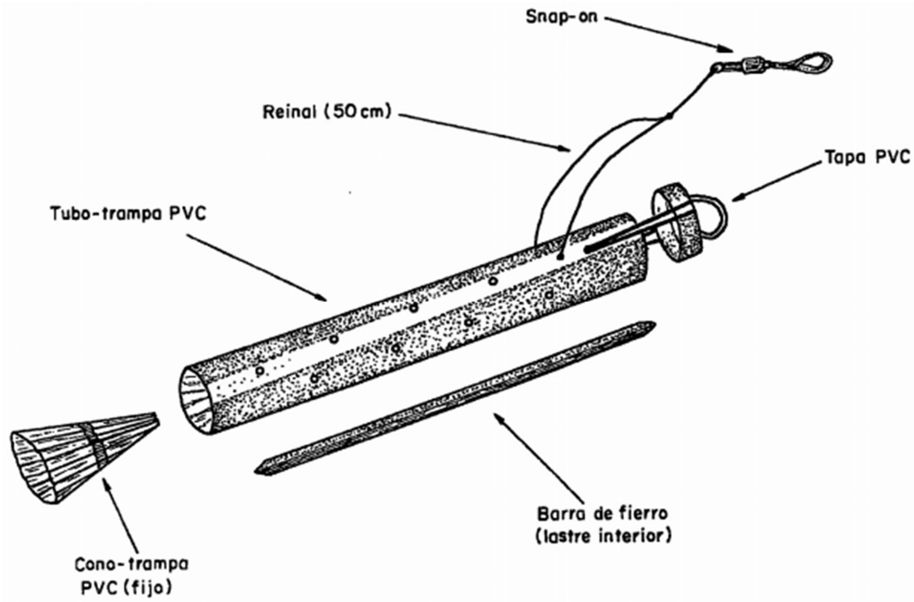

Figure A2. Tube-trap components for capture of eels (Arancibia et al. 2000).

PART B. SIMULATION MODELING

Operating model

This report and accompanying R code provide a preliminary demonstration of operating model (OM) building using the openMSE framework. The OM is developed with emphasis on fisheries operating near Tumbes, Peru. Development of the OM emphasized three elements: life history parameters, the historical trend in fishing effort, and the current state of resource depletion. Following this introductory paragraph, specific details of OM parameters are provided.

Uncertainty in life history parameters (see Part A of this report) was reflected in development of the OM. Where several life history studies were available, but not in agreement on parameter estimates, the ranges of these parameter estimates were used to reflect parameter uncertainty. The length of 50% maturity, for example, was specified from 39 to 63.7 cm. For many of the life history parameters, openMSE utilizes a Monte Carlo approach, with life history parameters drawn from statistical sampling distributions in each simulation. This approach results in each simulation being a slightly different characterization of life history, and thus, performance evaluation of management procedures integrates life history uncertainty.

An historical trend in fishing effort was derived from reported annual number of traps (millions) in the eel fishery. This information is reported in SAI (2021) and was digitized for use in OM development. openMSE utilizes this effort trend (which is normalized to a maximum value of 1) to create a time series of fishing mortality (i.e., since fishing mortality is assumed proportional to fishing effort). The magnitude of fishing mortality is scaled by openMSE using an algorithm that results a specified depletion level (depletion is spawning stock biomass relative to unfished spawning stock biomass) in the terminal year of the historical period (Fig. B1 & B2).

For the eel OM, the historical period is 1990 through 2019, as per available trap effort time series (SAI 2021). In the OM, the fishery is assumed to be in an unfished state prior to the start of fishing in 1990.

Uncertainty in the current state of resource depletion is incorporated in a similar manner to specifying life history uncertainty. Current depletion was taken from production model results from the stock assessment (IMARPE 2020). The terminal year of the stock assessment was 2019. openMSE requires current depletion to be specified as relative spawning biomass; however, production models report relative vulnerable biomass. Thus, a brief tuning exercise was conducted such that the specified range of relative spawning biomass (depletion) resulted in an operating model where 95% of historical simulations had relative vulnerable biomass between 0.7 and 0.86, as per the reported 95% credible interval from the stock assessment (Figs. B3 & B4). Like specification of life history uncertainty, a Monte Carlo approach is used to sampling current depletion for each simulation, thus resulting in integration of this uncertainty in the evaluation of management procedures.

Species information

Species: *Ophichthus remiger*

Common Name: Common eel

Management Agency: Instituto del Mar del Peru (IMARPE)

Region: Tumbes, Peru

Sponsor: The Nature Conservancy

Operating model parameters

OM Name: Name of the operating model: Data-limited training

nsim: The number of simulations: 48

proyears: The number of projected years: 100

interval: The assessment interval - how often would you like to update the management system? 5

maxF: Maximum instantaneous fishing mortality rate that may be simulated for any given age class: 0.8

reps: Number of samples of the management recommendation for each method. Note that when this is set to 1, the mean value of the data inputs is used. 1

Source: A reference to a website or article from which parameters were taken to define the operating model

Stock parameters

Mortality and age: maxage, R0, M, Msd

maxage: The maximum age of individuals that is simulated. There are maxage+1 (recruitment to age-0) age classes in the storage matrices. maxage is the plus group where all age-classes > maxage are grouped, unless option switched off with OM@cpars$plusgroup=0 . Single value. Positive integer.

Specified Value(s): 16

Maximum age was set a little higher than the maximum observed age of 14 years.

R0: Initial number of unfished recruits to age-0. This number is used to scale the size of the population to match catch or data, but does not affect any of the population dynamics unless the OM has been conditioned with data. As a result, for a data-limited fishery any number can be used for R0 . In data-rich stocks R0 may be estimated as part of a stock assessment, but for data limited stocks users can choose either an arbitrary number (say, 1000) or choose a number that produces simulated catches in recent historical years that are similar to real world catch data. Single value. Positive real number.

Specified Value(s): 1000

Scaling parameter set at arbitrary value.

M: The instantaneous rate of natural mortality. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Uniform distribution lower and upper bounds. Non-negative real numbers.

Specified Value(s): 0.2, 0.31

Natural mortality was specified for the range reported in the MSC pre-assessment SAI (2021).

Msd: Inter-annual variation in M expressed as a coefficient of variation of a log-normal distribution. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. If this parameter is positive, yearly M is drawn from a log-normal distribution with a mean specified by log(M) drawn for that simulation and a standard deviation in log space specified by the value of Msd drawn for that simulation. Uniform distribution lower and upper bounds. Non-negative real numbers

Specified Value(s): 0.05, 0.1

To address the possibility of M changing among years in these simulations we set a modest, arbitrary level of inter-annual variability with a lognormal CV of between 5% and 10% (i.e. 0.05 - 0.1), corresponding with 95% probability interval of +/-10% to +/- 20%.

Recruitment: h, SRrel, Perr, AC

h: Steepness of the stock recruit relationship. Steepness governs the proportion of unfished recruits produced when the stock is at 20% of the unfished population size. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the same in all years of a given simulation. Uniform distribution lower and upper bounds. Values from 1/5 to 1.
Specified Value(s): 0.3, 0.9
Highly uncertain parameter. Given current emphasis on surplus production modeling, a wide range for steepness was specified over which the performance of SP models could be evaluated.

SRrel: Type of stock-recruit relationship. Use 1 to select a Beverton Holt relationship, 2 to select a Ricker relationship. Single value. Integer
Specified Value(s): 1
Beverton-Holt form assumed.

Perr: Recruitment process error, which is defined as the standard deviation of the recruitment deviations in log space. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Uniform distribution lower and upper bounds. Non-negative real numbers.

Specified Value(s): 0.6, 0.9

No estimates for recruitment variability were available at time of OM specification. Bounds for this parameter were set to reflect highly variable recruitment.

AC: Autocorrelation in the recruitment deviations in log space. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided, and used to add lag-1 auto-correlation to the log recruitment deviations. Uniform distribution lower and upper bounds. Non-negative real numbers.

Specified Value(s): 0.1, 0.6

A wide range of values was used for auto-correlation in recruitment to reflect the uncertainty in this parameter.

Growth: Linf, K, t0, LenCV, Ksd, Linfsd

Linf: The von Bertalanffy growth parameter Linf, which specifies the average maximum size that would reached by adult fish if they lived indefinitely. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the same in all years unless Linfsd is a positive number. Uniform distribution lower and upper bounds. Positive real numbers.

Specified Value(s): 98, 137

Used range reported by SAI (2021), based on studies that collected otoliths for age estimation.

K: The von Bertalanffy growth parameter k, which specifies the average rate of growth. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the same in all years unless Ksd is a positive number. Uniform distribution lower and upper bounds. Positive real numbers.

Specified Value(s): 0.12, 0.14

Used range reported by SAI (2021), based on studies that collected otoliths for age estimation.

t0: The von Bertalanffy growth parameter t0, which specifies the theoretical age at a size 0. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Uniform distribution lower and upper bounds. Non-positive real numbers.

Specified Value(s): 0.1, 2.55

Used range reported by SAI (2021), based on studies that collected otoliths for age estimation.

LenCV: The coefficient of variation (defined as the standard deviation divided by mean) of the length-at-age. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided to specify the distribution of observed length-at-age, and the CV of this distribution is constant for all age classes (i.e, standard deviation increases proportionally with the mean). Uniform distribution lower and upper bounds. Positive real numbers.

Specified Value(s): 0.1, 0.15

Unknown. Default values used.

Ksd: Inter-annual variation in K. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. If this parameter has a positive value, yearly K is drawn from a log-normal distribution with a mean specified by the value of K drawn for that simulation and a standard deviation (in log space) specified by the value of Ksd drawn for that simulation. Uniform distribution lower and upper bounds. Non-negative real numbers.

Specified Value(s): 0, 0.05

Inter-annual variability unknown. Assumed up to 5%

Linfsd: Inter-annual variation in Linf. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. If this parameter has a positive value, yearly Linf is drawn from a log-normal distribution with a mean specified by the value of Linf drawn for that simulation and a standard deviation (in log space) specified by the value of Linfsd drawn for that simulation. Uniform distribution lower and upper bounds. Non-negative real numbers.

Specified Value(s): 0, 0.05

Inter-annual variability unknown. Assumed up to 5%

Maturity: L50, L50_95

L50: Length at 50% maturity. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. The L50 and L50_95 parameters are converted to ages using the growth parameters provided and used to construct a logistic curve to determine the proportion of the population that is mature in each age class. Uniform distribution lower and upper bounds. Positive real numbers.

Specified Value(s): 39, 63.7

Used range of values reported for geographies in proximity to Tumbes

L50_95: Difference in lengths between 50% and 95% maturity. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. The value drawn is then added to the length at 50% maturity to determine the length at 95% maturity. This parameterization is used instead of specifying the size at 95 percent maturity to avoid situations where the value drawn for the size at 95% maturity is smaller than that at 50% maturity. The L50 and L50_95 parameters are converted to ages using the growth parameters provided and used to construct a logistic curve to determine the proportion of the population that is mature in each age class. Uniform distribution lower and upper bounds. Positive real numbers.

Specified Value(s): 9.7, 34.3

Used range of values reported for geographies in proximity to Tumbes.

Stock depletion and Discard Mortality: D, Fdisc

D: Estimated current level of stock depletion, which is defined as the current spawning stock biomass divided by the unfished spawning stock biomass. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This parameter is used during model initialization to select a series of yearly historical recruitment values and fishing mortality rates that, based on the information provided, could have resulted in the specified depletion level in the simulated last historical year. Uniform distribution lower and upper bounds. Positive real numbers (typically < 1)

Specified Value(s): 0.6, 0.7

Since the minimum size limit is within proximity to size at maturity, the 95% credible interval of relative vulnerable biomass from the stock assessment was used as a proxy for depletion range.

Fdisc: The instantaneous discard mortality rate the stock experiences when fished using the gear type specified in the corresponding fleet object and discarded. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Uniform distribution lower and upper bounds. Non-negative real numbers.

Specified Value(s): 0, 0

The base-case model assumed no discarding and no discard mortality.

Length-weight conversion parameters: a, b

a: The alpha parameter in allometric length-weight relationship. Single value. Weight parameters are used to determine catch-at-age and population-at-age from the number of individuals in each age class and the length of each individual, which is drawn from a normal distribution determined by the Linf , K , t0 , and LenCV parameters. As a result, they function as a way to scale between numbers at age and biomass, and are not stochastic parameters. Single value. Positive real number.

Specified Value(s): 0.003

Chicaiza (2013, 2016)

b: The beta parameter in allometric length-weight relationship. Single value. Weight parameters are used to determine catch-at-age and population-at-age from the number of individuals in each age class and the length of each individual, which is drawn from a normal distribution determine by the Linf , K , t0 , and LenCV parameters. As a result, they function as a way to scale between numbers at age and biomass, and are not stochastic parameters. Single value. Positive real number.

Specified Value(s): 3.34

Chicaiza (2013, 2016)

Spatial distribution and movement: Size_area_1, Frac_area_1, Prob_staying

Size_area_1: The size of area 1 relative to area 2. The fraction of the unfished biomass in area 1. Please specify numbers between 0 and 1. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. For example, if Size_area_1 is 0.2, then 20% of the total area is allocated to area 1. Fishing can occur in both areas, or can be turned off in one area to simulate the effects of a no take marine reserve. Uniform distribution lower and upper bounds. Positive real numbers.

Specified Value(s): 0.5, 0.5

A mixed stock is assumed.

Frac_area_1: The fraction of the unfished biomass in area 1. Please specify numbers between 0 and 1. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. For example, if Frac_area_1 is 0.5, then 50% of the unfished biomass is allocated to area 1, regardless of the size of area 1 (i.e, size and fraction in each area determine the density of fish, which may impact fishing spatial targeting). In each time step recruits are allocated to each area based on the proportion specified in Frac_area_1. Uniform distribution lower and upper bounds. Positive real numbers.

Specified Value(s): 0.5, 0.5

A mixed stock is assumed.

Prob_staying: The probability of individuals in area 1 remaining in area 1 over the course of one year. Please specify numbers between 0 and 1. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. For example, in an area with a Prob_staying value of 0.95 each fish has a 95% probability of staying in that area in each time step, and a 5% probability of moving to the other area. Uniform distribution lower and upper bounds. Positive fraction.

Specified Value(s): 0.5, 0.5

A mixed stock is assumed

Fleet parameters

Historical years of fishing, spatial targeting: nyears, Spat_targ

nyears: The number of years for the historical simulation. Single value. For example, if the simulated population is assumed to be unfished in 1975 and this is the year you want to start your historical simulations, and the most recent year for which there is data available is 2019, then nyears equals 45.

Specified Value(s): 30

Fishery began in 1990 with an experimental fishery and time series of catches is available through 2019. Thus, nyears = 30.

Spat_targ: Distribution of fishing in relation to vulnerable biomass (VB) across areas. The distribution of fishing effort is proportional to VB^Spat_targ. Upper and lower bounds of a uniform distribution. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This parameter allows the user to model either avoidance or spatial targeting behavior by the fleet. If the parameter value is 1, fishing effort is allocated across areas in proportion to the population density of that area. Values below 1 simulate an avoidance behavior and values above 1 simulate a targeting behavior.

Specified Value(s): 1, 1

Borrowed from: Generic_Increasing effort

Trend in historical fishing effort (exploitation rate), interannual variability in fishing effort: EffYears, EffLower, EffUpper, Esd

EffYears: Vector indicating the historical years where there is information available to infer the relative fishing effort expended.This vector is specified in terms of the position of the year in the vector rather than the calendar year. For example, say our simulation starts with an unfished stock in 1975,and the current year (the last year for which there is data available) is 2019. Then there are 45 historical years simulated, and EffYears should include numbers between 1 and 45. Note that there may not be information available for every historical year, especially for data poor fisheries. In these situations, the EffYears vector should include only the positions of the years for which there is information, and the vector may be shorter than the total number of simulated historical years (nyears).

Annual traps (millions) digitized from SAI (2021) and used as relative effort trend.

EffLower: Lower bound on relative fishing effort corresponding to EffYears. EffLower must be a vector that is the same length as EffYears describing how fishing effort has changed over time. Information on relative fishing effort can be entered in any units provided they are consistent across the entire vector because the data provided will be scaled to 1 (divided by the maximum number provided).

Point estimate of relative effort specified without range (i.e., EffLower = EffUpper).

EffUpper: Upper bound on relative fishing effort corresponding to EffYears. EffUpper must be a vector that is the same length as EffYears describing how fishing effort has changed over time. Information on relative fishing effort can be entered in any units provided they are consistent across the entire vector because the data provided will be scaled to 1 (divided by the maximum number provided).

Point estimate of relative effort specified without range (i.e., EffLower = EffUpper).

Esd: Additional inter-annual variability in fishing mortality rate. For each historical simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. If this parameter has a positive (non-zero) value, the yearly fishing mortality rate is drawn from a log-normal distribution with a standard deviation (in log space) specified by the value of Esd drawn for that simulation. This parameter applies only to historical projections.

Specified Value(s): 0.1, 0.4

Borrowed from: Generic_Increasing effort

Annual increase in catchability, interannual variability in catchability: qinc, qcv qinc: Mean temporal trend in catchability (also though of as the efficiency of fishing gear) parameter, expressed as a percentage change in catchability (q) per year. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Positive numbers indicate an increase and negative numbers indicate a decrease. q then changes by this amount for in each year of the simulation This parameter applies only to forward projections.

Specified Value(s): -2, 2

Borrowed from: Generic_Increasing effort

qcv: Inter-annual variability in catchability expressed as a coefficient of variation. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This parameter applies only to forward projections.

Specified Value(s): 0.1, 0.3

Borrowed from: Generic_Increasing effort

Fishery gear length selectivity: L5, LFS, Vmaxlen, isRel

L5: Shortest length at which 5% of the population is vulnerable to selection by the gear used in this fleet. Values can either be specified as lengths (in the same units used for the maturity and growth parameters in the stock object) or as a percentage of the size of maturity (see the parameter isRel for more information). For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the same in all years unless cpars is used to provide time-varying selection.

Specified Value(s): 28.3, 41

Length frequency distributions of the catch were digitized from SAI (2021). Left-hand tail of each annual distribution was used to quantify a range for L5.

LFS: Shortest length at which 100% of the population is vulnerable to selection by the gear used by this fleet. Values can either be specified as lengths (in the same units used for the maturity and growth parameters in the stock object) or as a percentage of the size of maturity (see the parameter isRel for more information). For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the same in all years unless cpars is used to provide time-varying selection.

Specified Value(s): 42, 42

Minimum size limit of 42 cm was specified for LFS.

Vmaxlen: Proportion of fish selected by the gear at the asymptotic length ('Stock@Linf'). Upper and Lower bounds between 0 and 1. A value of 1 indicates that 100% of fish are selected at the asymptotic length, and the selection curve is logistic. If Vmaxlen is less than 1 the selection curve is dome shaped. For example, if Vmaxlen is 0.4, then only 40% of fish are vulnerable to the fishing gear at the asymptotic length.

Specified Value(s): 1, 1

Logistic selectivity was assumed, thus Vmaxlen was fixed at 1.

isRel: Specify whether selection and retention parameters use absolute lengths or relative to the size of maturity. Single logical value (TRUE or FALSE).

Specified Value(s): FALSE

Set to FALSE. Used absolute lengths for selectivity parameters so that selectivity did not vary with uncertainty in length-at-maturity.

Fishery length retention: LR5, LFR, Rmaxlen, DR

LR5: Shortest length at which 5% of the population is vulnerable to retention by the fleet. Values can either be specified as lengths (in the same units used for the maturity and growth parameters in the stock object) or as a percentage of the size of maturity (see the parameter isRel for more information). For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the same in all years unless cpars is used to provide time-varying selection.

Specified Value(s): 0, 0

Borrowed from: Generic_Increasing effort

LFR: Shortest length where 100% of the population is vulnerable to retention by the fleet. Values can either be specified as lengths (in the same units used for the maturity and growth parameters in the stock object) or as a percentage of the size of maturity (see the parameter isRel for more information). For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the same in all years unless cpars is used to provide time-varying selection.

Specified Value(s): 0, 0

Borrowed from: Generic_Increasing effort

Rmaxlen: Proportion of fish retained at the asymptotic length (‘Stock@Linf’). Upper and Lower bounds between 0 and 1. A value of 1 indicates that 100% of fish are retained at the asymptotic length, and the selection curve is logistic. If Rmaxlen is less than 1 the retention curve is dome shaped. For example, if Rmaxlen is 0.4, then only 40% of fish at the asymptotic length are retained.

Specified Value(s): 1, 1

Borrowed from: Generic_Increasing effort

DR: Discard rate, defined as the proportion of fully selected fish that are discarded by the fleet. Upper and Lower bounds between 0 and 1, with a value of 1 indicates that 100% of selected fish are discarded. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided.

Specified Value(s): 0, 0

Borrowed from: Generic_Increasing effort

Current Year: CurrentYr

CurrentYr: The last historical year simulated before projections begin. Single value. Note that this should match the last historical year specified in the Data object, which is usually the last historical year for which data is available.

Specified Value(s): 2019

Available time series 1990 - 2019.

Existing Spatial Closures: MPA

MPA: Logical argument (TRUE or FALSE). Creates an MPA in Area 1 for all years if true is selected. Defaults to FALSE.

Specified Value(s): FALSE

None.

Observation model parameters

Catch statistics: Cobs, Cbiascv, CAA_nsamp, CAA_ESS, CAL_nsamp, CAL_ESS

Cobs: Observation error around the total catch. Observation error in the total catch is expressed as a coefficient of variation (CV). Cobs requires upper and lower bounds of a uniform distribution, and for each simulation a CV is sampled from this distribution. Each CV is used to specify a log-normal error distribution with a mean of 1 and a standard deviation equal to the sampled CV. The yearly observation error values for the catch data are then drawn from this distribution. For each time step the simulation model records the true catch, but the observed catch is generated by applying this yearly error term (plus any bias, if specified) to the true catch.

Specified Value(s): 0.1, 0.2

Borrowed from: Precise-Unbiased

Cbiascv: Log-normally distributed coefficient of variation controlling the sampling bias in observed catch for each simulation. Bias occurs when catches are systematically skewed away from the true catch level (for example, due to underreporting of catch or undetected illegal catches). Cbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

CAA_nsamp: Number of catch-at-age observations collected per time step. For each time step a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Positive integers.

Specified Value(s): 150, 300

Borrowed from: Precise-Unbiased

CAA_ESS: Effective sample size of catch-at-age observations collected per time step. For each time step a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. CAA_ESS should not exceed CAA_nsamp. Positive integers.

Specified Value(s): 50, 100

Borrowed from: Precise-Unbiased

CAL_nsamp: Number of catch-at-length observations collected per time step. For each time step a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Positive integers.

Specified Value(s): 150, 300

Borrowed from: Precise-Unbiased

CAL_ESS: Effective sample size. For each time step a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. CAL_ESS should not exceed CAL_nsamp. Positive integers.

Specified Value(s): 50, 100

Borrowed from: Precise-Unbiased

Index imprecision, bias and hyperstability: Iobs, Btobs, Btbiascv, beta

Iobs: Observation error in the relative abundance index expressed as a coefficient of variation (CV). Iobs requires upper and lower bounds of a uniform distribution, and for each simulation a CV is sampled from this distribution. Each CV is used to specify a log-normal error distribution with a mean of 1 and a standard deviation equal to the sampled CV. The yearly observation error values for the index of abundance data are then drawn from this distribution. For each time step the simulation model records the true change in abundance, but the observed index is generated by applying this yearly error term (plus any bias, if specified) to the true relative change in abundance. Positive real numbers.

Specified Value(s): 0.1, 0.25

Borrowed from: Precise-Unbiased

Btobs: Observation error in the absolute abundance expressed as a coefficient of variation (CV). Btobs requires upper and lower bounds of a uniform distribution, and for each simulation a CV is sampled from this distribution. Each CV is used to specify a log-normal error distribution with a mean of 1 and a standard deviation equal to the sampled CV. The yearly observation error values for the absolute abundance data are then drawn from this distribution. For each time step the simulation model records the true abundance, but the observed abundance is generated by applying this yearly error term (plus any bias, if specified) to the true abundance. Positive real numbers.

Specified Value(s): 0.05, 0.2

Borrowed from: Precise-Unbiased

Btbiascv: Log-normally distributed coefficient (CV) controlling error in observations of the current stock biomass. Bias occurs when the observed index of abundance is is systematically higher or lower than the true relative abundance. Btbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05, NA

Borrowed from: Precise-Unbiased

beta: A parameter controlling hyperstability/hyperdepletion in the measurement of abundance. For each simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. Values below 1 lead to hyperstability (the observed index decreases more slowly than the true abundance) and values above 1 lead to hyperdepletion (the observed index decreases more rapidly than true abundance). Positive real numbers.

Specified Value(s): 0.67, 1.5

Borrowed from: Precise-Unbiased

Bias in maturity, natural mortality rate and growth parameters: LenMbiascv, Mbiascv, Kbiascv,t0biascv, Linfbiascv

LenMbiascv: Log-normal coefficient of variation for sampling bias in observed length at 50 percent maturity. LenMbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

Mbiascv: Log-normal coefficient of variation for sampling bias in observed natural mortality rate. Uniform distribution lower and upper bounds. Mbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

Kbiascv: Log-normal coefficient of variation for sampling bias in observed growth parameter K. Kbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

t0biascv: Log-normal coefficient of variation for sampling bias in observed t0. t0biascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

Linfbiascv: Log-normal coefficient of variation for sampling bias in observed maximum length. Linfbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

Bias in length at first capture, length at full selection: LFCbiascv, LFSbiascv

LFCbiascv: Log-normal coefficient of variation for sampling bias in observed length at first capture. LFCbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

LFSbiascv: Log-normal coefficient of variation for sampling bias in length-at-full selection. LFSbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.
Specified Value(s): 0.05
Borrowed from: Precise-Unbiased

Bias in fishery reference points, unfished biomass, FMSY, FMSY/M ratio, biomass at MSY relative to unfished: FMSY_Mbiascv, BMSY_B0biascv

FMSY_Mbiascv: Log-normal coefficient of variation for sampling bias in estimates of the ratio of the fishing mortality rate that gives the maximum sustainable yield relative to the assumed instantaneous natural mortality rate. FMSY/M. FMSY_Mbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.
Specified Value(s): 0.25
Borrowed from: Precise-Unbiased

BMSY_B0biascv: Log-normal coefficient of variation for sampling bias in estimates of the BMSY relative to unfished biomass (BMSY/B0). BMSY_B0biascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.1

Borrowed from: Precise-Unbiased

Management targets in terms of the index (i.e., model free), the total annual catches and absolute biomass levels: Irefbiascv, Crefbiascv, Brefbiascv

Irefbiascv: Log-normal coefficient of variation for sampling bias in the observed relative index of abundance (Iref). Irefbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.1

Borrowed from: Precise-Unbiased

Crefbiascv: Log-normal coefficient of variation for sampling bias in the observed reference catch (Cref). Crefbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.1

Borrowed from: Precise-Unbiased

Brefbiascv: Log-normal coefficient of variation for sampling bias in the observed reference biomass (Bref). Brefbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.1

Borrowed from: Precise-Unbiased

Depletion bias and imprecision: Dbiascv, Dobs

Dbiascv: Log-normal coefficient of variation for sampling bias in the observed depletion level. Dbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.2

Borrowed from: Precise-Unbiased

Dobs: Log-normal coefficient of variation controlling error in observations of stock depletion among years. Observation error in the depletion expressed as a coefficient of variation (CV). Dobs requires the upper and lower bounds of a uniform distribution, and for each simulation a CV is sampled from this distribution. Each CV is used to specify a log-normal error distribution with a mean of 1 and a standard deviation equal to the sampled CV. The yearly observation error values for the depletion data are then drawn from this distribution. For each time step the simulation model records the true depletion, but the observed depletion is generated by applying this yearly error term (plus any bias, if specified) to the true depletion.

Specified Value(s): 0.03, 0.1

Borrowed from: Precise-Unbiased

Recruitment compensation and trend: hbiascv, Recbiascv, sigmaRbiascv

hbiascv: Log-normal coefficient of variation for sampling persistent bias in steepness. hbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.1

Borrowed from: Precise-Unbiased

Recbiascv: Log-normal coefficient of variation for sampling persistent bias in recent recruitment strength. Recbiascv requires the upper and lower bounds of a uniform distribution, and for each simulation a CV is sampled from this distribution. Each CV is used to specify a log-normal error distribution with a mean of 1 and a standard deviation equal to the sampled CV. The yearly bias values for the depletion data are then drawn from this distribution. Positive real numbers.

Specified Value(s): 0.05, 0.1

Borrowed from: Precise-Unbiased

sigmaRbiascv: Log-normal coefficient of variation for sampling persistent bias in recruitment variability. sigmaRbiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years. Positive real numbers.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

Effort: Eobs, Ebiascv

Eobs: Observation error around the total effort. Observation error in the total effort is expressed as a coefficient of variation (CV). Eobs requires upper and lower bounds of a uniform distribution, and for each simulation a CV is sampled from this distribution. Each CV is used to specify a log-normal error distribution with a mean of 1 and a standard deviation equal to the sampled CV. The yearly observation error values for the effort data are then drawn from this distribution. For each time step the simulation model records the true effort, but the observed effort is generated by applying this yearly error term (plus any bias, if specified) to the true effort.

Specified Value(s): 0.1, 0.2

Borrowed from: Precise-Unbiased

Ebiascv: Log-normally distributed coefficient of variation controlling the sampling bias in observed effort for each simulation. Bias occurs when effort is systematically skewed away from the true effort level. Ebiascv is a single value specifying the standard deviation of a log-normal distribution with a mean of 1 and a standard deviation equal to the sampled CV. For each simulation a bias value is drawn from this distribution, and that bias is applied across all years.

Specified Value(s): 0.05

Borrowed from: Precise-Unbiased

Implementation parameters

Output Control Implementation Error: TACFrac, TACSD

TACFrac: Mean fraction of recommended TAC that is actually taken. For each historical simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the mean TAC fraction obtained across all years of that simulation, and a yearly TAC frac is drawn from a log-normal distribution with the simulation mean and a coefficient of variation specified by the value of TACSD drawn for that simulation. If the value drawn is greater than 1 the amount of catch taken is greater than that recommended by the TAC, and if it is less than 1 the amount of catch taken is less than that recommended by the TAC. Positive real numbers.

Specified Value(s): 1, 1

Borrowed from: Perfect_Imp

TACSD: Log-normal coefficient of variation in the fraction of recommended TAC that is actually taken. For each historical simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is used, along with the TACFrac drawn for that simulation, to create a log-normal distribution that yearly values specifying the actual amount of catch taken are drawn from. Positive real numbers.

Specified Value(s): 0, 0

Borrowed from: Perfect_Imp

Effort Control Implementation Error: TAEFrac, TAESD

TAEFrac: Mean fraction of recommended TAE that is actually taken. For each historical simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the mean TAE fraction obtained across all years of that simulation, and a yearly TAE frac is drawn from a log-normal distribution with the simulation mean and a coefficient of variation specified by the value of TAESD drawn for that simulation. If the value drawn is greater than 1 the amount of effort employed is greater than that recommended by the TAE, and if it is less than 1 the amount of effort employed is less than that recommended by the TAE. Positive real numbers.

Specified Value(s): 1, 1

Borrowed from: Perfect_Imp

TAESD: Log-normal coefficient of variation in the fraction of recommended TAE that is actually taken. For each historical simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is used, along with the TAEFrac drawn for that simulation, to create a log-normal distribution that yearly values speciying the actual amount of efort employed are drawn from. Positive real numbers.

Specified Value(s): 0, 0

Borrowed from: Perfect_Imp

Size Limit Control Implementation Error: SizeLimFrac, SizeLimSD

SizeLimFrac: Mean fraction of recommended size limit that is actually retained. For each historical simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is the mean size limit fraction obtained across all years of that simulation, and a yearly size limit fraction is drawn from a log-normal distribution with the simulation mean and a coefficient of variation specified by the value of SizeLimSD drawn for that simulation. If the value drawn is greater than 1 the size of fish retained is greater than that recommended by the size limit, and if it is less than 1 the amount of size of fish retained is less than that recommended by the size limit. Positive real numbers.

Specified Value(s): 1, 1

Borrowed from: Perfect_Imp

SizeLimSD: Log-normal coefficient of variation in the fraction of recommended size limit that is actually retained. For each historical simulation a single value is drawn from a uniform distribution specified by the upper and lower bounds provided. This value is used, along with the SizeLimFrac drawn for that simulation, to create a log-normal distribution that yearly values speciying the actual fraction of the size limit retained are drawn from. Positive real numbers.

Specified Value(s): 0, 0

Borrowed from: Perfect_Imp

Preliminary management procedures

Management procedures

A management procedure (MP) is a pre-agreed decision process for adjusting harvest controls as a function of resource status (Punt et al. 2016). An MP consists of three parts: data collection, a method of analysis yielding quantities used in decision-making (e.g., via data-limited assessment or from direct empirical observation), and a decision rule or harvest control rule (HCR; Sainsbury et al., 2020; Butterworth, 2007). The HCR guides the adjustment to a management measure. In all MPs considered in this report the management measure is total allowable catch (TAC). MPs are sometimes referred to as harvest strategies or management strategies. The design of an MP determines the degree of responsiveness to prevailing estimates of resource status. Responsiveness is governed by three factors. The first factor is the precision with which indicators used in decision-making can detect changes in resource status. The second factor is the magnitude of adjustment to a TAC in response to a detected change. And the third factor is the interval between assessments. The first two factors are specific to each MP that is presented in this report, with the latter factor set to 5 years for all MPs.

MPs seeking optimal catches

A set of three MPs was specified that invoke concepts of maximum sustainable yield (MSY), or related quantities of fishing mortality rate that results in MSY (*Fmsy*) or biomass associated with *Fmsy* fishing (*Bmsy*). This set of MPs was motivated by the use of Bayesian surplus production modeling used in assessment of the common eel fishery (IMARPE 2020). As a preliminary exploration, this set of MPs explores the use surplus production-based MPs, as well as alternatives that utilize length composition data instead of catch and relative abundance indices. In the corresponding openMSE R code and in the results section, these MPs are labeled: SP_SS1, SP_SS2, and Lratio_BHI.

SP_SS1:

This MP relies on a state-space surplus production model for stock assessment (Table B1). Details about this stock assessment model are described in the Stock Assessment Methods toolkit (SAMtool). The surplus production model uses time-series of catches and relative abundance to estimate a time series of vulnerable biomass as well as unfished vulnerable biomass. The model uses the Fletcher formulation and is parameterized with *Fmsy* and MSY as leading parameters. This MP is specified so that unfished conditions occur in the first year of the time series and that biomass at MSY occurs at half of carrying capacity (i.e., a symmetric production function). An informative prior for intrinsic rate of increase, *r*, is generated according to the Euler-Lotka method of McAllister et al. (2001) (Fig. B5). This prior is generated based on input distributions of natural mortality and steepness of the Beverton-Holt stock-recruit relationship. The corresponding decision rule calculates the TAC as the product of current vulnerable biomass and *Umsy* (the fraction of biomass removed, calculated as a function of *Fmsy*).

SP_SS2:

This MP follows the same specification of SP_SS1, except for the specification of the prior for intrinsic rate of increase, *r*. For SP_SS2, intrinsic rate of increase is specified using a normal distribution with mean 0.9 and standard deviation of 0.1 (Fig. B5). Given the preliminary nature of this evaluation, this prior was chosen for consistency with the posterior distribution for *r* reported from the Bayesian stock assessment applied to the eel fishery (IMARPE 2020).

Lratio_BHI:

This MP adjusts the previous year's catch in relation to a ratio that reflects the proximity of the fish population to *Bmsy* (Jardim et al. 2015). Details about this MP are described in the Data

Limited Methods toolkit (DLMtool). The data used in this MP are current mean length in the catch and the previous year's total catch. This data-limited MP relies on a reference point, *Lref*, which is the mean length in the catch expected when the fish population is at *Bmsy*. In the absence of direct information on *Bmsy*, *Lref* is used a proxy for the resource state producing MSY. *Lref* is calculated using the following simplifying assumptions about the dynamics of the fish population, namely that $M/K = 1.5$ and $Fmsy/M = 1$, and that length at full vulnerability to fishing is known. The TAC is calculated as the product of the previous year's catch and the ratio current mean length to *Lref*.

MPs maintaining stable biomass

Two MPs were specified under the objective of maintaining stable catch rates relative to historical conditions. Given the preliminary nature of this report, these alternatives were explored under the assumption that decision-makers could be interested in MPs that are aimed at maintaining stable catch rates at roughly current levels of resource biomass. This approach is an alternative to the MPs described above that emphasize MSY-oriented management objectives. These stable catch MPs were considered on the basis that the eel population is not in a depleted state, as per the Bayesian surplus production stock assessment (i.e., relative vulnerable biomass credible interval: 0.7 to 0.86; IMARPE 2020). Further, these stable biomass MPs could be considered simpler alternatives to those based on stock assessment.

Islope1:

This MP adjusts the TAC to maintain to constant CPUE (Geromont & Butterworth 2014; Carruthers et al. 2015). Details about this MP are described in the Data Limited Methods toolkit

(DLMtool). This MP uses a recent trend in CPUE as an indicator of current stock condition. The slope of the recent CPUE is calculated for the 5 most recent years. Positive slope leads to a recommended TAC increase, whereas negative slope leads to a recommended TAC decrease.

LstepCC3:

This MP adjusts the TAC to maintain to constant mean length in the catch (Geromont & Butterworth 2014; Carruthers et al. 2015). Details about this MP are described in the Data Limited Methods toolkit (DLMtool). The data used in this MP are a time series of mean length in the catch. The ratio of recent mean length to historical mean length is calculated as an indicator of stock status. The value of this ratio determines the magnitude of change in the TAC, with maximum changed capped at 5% between assessment intervals.

Reference MP

The reference MP FMSYref is used to provide a frame of reference for MP performance. FMSYref assumes perfect information about FMSY (i.e., FMSY is obtained from the operating model). This MP is implemented by setting the fishing mortality to the 'true' values of *Fmsy*.

Performance metrics

MP performance is evaluated in terms of whether management objectives are likely to be achieved. In practical terms, we asked whether MPs were likely to achieve their intended purposes or whether there would be a considerable chance of management failure. For the MPs seeking optimal catches, their performance was evaluated in relation to *Fmsy*, *Bmsy*, and MSY.

For the MPs aimed at maintaining stable catch rates, their performance was evaluated relative to mean biomass and mean catches in the five most recent historical years just prior to MP application. Each performance metric is calculated over x projection years. Three time periods were considered for evaluating performance: short-term performance (first 10 years of projections), long-term performance (last 10 years of projections), and across all projection years.

Performance metrics included in openMSE

PNOF: Probability of not overfishing. The probability that fishing mortality rate is less than the fishing mortality rate that results in MSY (i.e., $F < Fmsy$).

P50: The probability that spawning biomass is above ½ of the spawning biomass that results in MSY (i.e., SB > 0.5SBmsy).

LTY: Long-term yield. The probability that yield is greater than ½ of MSY in the last 10 years of the projection period.

STY: Short-term yield. The probability that yield is greater than ½ of MSY in the first 10 years of the projection period.

AAVY: Variability in yield. The probability that inter-annual variability in yield is less than 20%

Custom performance metrics

CREL: Relative catch. The probability that the ratio of historical catch to current catch is greater than 0.8. Historical catch is the average catch in the final five historical years, just prior application of MP. This performance metric examines whether at least 80% of historical catch is preserved by the MP.

BREL: Relative biomass. The probability that the ratio of historical spawning biomass to current spawning biomass is greater than 0.8. Historical spawning biomass is the average of the final five historical years, just prior application of MP. This performance metric examines whether at least 80% of historical biomass is preserved by the MP.

Results

For the MSY-seeking MPs, SP_SS1 and SP_SS2 both produce reasonable outcomes in terms of maintaining spawning biomass above ½ of *Bmsy* and producing reasonably high catches (Table B2; Fig. B6). These two MPs differ only in terms of how the prior for intrinsic rate of increase is specified; however, this detail leads to important performance differences. First, SP_SS2 produces a cyclical pattern in fishing mortality, resulting in cyclical catches. This result likely occurs because the value of *Fmsy* implied by the *r* prior (i.e., *Fmsy* = *r/2*) is much higher for SP_SS2 than SP_SS1 (Fig. B5). Consequently, SP_SS2 sometimes produces catches that result in low spawning biomass.

Lratio_BHI is an MSY-seeking MP that produces very different performance relative to SP_SS1 and SP_SS2 (Table B2; Fig. B6). Lratio_BHI maintains much higher spawning biomass, but at the expense of catches. This result is produced by the simplifying assumptions about eel life history that are used in calculating *Lref*. Thus, while this MP may be well suited for protecting eel biomass in very data-limited circumstances because if requires very few life history inputs and utilizes an indicator of mean length in the catch, this simplicity comes at a cost to catches.

Comparison of two MPs aimed at maintaining stable biomass resulted in, on average, reasonably stable spawning biomass trends that were achieved through reductions in catches (Table B2; Fig. B7). Noting that the simulated dynamics of the eel population are not in a stable equilibrium state at the end of the historical period, the negative trend in catches is a result of the MP acting to stabilize biomass. An important difference in the performance of Islope1 and LstepCC3 is the variation in long-term performance outcomes. Islope1 produces substantially more variable biomass trajectories than LstepCC3, which is concerning. The observed precision of the indicators can play an important role in this outcome, although coefficient of variation in relative abundance and multinomial variance of length observation were both low as per the 'Precise_unbiased' observation model used in analysis of Islope1 and LstepCC3, respectively. The more likely culprit of variable biomass trajectories in Islope1 is that its aim is to maintain stable biomass and does so by attempting to maintain a relatively 'flat' trend in CPUE. This aim is achieved through a '5 year moving window' of the slope of CPUE observations, which can consequently become disconnected from the historical CPUE. Conversely, LstepCC3 is aimed at maintaining stable biomass by comparing current conditions (in mean length in the catch) to an historical reference point. An additional consideration is that LstepCC3 is constrained to +/-5% change in TAC between assessment intervals; whereas, Islope3 is not constrained in the same manner, perhaps contributing to its instability. Thus, there are a variety of fine details in MP specification that can have important consequences. These details are worth considering in the development of suitable MPs.

Considerations for refining the MSE

Developing an OM and conducting a demonstration of MSE was instructive with respect to amalgamation of available information but was also instructive for identifying information gaps. The OM incorporates uncertainty in life history information, current level of stock depletion, and coarsely represents plausible trends in historical population dynamics by incorporating effort information (i.e., traps per year). However, a more thorough evaluation of data sets, including length frequency distribution and CPUE, could provide an opportunity to generate an OM where the plausibility of historical trends is supported by fitting to data. Within openMSE, this process is referred to as conditioning and is described as a 'rapid conditioning model' within openMSE documentation. Additionally, simulation of observation of data streams, such as catch and CPUE that are used by the MPs, requires attention. In this report, observation was specified as 'precise unbiased' using built-in functionality of openMSE. However, the actual level of precision in observing quantities such as catch, CPUE, and length composition has important consequences for how well MPs perform in achieving management objectives. It is strongly recommended that realistic levels of precision are quantified and incorporated into the simulated observation process to gain a more complete understanding of expected MP performance.

As demonstrated, not all MPs will achieve the same balance between performance metrics, and thus, trade-offs between achievement of management objectives must be considered. Achievement of management objectives is made more complicated when using data-limited MPs, as these MPs often differ in their aims. In the preliminary MSE, MPs were explored that were either MSY-seeking or stable biomass-seeking. The reader is encouraged to review these trade-offs (Figs. B8 & B9). In these trade-off plots, larger values of performance metrics plotted on X and Y axes suggest better performance, thus the best performing MPs will have higher values for each of the performance metrics. A more thorough evaluation of MPs must first address the need for clearly defined ecological, social, and economic management objectives at local and national scales in Peru, as well as in reference to Fisheries Standards principle 1, where MSC certification is sought.

An MP is a pre-agreed procedure for adjusting management measures that requires all parties to agree to its elements so that *ad hoc* decision-making can be avoided (Butterworth 2007). To create a pre-agreed procedure will require a variety for finer details to be confronted. These details include translating management objective into operationalized performance metrics that are measurable and meaningful to the eel fishery. The most suitable information streams to be utilized in an MP will also require scrutiny. This decision will need to account for data reliability as well as capacity for data collection into the foreseeable future. Further, the choice of information streams and their use within a decision rule is likely to require a balance between their grounding in ecological theory as well as their grounding in straightforward observation of physical and biological variables (Rice and Rochet 2005). In the preliminary MSE, this issue is highlighted by comparing MPs that rely on different types of data inputs (i.e., catch and CPUE vs. mean length in the catch; Table B2).

Related to information streams, are considerations related to simplifying assumptions that are used in translating data inputs into measures to stock status. In data-limited MPs, this typically means reliance on simplified population dynamics models or assumptions about fish life history are employed in determining stock status and consequently in application of a decision rule. For example, Lratio_BHI uses a simple population dynamics model to produce the reference point, *Lref*, which has an important effect on determining stock status and whether TACs should be increased or decreased. Such assumptions are not trivial and the suitability of these assumptions for the eel fishery requires in-depth analysis. Simplifying assumptions also often introduce their own unique trade-offs. In the case of Lratio_BHI, this MP required very few data inputs and produced reasonable expectations about conservation of spawning biomass, which could be viewed as benefits to this approach. However, Lratio_BHI produced yields that were rather conservative in relation to optimal yield-based MP alternatives.

Together, the processes of developing an OM and discovering the right MP for the eel fishery will require pragmatism. In data-limited fisheries, the need for pragmatism emerges in managing expectations and in reconciling data limitations against defining and subsequent achievement of objectives (Cadrin and Pastoors 2008; Dowling et al. 2015). Trade-offs between achievement of various management objectives abound and will require critical thinking early and often during the MP design process (Bentley and Stokes 2009).

Tables and Figures

Table B1. Summary of management procedures (MPs).

MP	Inputs	Outputs used in decision-rule	More information
SP_SS1	• Catch time series • CPUE time series • Prior for M and steepness • Growth and maturity	• Terminal vulnerable biomass • *Fmsy*	https://samtool.openmse.com https://openmse.com/features-assessment-models/3-sp/
SP_SS2	• Catch & CPUE time series • *r* prior	• Terminal vulnerable biomass • *Fmsy*	https://samtool.openmse.com https://openmse.com/features-assessment-models/3-sp/
Lratio_BHI	• Current mean length in the catch • Length at full selection	• *Lref*, the expected mean length at MSY • Ratio mean length to *Lref*	Jardim et al. 2011 https://dlmtool.openmse.com/reference/Lratio_BHI.html
Islope1	• CPUE time series	• Slope 5 recent years CPUE	Geromont & Butterworth (2014); Carruthers et al. (2015) https://dlmtool.openmse.com/reference/Islope1.html
LstepCC3	• Time series of mean length in the catch	• Ratio of recent mean length to historical mean length	Geromont & Butterworth (2014); Carruthers et al. (2015) https://dlmtool.openmse.com/reference/LstepCC1.html
FMSYref	• None	• Perfect information about *Fmsy* borrowed from the OM	

Table B2. Mean performance of management procedures.

Metric	SP_SS1	SP_SS2	Lratio_BHI	Islope1	LstepCC3	FMSYref
PNOF all years	0.79	0.60	0.82	0.76	0.82	0.51
PNOF long-term	0.86	0.68	0.75	0.68	0.78	0.53
PNOF short-term	0.59	0.45	0.84	0.86	0.91	0.54
P50 all years	0.86	0.66	0.86	0.83	0.86	0.86
P50 long-term	0.91	0.74	0.79	0.72	0.81	0.85
P50 short-term	0.86	0.75	0.99	1.00	1.00	1.00
LTY	0.76	0.60	0.18	0.35	0.29	0.90
STY	0.68	0.76	0.57	0.57	0.56	0.95
AAVY all years	0.96	0.79	0.88	0.83	0.83	0.02
AAVY long-term	1.00	0.88	0.81	0.73	0.81	0.08
AAVY short-term	0.71	0.50	1.00	1.00	1.00	0.08
CREL all years	0.67	0.61	0.35	0.60	0.37	0.75
CREL long-term	0.65	0.65	0.20	0.54	0.33	0.67
CREL short-term	0.82	0.80	0.65	0.71	0.48	0.90
BREL all years	0.43	0.29	0.70	0.61	0.67	0.19
BREL long-term	0.45	0.40	0.66	0.52	0.56	0.16
BREL short-term	0.53	0.42	0.75	0.75	0.78	0.45

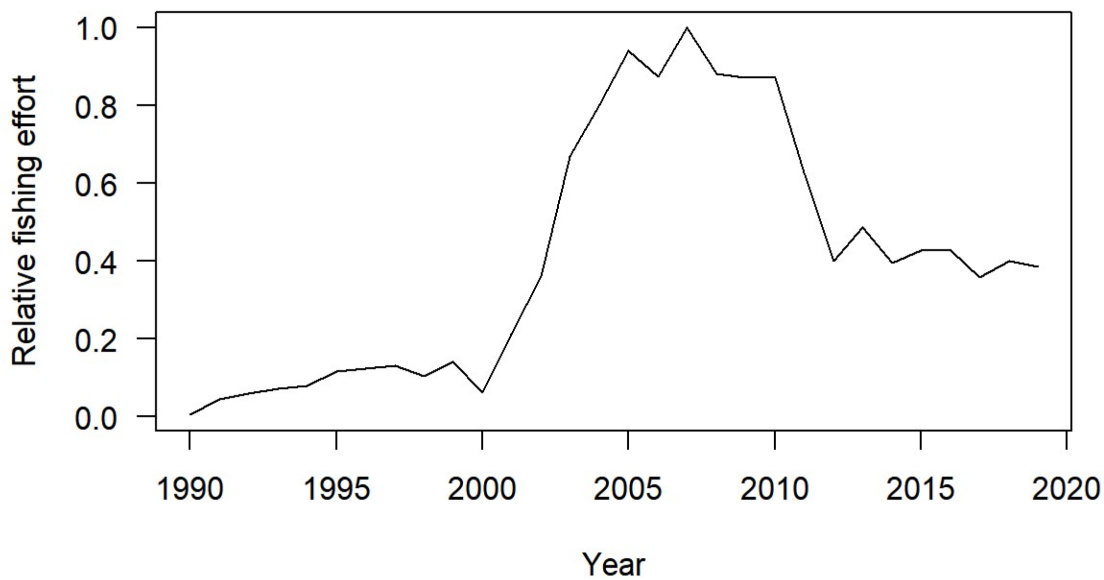

Figure B1. Relative fishing effort used in tuning of the operating model. Estimates were obtained from annual traps (millions; SAI (2021)), which were normalized to maximum effort of 1.0.

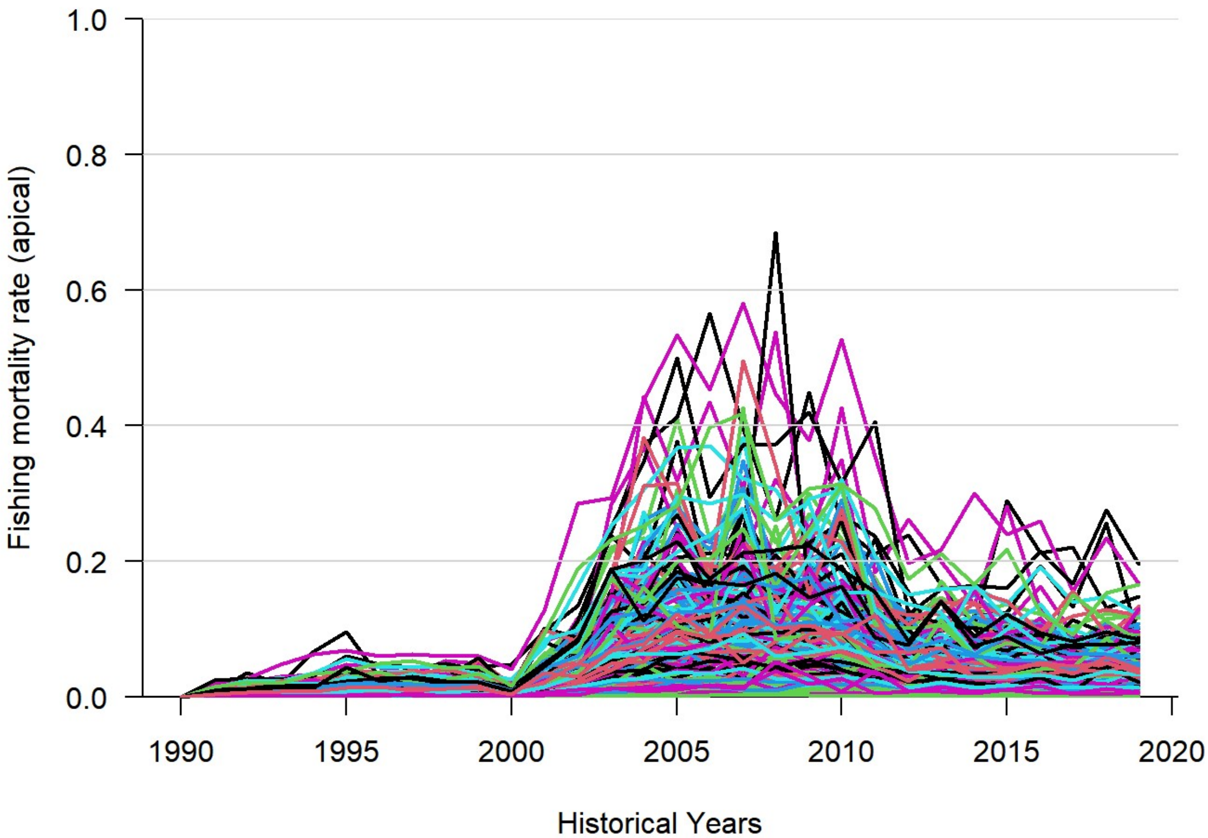

Figure B2. Simulated historical trend in fishing mortality rate.

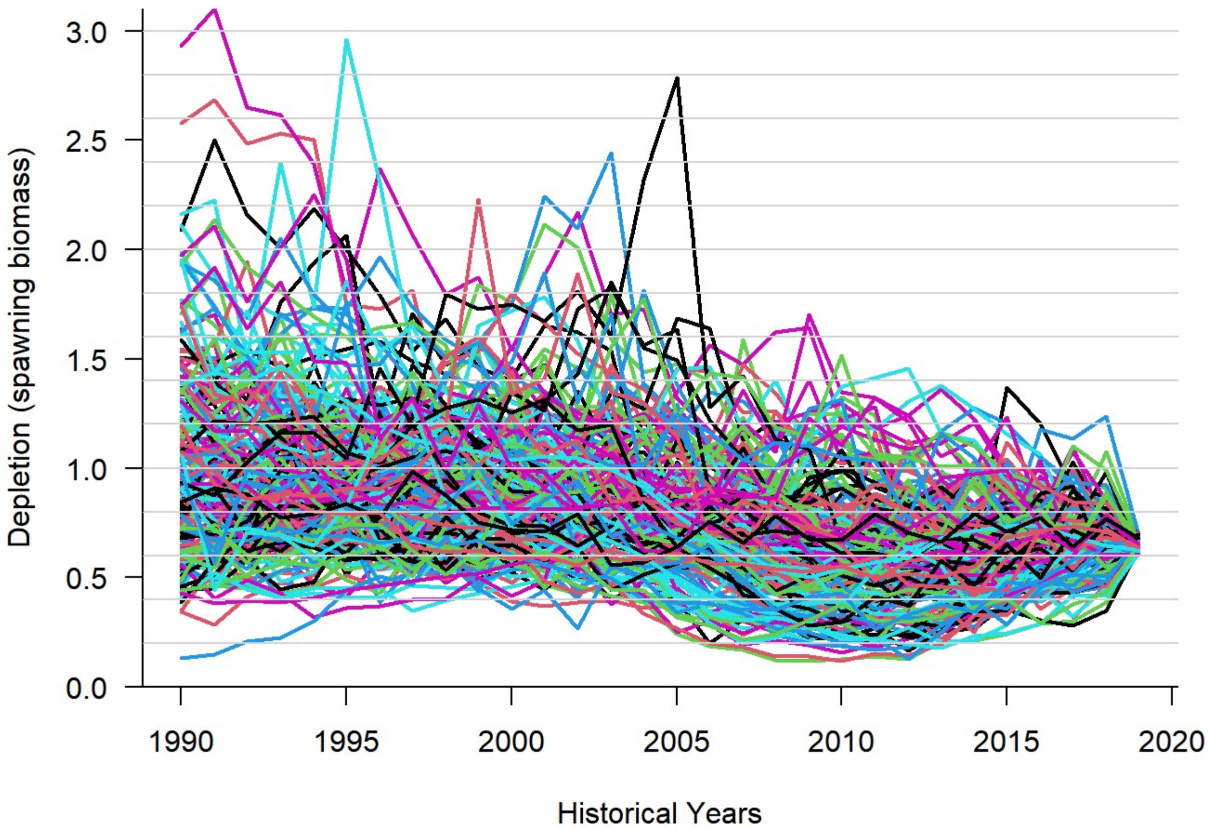

Figure B3. Simulated historical depletion of spawning biomass.

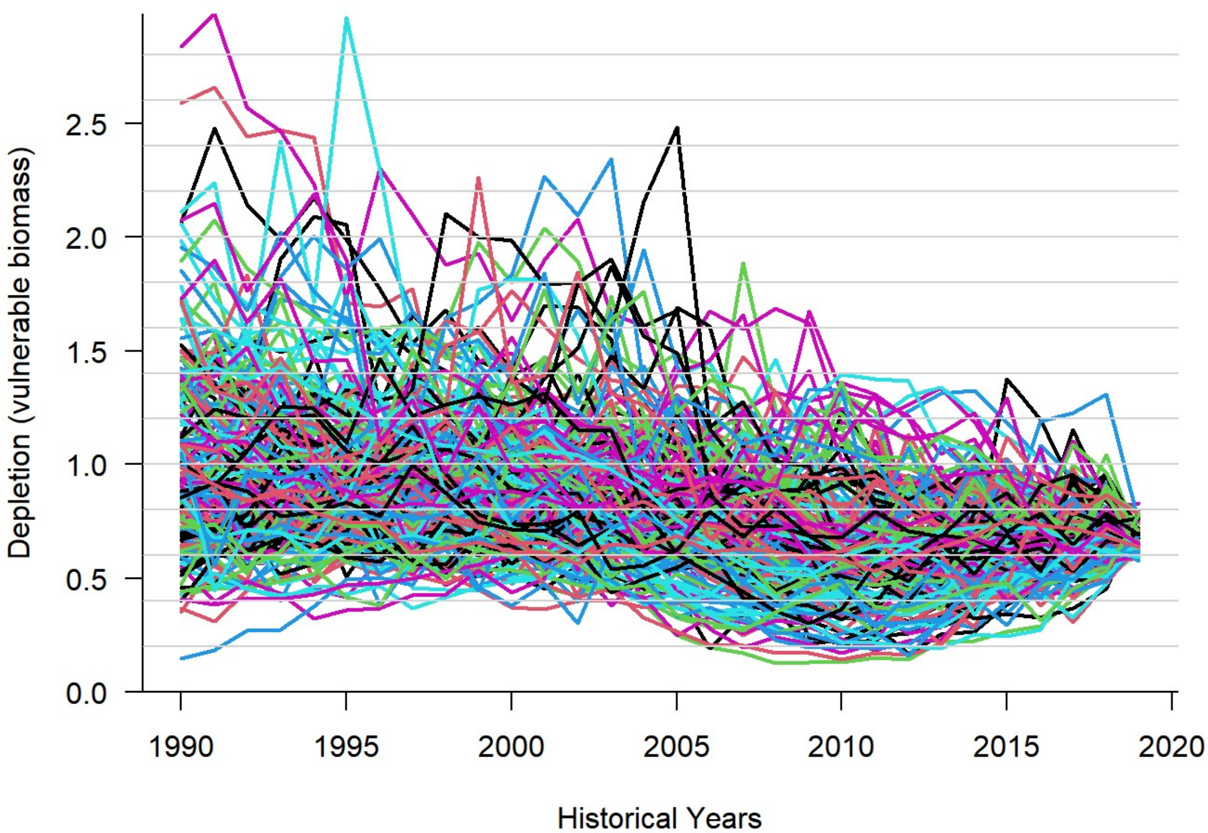

Figure B4. Simulated historical depletion of vulnerable biomass.

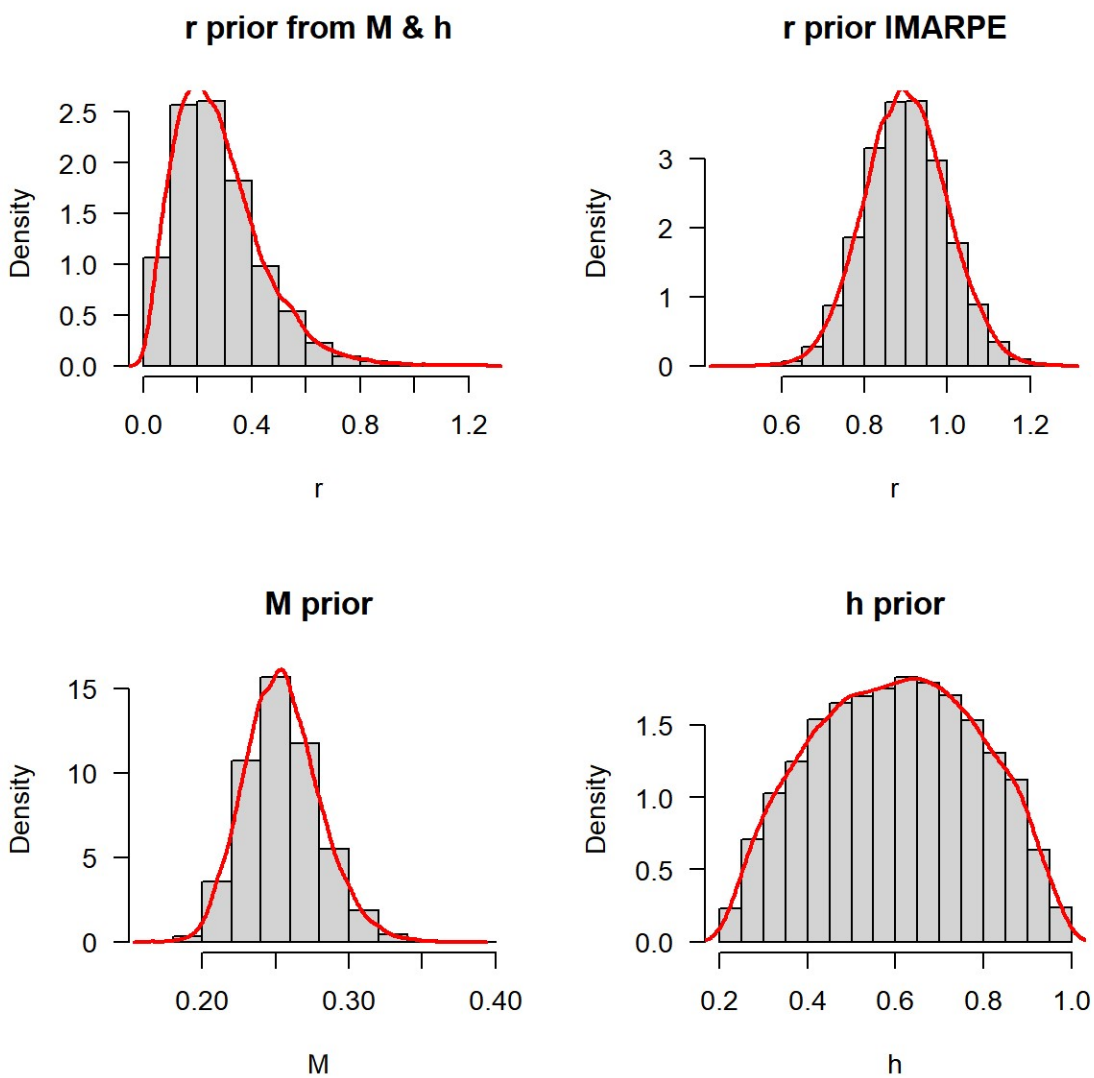

Figure B5. Prior probability distributions for intrinsic rate of increase used in fitting surplus production models used in SP_SS1 and SP_SS2.

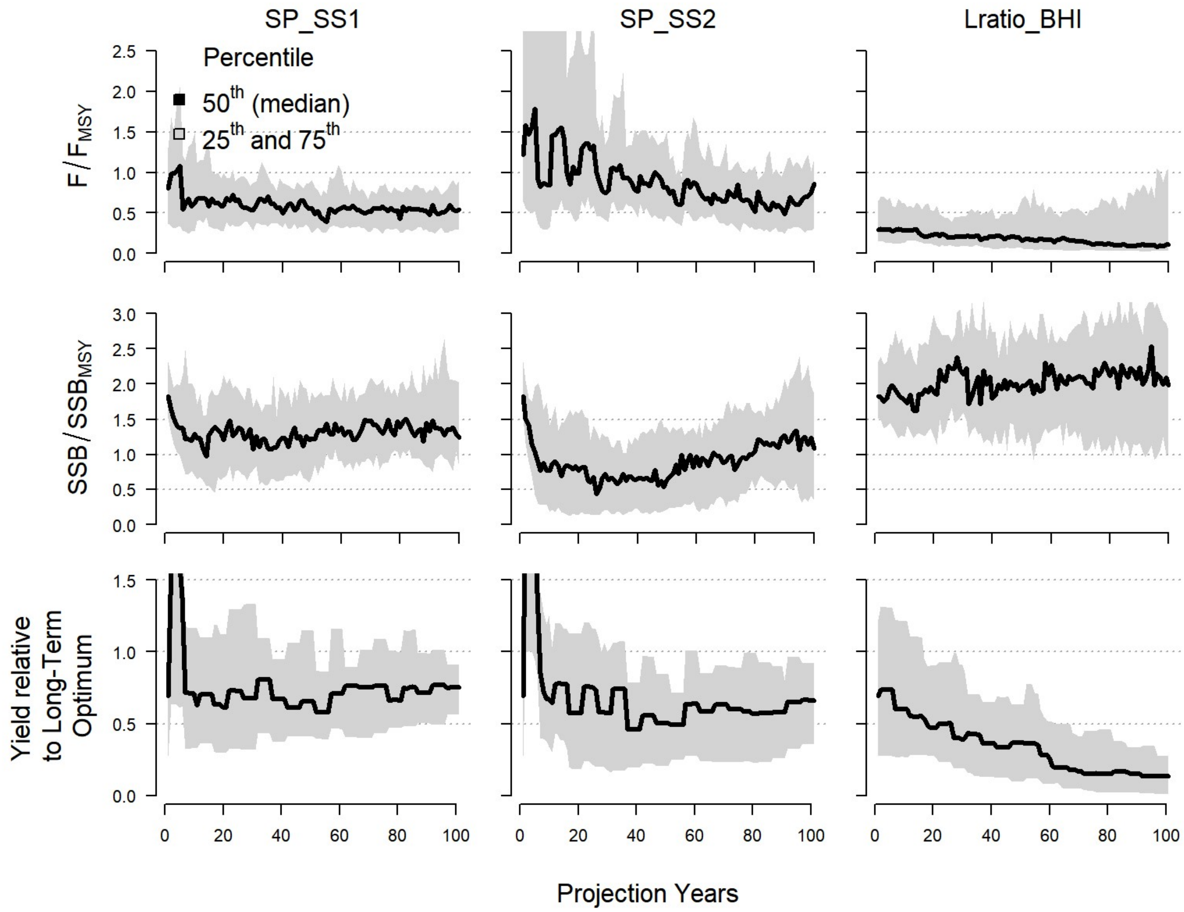

Figure B6. Time series of performance of MSY-seeking MPs.

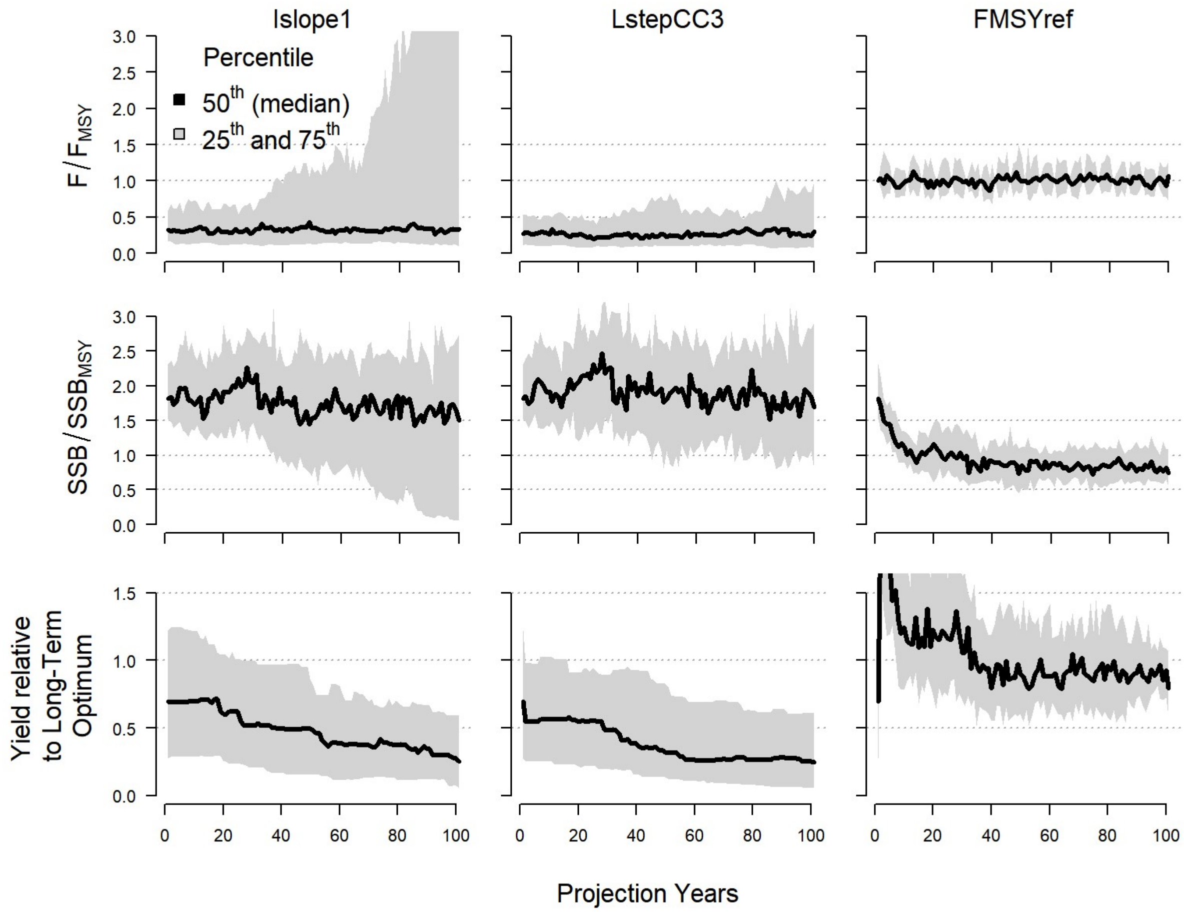

Figure B7. Time series of performance of stable biomass-seeking MPs (Islope1 and LstepCC3) and the FMSYref reference MP.

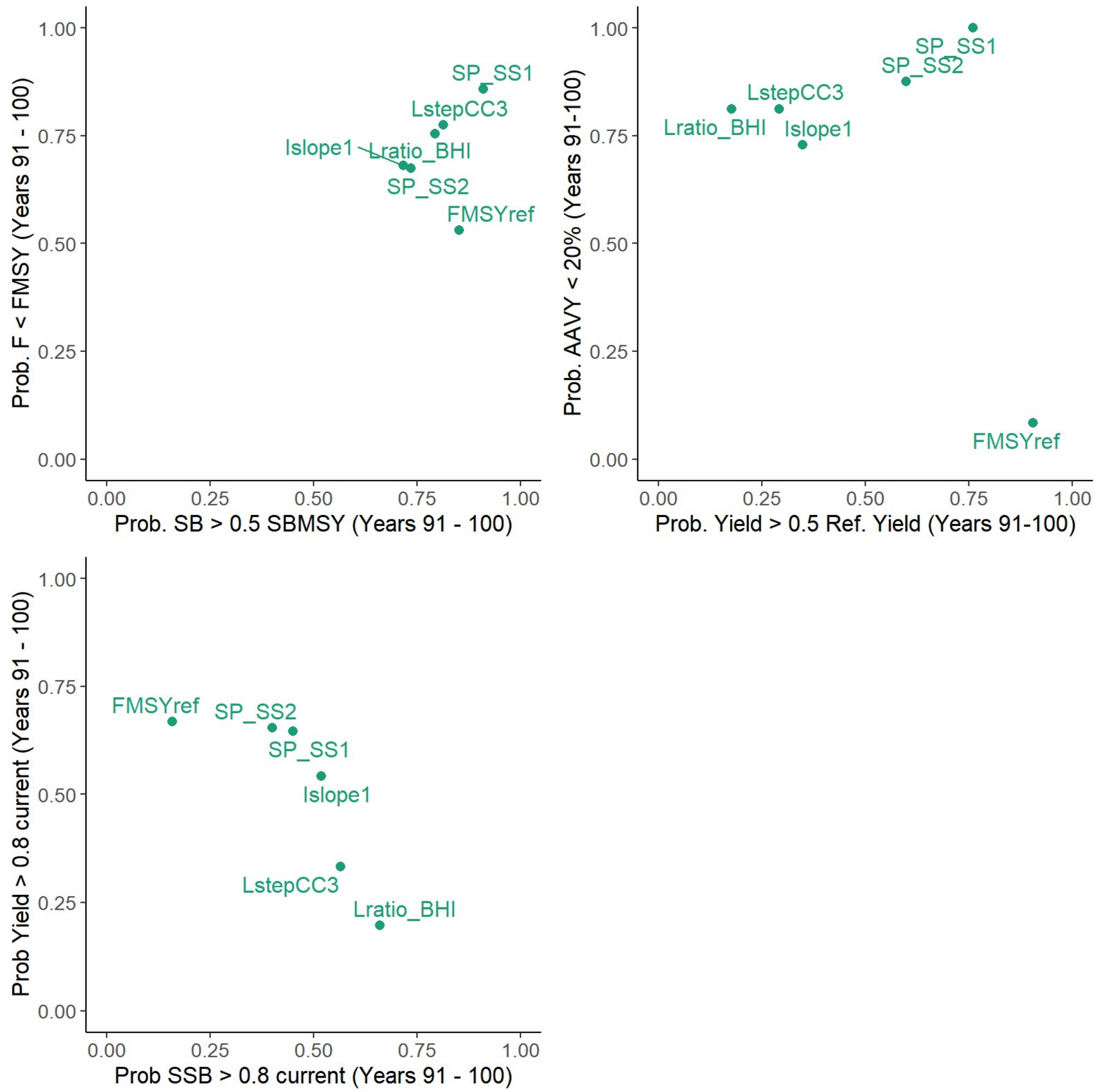

Figure B8. Long-term trade-offs among performance metrics.

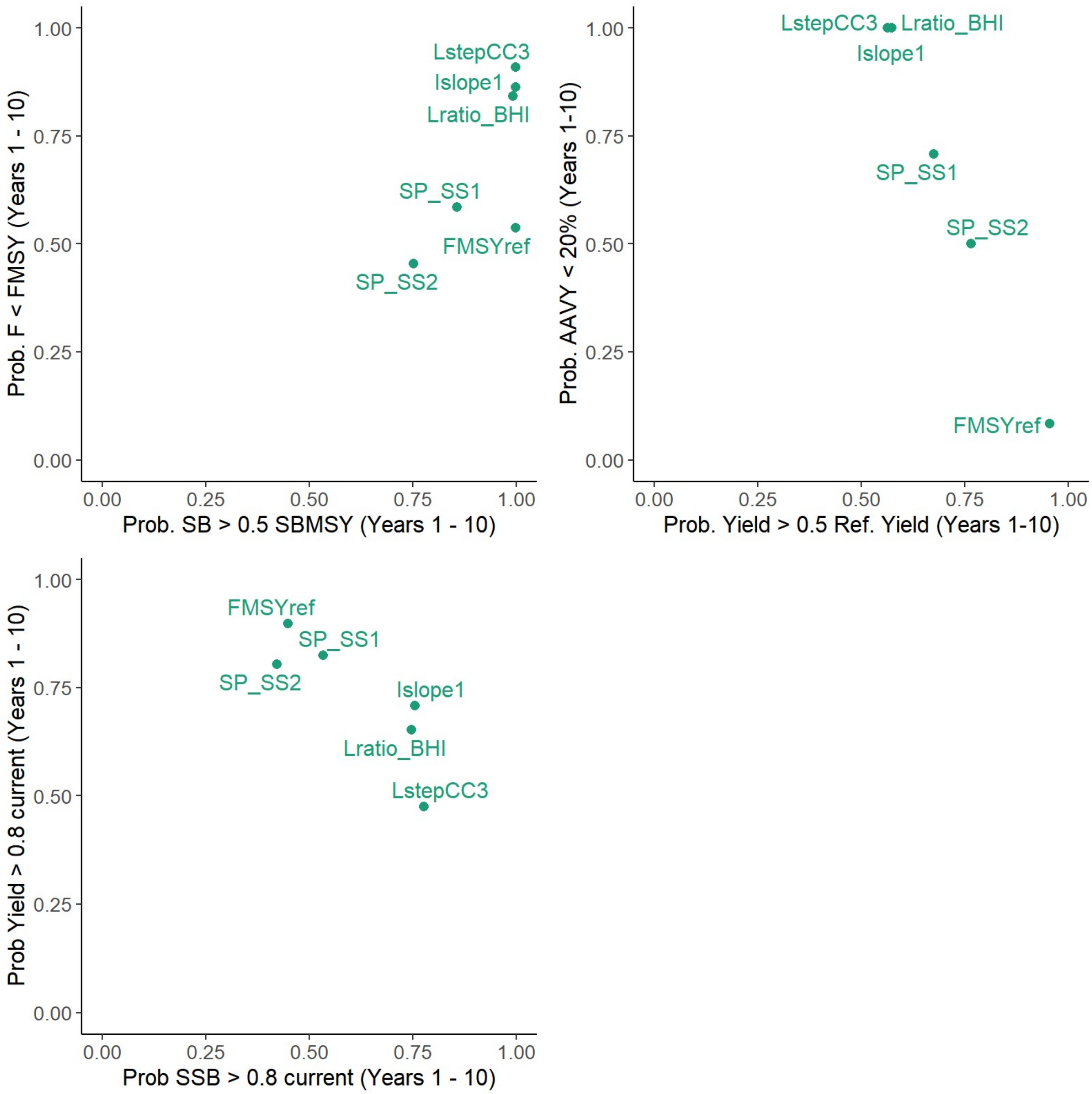

Figure B9. Short-term trade-offs among performance metrics.

PART C. A PROPOSAL FOR MSE WORKSHOPS

The following is a proposal for a series of workshops to advance the MSE work presented in this report and to support capacity building for Peruvian fisheries. Each workshop is proposed as a 2-to-3-hour work session that includes presentations, discussions, and analysis co-led by the facilitator and parties involved (e.g., IMARPE and TNC).

Workshop 1: Introductory materials and sharing of background information

- Eel biology, fishery characteristics, stock assessment history, current management regulations.
- Discussion on fishery management objectives
- Discussion of data availability and any needed analyses to support OM and MSE.
- Introduction to MSE

Workshop 2: Operating model(s)

- Overview of OM developed in this report
- Discussion of needed improvements to OM
- R-based examples of OM development and/or analyses to improve OM

Workshop 3: Rapid conditioning model

- Improve plausibility of historical population dynamics using conditioning
- R-based example of conditioning against data

Workshop 4: Management procedures

- Introduction to designing management procedures
- Discussion of MPs applied in this report
- Designing custom MPs in openMSE

Workshop 5: Performance metrics

- Introduction to performance metrics
- Designing custom performance metrics in openMSE
- Finalize workplan for a refined MSE

Workshop 5: MSE results

- Group shares results of refined MSE
- Identify and conduct sensitivity analyses
- Discuss any needed further refinements
- Finalize workplan for workshop report.

Deliverable: Workshop report containing refined MSE.

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