Application of Bayesian biomass dynamic models to neritic tuna species in the Indian Ocean

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SUMMARY

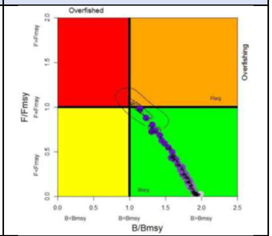
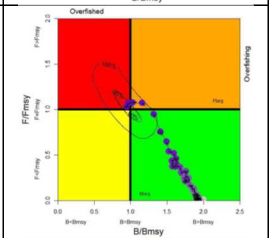
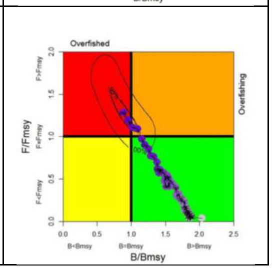
Stock assessment has been conducted for three neritic species, Kawakawa, longtail tuna and narrow-barred Spanish mackerel, in the Indian Ocean based on the biomass dynamic models. Two different approaches were applied; 1) state-space biomass dynamics models using both of catch series and standardized abundance index (here, the Iranian coastal gillnet CPUE, annually averaged) and 2) Catch only analyses using the Cmsy method. In the second analyses, we focused on the sensitivity/robustness of the results to i) the assumption of prior distributions for r, K, initial and final depletions and ii) the assumption of production functions. For all the analyses, we employed Bayesian methods to estimate parameters and evaluate associated estimation uncertainty. Non-informative priors were used, and posterior samples were generated using a Markov chain Monte Carlo (MCMC) method or acceptance/rejection sampling. Our overall conclusions were a) analyses with CPUE series looked too optimistic for all the species, which was driven by a recent increasing trend of CPUE; b) Cmsy method provided with robust results to some extent even when the prior assumptions were moderately changed; c) however the result of the Cmsy method seemed sensitive to the production functions, and therefore there should be careful diagnostic examinations using retrospective analyses and hindcasting approaches.

Contents

1. INTRODUCTION

The last stock assessment for neritic tuna species was conducted in 2015. In the assessment, the "Optimized Catch Only Method (OCOM)", which is a one of data limited stock assessment methods (say, DLSAs), was applied. Although there was a contrast in the stock status over the species, the trend was quite similar; the population level has been going down while the fishing intensity has been increasing. If these trends monotonically continue, the populations might be collapsing.

Table 1. Summary of stock assessment and status for Kawakawa, longtail tuna and narrow-barred Spanish mackerel.

Species	Last stock assessment	Data	Indicators and 2019 status determination	Kobe plot
Kawakawa	2015 by OCOM [Add-doc number and author]	Catch series (1950-2013)	Catch 2018[2]: 173,367 t Average catch 2014-2018: 161,844 t MSY (1,000 t) [*] 152 [125 –188] F_{MSY} [*] 0.56 [0.42–0.69] B_{MSY} (1,000 t) [*] 202 [151–315] F_{2013}/F_{MSY} [*] 0.98 [0.85–1.11] B_{2013}/B_{MSY} [*] 1.15 [0.97–1.38] B_{2013}/B_0 [*] 0.58 [0.33–0.86]	
Longtail tuna	2015 by OCOM	Catch series (1950-2013)	Catch 2018[2]: 136,906 t Average catch 2014–2018: 138,352 t MSY (1,000 t) (*): 140 (103–184) F_{MSY} (*): 0.43 (0.28–0.69) B_{MSY} (1,000 t) (*): 319 (200–623) F_{2015}/F_{MSY} (*): 1.04 (0.84–1.46) B_{2015}/B_{MSY} (*): 0.94 (0.68–1.16) B_{2015}/B_0 (*): 0.48 (0.34–0.59) 67%	
Narrow-barred Spanish mackerel	2015 by OCOM	Catch series (1950-2013)	Catch 2018[2]: 149,263 t Average catch 2014-2018: 163,209 t MSY (1,000 t) [*]: 131 [96–180] F_{MSY} [*]: 0.35 [0.18–0.7] B_{MSY} (1,000 t) [*]: 371 [187–882] F_{2015}/F_{MSY} [*]: 1.28 [1.03–1.69] B_{2015} B_{MSY} [*]: 0.89 [0.63–1.15] B_{2015}/B_0 [*]: 0.44 [0.31–0.57] 89%	

*OCOM: Optimized Catch Only Method

Since the last assessment, several types of data limited methods have been discussed internally and externally to the IOTC. A mainstream of DLSA is still the catch only method. And this sort of method can be applied to the IOTC neritic tuna stocks because the data requirement of the method is low; availability of catch series. However, there are some studies or existing pieces of information on the abundance indices, and therefore to address the necessity of future development of abundance indices for better stock assessment, we intentionally used an available standardized CPUE for fitting the biomass dynamic models. Also, to conduct sensitivity tests in DLSA, we also applied a simple catch-only method.

2. MATERIALS AND METHODS

2.1 Data

We used the following data set: aggregated annual catch series from 1950 to 2018 and standardized CPUE for Iranian gillnet (inshore) from 2008 to 2017 (Fu et al. 2019). The time trajectories of the catch and CPUE for Kawakawa, longtail tuna and narrow-barred Spanish mackerel are shown in Figure 1.

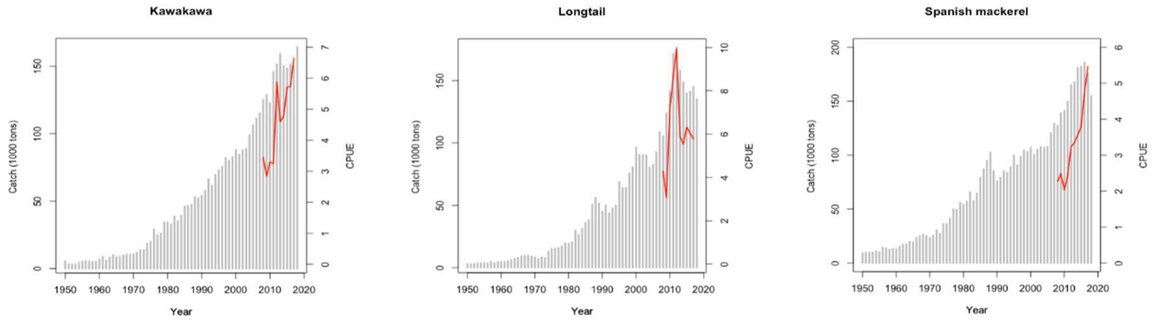


Figure 1. Time series of catch and CPUE used in this paper.

2.2 METHODS

We conducted two different types of procedures:

- Bayesian state-space biomass dynamic models using catch series data and a standardized abundance index [BDM-CPUE, see Tables 2 and 3 for the specification]
- Bayesian state-space biomass dynamic models using catch series only (Cmsy method, Froese et al. 2017) to investigate sensitivity/robustness to the assumptions of prior distributions [BDM-CatchOnly-1, see Table 4 for the specification]
- Bayesian state-space biomass dynamic models using catch series only (Cmsy method, Froese et al. 2017) to investigate sensitivity/robustness to the assumptions of production functions [BDM-CatchOnly-2, see Table 5 for the specification]

In the analyses mentioned above, we mainly assumed two different surplus production curves (Schaefer and Fox). The models basically include the process error, but due to the limited information from the short period of CPUE, we also conducted analyses without the process error or with the process error having a fixed process error variance.

For all the analyses, we used Bayesian methods to estimate parameters and evaluate associated estimation uncertainty. Non-informative priors were used, and posterior samples were generated using a Markov chains Monte Carlo (MCMC) method.

Table 2. Summary of model specification for analyses of BDM-CPUE

Scenario	Abbreviation	Initial year	Production curve	Process error
1	Y1950_SC_PE	1950	Schaefer	Estimated
2	Y1950_FX_PE	1950	Fox	Estimated
3	Y1950_SC_OE	1950	Schaefer	CV fixed at 0
4	Y1950_FX_OE	1950	Fox	CV fixed at 0
5	Y2008_SC_PE	2008	Schaefer	Estimated
6	Y2008_FX_PE	2008	Fox	Estimated
7	Y2008_SC_OE	2008	Schaefer	CV fixed at 0
8	Y2008_FX_OE	2008	Fox	CV fixed at 0

Table 3. Summary of prior distributions used in BDM-CPUE

Parameter	Kawakawa	Longtail	Spanish mackerel
r	U(0.01, 2)	Ditto	Ditto
K (1000 tons)	U(0, 1000)	Ditto	Ditto
Initial depletion	U(0.01, 1)	Ditto	Ditto
CV for process error	U(0.01, 1)	Ditto	Ditto
CV for observation error	U(0.01, 1)	Ditto	Ditto
q	U(0.01, infinity)	Ditto	Ditto

Table 4. Summary of model specification for analyses of BDM-CatchOnly-1. In all the model, the process error cv is fixed at 0.1.

Scenario	Abbreviation	Initial year	Prior for initial depletion (uniform)	Prior for final depletion (uniform)	r (uniform)	K (uniform)
1	S1_Y1950_Df(0.5-0.9)	1950	0.5-0.9	0.5-0.9	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow
2	S2_Y1950_Df(0.3-0.9)	1950	0.5-0.9	0.3-0.9	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow
3	S3_Y1950_Df(0.3-0.7)	1950	0.5-0.9	0.3-0.7	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow
4	S4_Y1950_Df(0.4-0.8)	1950	0.5-0.9	0.4-0.8	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow
5	S5_Y1950_Df(0.2-0.6)	1950	0.5-0.9	0.2-0.6	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow
6	S6_Y1950_DI(0.6-1.0)	1950	0.6-1	0.3-0.7	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow
7	S7_Y1950_DI(0.8-1.0)	1950	0.8-1	0.3-0.7	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow
8	S8_Y1950_r(0-2)_K2	1950	0.5-0.9	0.3-0.7	0.0-2.0	Max(catch),50*max(catch)
9	S9_Y1950_ r(0-2)_K3	1950	0.5-0.9	0.3-0.7	0.0-2.0	0-1000
10	S10_Y2008_DI(0.3-0.7)	2008	0.3-0.7	0.5-0.9	0.6-1.5	Max catch/rhigh ,4 max(ct)/rlow

Table 5. Summary of model specification for analyses of BDM-CatchOnly-2 (Schaefer and Fox). In all the model, the process error cv is fixed at 0.1.

Species	r	K	Initial depletion	Final depletion
Kawakawa	0.6-1.5	301-902	0.9-1	0.2-0.6
Longtail Tuna	0.6-1.5	315 - 946	0.9-1	0.2-0.6
Spanish Mackerel	0.6-1.5	344-1033	0.9-1	0.2-0.6

3. RESULTS

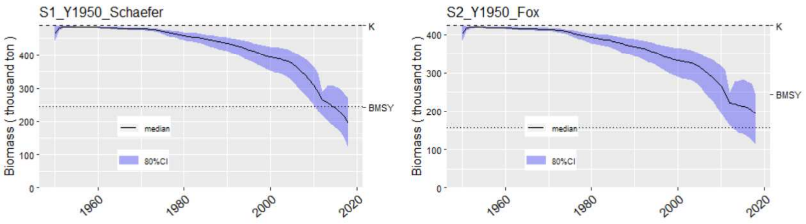
In general, BDM-CPUE analyses fitted to the data well except in the models without the process error (see Appendix A1-A3). However, due to unrealistic CPUE's increasing trend, the population status looks too optimistic, and therefore we are not confident with the results of stock assessment. Rather, these pieces of results warrant further investigation of CPUE for all the three neritic species analyzed in this paper. Therefore, we do not put all the results of BDM-CPUE in the following sections but into Appendices A1-A3 for Kawakawa, longtail and Spanish mackerel, respectively.

Also, the intention of this paper is to address the sensitivity/robustness of the stock assessment results by Cmsy methods to the several informative priors, so as in the case of BDM-CPUE, all the results of the BDM-CatchOnly-1 are summarized in Appendices B1-B3 in the same order of species.

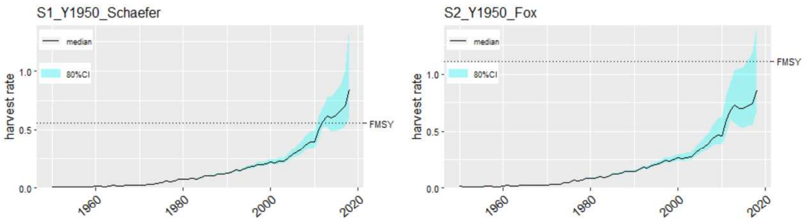
In this section, therefore, we focus on the comparison of results for Schaefer and Fox production function for a single set of prior distribution for each species. A simple retrospective analysis was also conducted.

3.1 Kawakawa

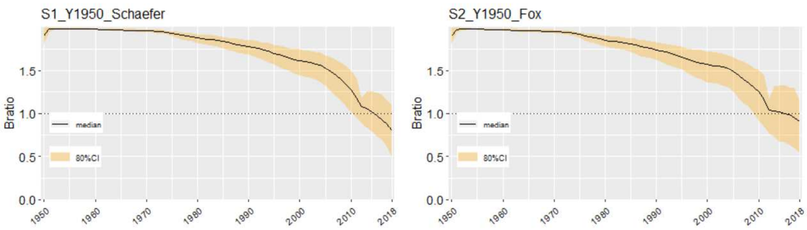
Time series Biomass



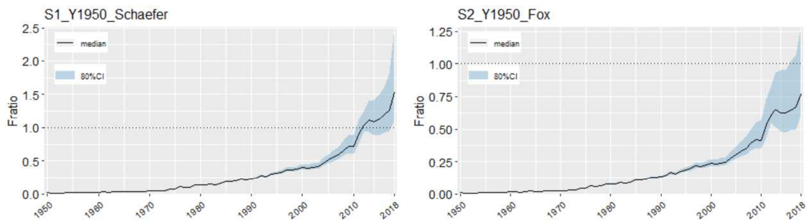
Time series Harvest rate



Time series Bratio



Time series Fratio



Time series B/K

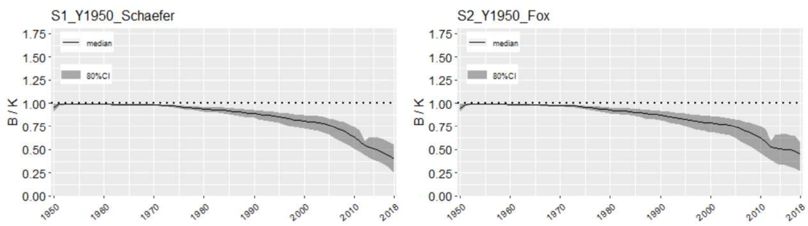


Figure K-1. Times series summaries for Cmsy analyses (BDM-CatchOnly-2) for Kawakawa under Shaefer (left) and Fox (right) models.

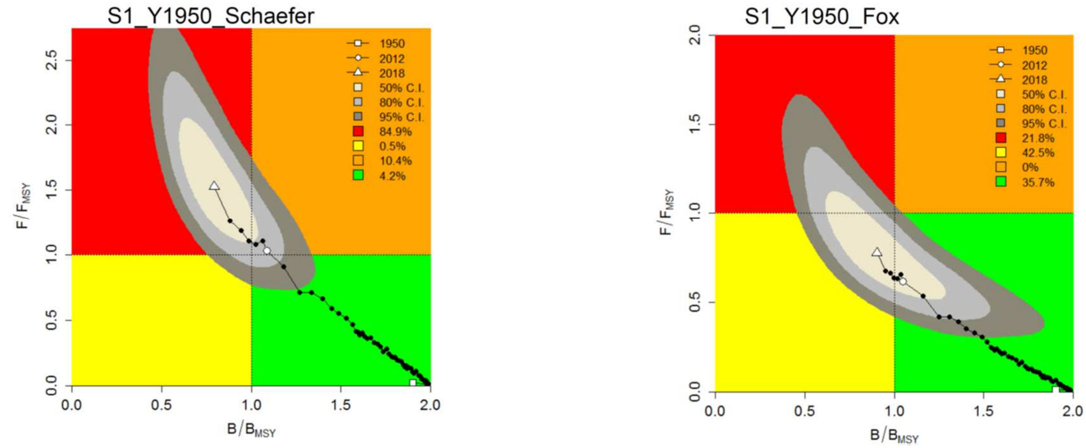


Figure K-2. Kobe plots for Cmsy analyses (BDM-CatchOnly-2) for Kawakawa under Shaefer (left) and Fox (right) models.

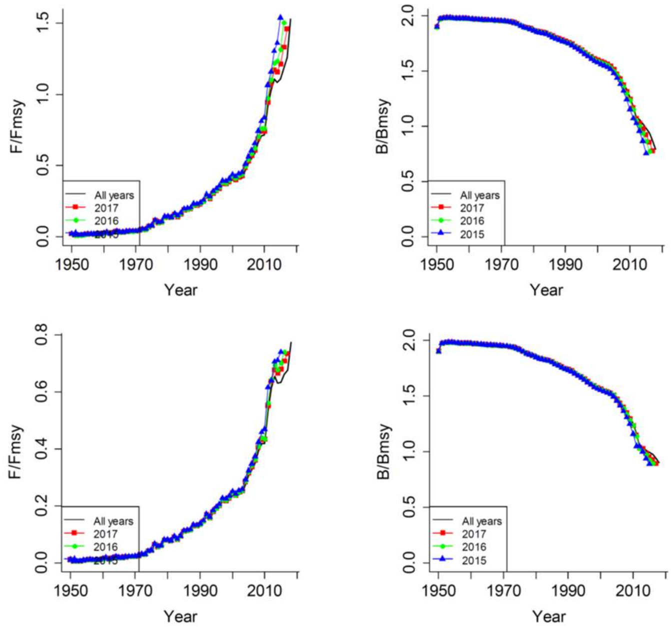


Figure K-3. Results of retrospective analyses in terms of F- and B-ratios for Cmsy analyses (BDM-CatchOnly-2) for Kawakawa under Shaefer (top) and Fox (bottom) models.

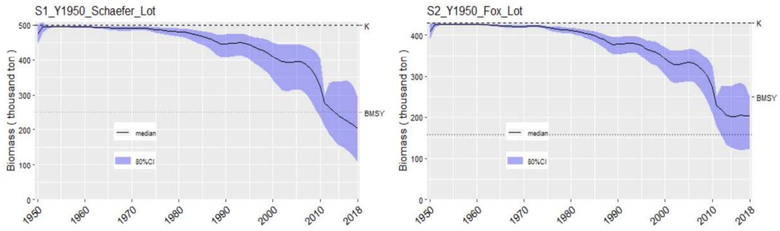
Table K-1. A short summary for estimates of key parameters and reference points for Kawakawa under Schaefer (left) and Fox (right) models.

	Estimates	LowerCI	HigherCI
r	1.11	0.784	1.58
K	490	353	679
MSY	134	110	176
Bmsy	245	176	340
Fmsy	0.557	0.392	0.791
D_{2018}	0.395	0.211	0.588

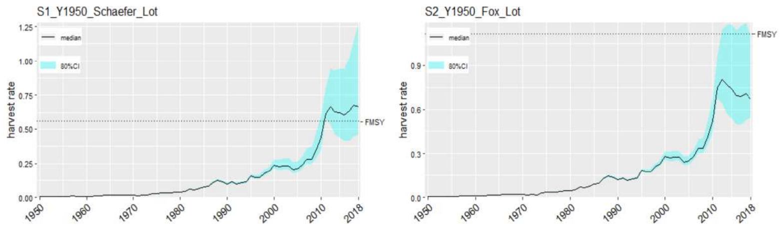
	Estimates	LowerCI	HigherCI
r	1.11	0.96	1.27
K	423	364	492
MSY	174	151	200
Bmsy	158	138	179
Fmsy	1.11	1.09	1.12
D_{2018}	0.453	0.272	0.572

3.2 Longtail tuna

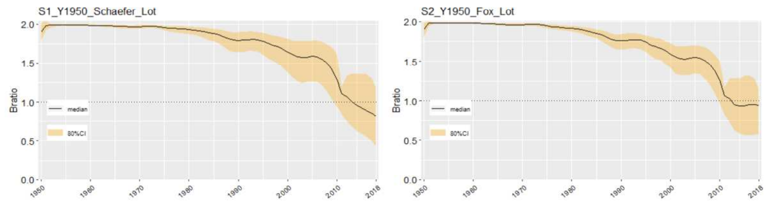
Time series Biomass



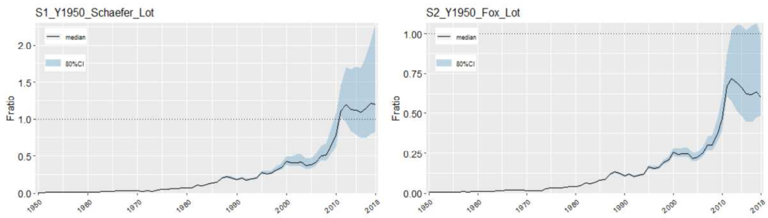
Time series Harvest rate



Time series Bratio



Time series Fratio



Time series B/K

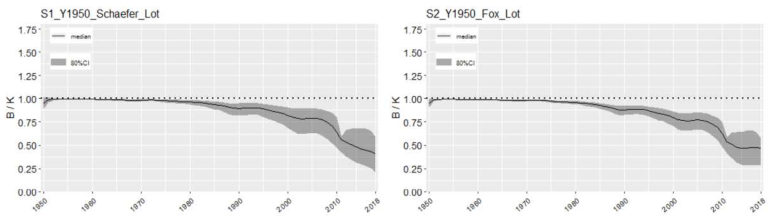


Figure L-1. Times series summaries for Cmsy analyses (BDM-CatchOnly-2) for longtail tuna under Shaefer (left) and Fox (right) models.

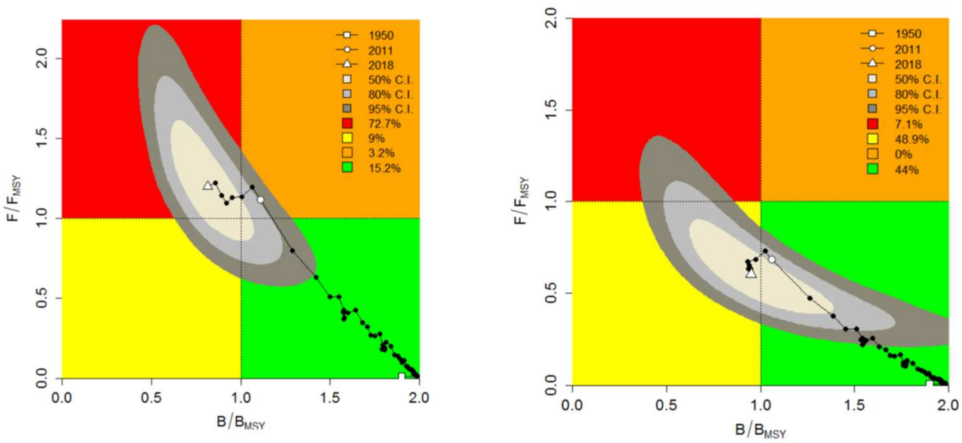


Figure L-2. Kobe plots for Cmsy analyses (BDM-CatchOnly-2) for longtail tuna under Shaefer (left) and Fox (right) models.

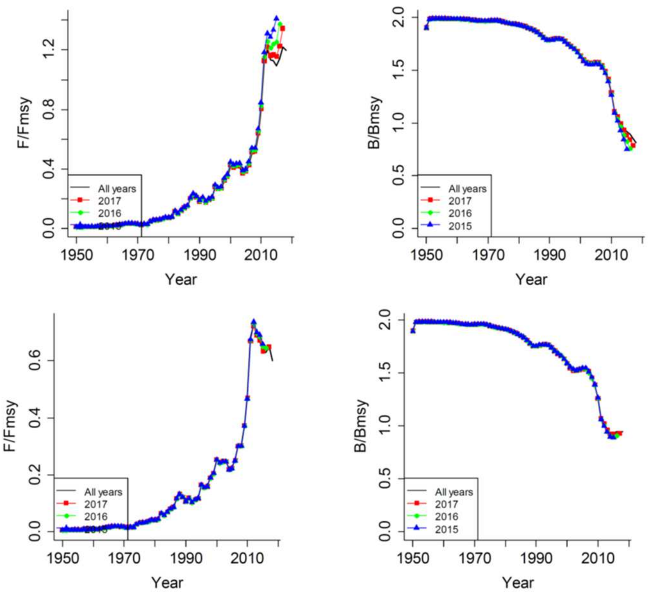


Figure L-3. Results of retrospective analyses in terms of F- and B-ratios for Cmsy analyses (BDM-CatchOnly-2) for longtail tuna under Shaefer (top) and Fox (bottom) models.

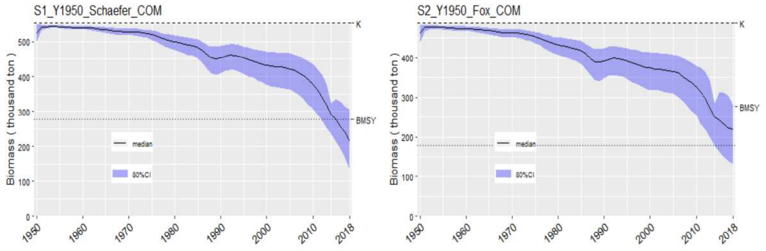
Table L-1. A short summary for estimates of key parameters and reference points for longtail tuna under Schaefer (left) and Fox (right) models.

	Estimates	LowerCI	HigherCI
r	1.11	0.784	1.57
K	501	366	697
MSY	137	112	176
Bmsy	250	188	349
Fmsy	0.557	0.392	0.791
D_{2018}	0.395	0.211	0.588

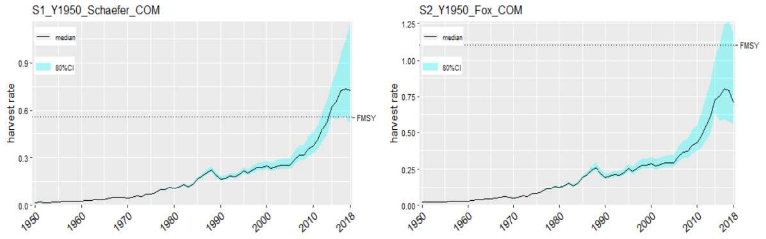
	Estimates	LowerCI	HigherCI
r	1.11	0.95	1.28
K	428	372	494
MSY	175	147	207
Bmsy	158	137	182
Fmsy	1.11	1.07	1.14
D_{2018}	0.47	0.28	0.57

3.3 Narrow-barred Spanish mackerel

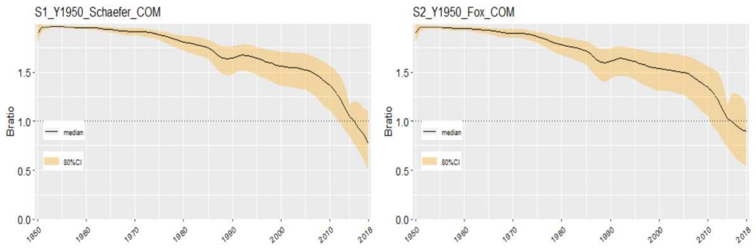
Time series Biomass



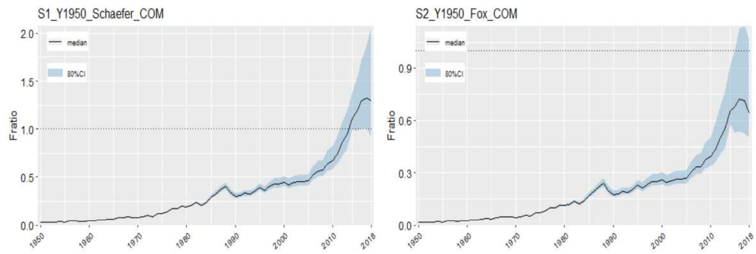
Time series Harvest rate



Time series Bratio



Time series Fratio



Time series B/K

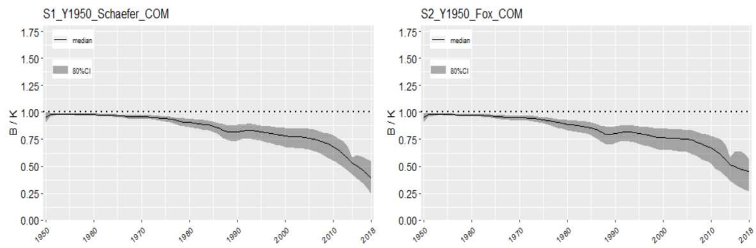


Figure S-1. Times series summaries for Cmsy analyses (BDM-CatchOnly-2) for Spanish mackerel under Shaefer (left) and Fox (right) models.

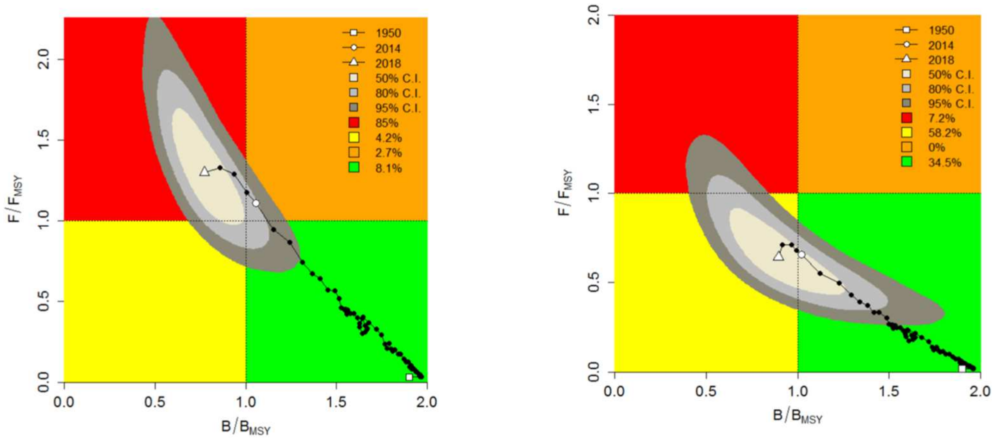


Figure S-2. Kobe plots for Cmsy analyses (BDM-CatchOnly-2) for Spanish mackerel under Shaefer (left) and Fox (right) models.

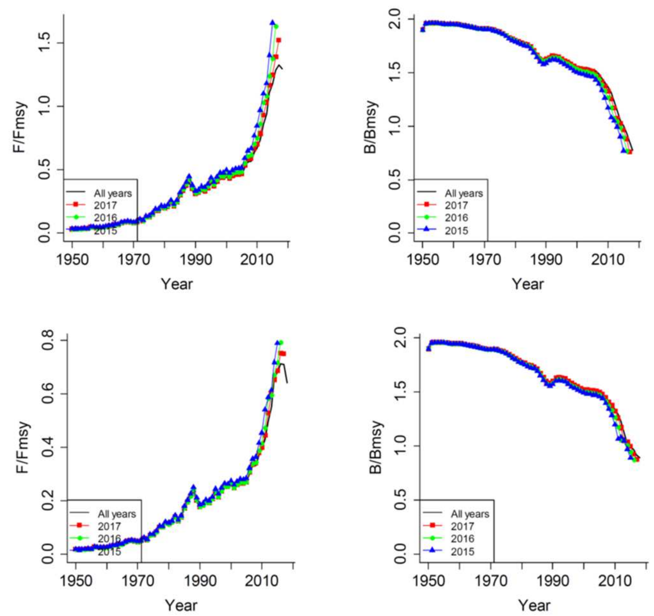


Figure S-3. Results of retrospective analyses in terms of F- and B-ratios for Cmsy analyses (BDM-CatchOnly-2) for Spanish mackerel under Shaefer (top) and Fox (bottom) models.

Table S-1. A short summary for estimates of key parameters and reference points for Spanish mackerel under Schaefer (left) and Fox (right) models.

	Estimates	LowerCI	HigherCI
r	1.12	0.97	1.28
K	553	484	633
MSY	152	135	173
Bmsy	277	242	317
Fmsy	0.558	0.485	0.642
D_{2018}	0.386	0.224	0.548

	Estimates	LowerCI	HigherCI
r	1.11	0.95	1.27
K	430	374	493
MSY	176	147	209
Bmsy	158	137	183
Fmsy	1.11	1.08	1.14
D_{2018}	0.473	0.296	0.578

4. DISCUSSION

Our overall conclusions are as follows:

a) analyses with CPUE series look too optimistic for all the species, which was driven by a recent increasing trend of CPUE;

b) Cmsy method provided with robust results to some extent even when the prior assumptions were changed;

c) however the result of the Cmsy method is sensitive to the production functions, and therefore there should be careful diagnostic examinations using retrospective analyses and hindcasting approaches (since we have not tested the predictability of models, we were not able to justify all the results shown in this paper).

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R. Froese, N. Demirel, G. Coro, K. M. Kleisner and H. Winker (2017) Estimating fisheries reference points from catch and resilience. Fish and Fisheries, 18: 506-526.

Appendix A-1. Results of BDM-CPUE for Kawakawa

Summary of estimates of parameters

S1_Y1995_SC_PE

	Mean	Median	Lower10th	Upper10th
r	1.350	1.334	0.953	1.787
K (thousand ton)	562.4	556.3	412.8	722.8
D1	1.00	1.00	1.00	1.00
sigma_Pro	0.20	0.21	0.06	0.30
sigma_CPUE	0.22	0.20	0.05	0.43
q	13.26	12.51	8.03	19.62
FMSY	0.68	0.67	0.48	0.89
BMSY (thousand ton)	281.2	278.1	206.4	361.4
MSY (thousand ton)	186.3	174.2	138.3	253.3

S2_Y1995_FX_PE

	Mean	Median	Lower10th	Upper10th
r	1.199	1.156	0.761	1.722
K (thousand ton)	506.2	493.2	331.9	698.2
D1	1.00	1.00	1.00	1.00
sigma_Pro	0.22	0.23	0.05	0.35
sigma_CPUE	0.24	0.23	0.05	0.45
q	16.50	14.56	8.18	27.29
FMSY	1.20	1.16	0.76	1.72
BMSY (thousand ton)	186.2	181.5	122.1	256.9
MSY (thousand ton)	217.9	190.3	143.8	341.9

S3_Y1995_SC_OE

	Mean	Median	Lower10th	Upper10th
r	1.510	1.564	1.012	1.917
K (thousand ton)	708.8	719.2	457.2	946.3
D1	1.00	1.00	1.00	1.00
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.39	0.37	0.27	0.55
q	8.73	7.65	5.34	13.61
FMSY	0.75	0.78	0.51	0.96
BMSY (thousand ton)	354.4	359.6	228.6	473.2
MSY (thousand ton)	262.2	248.8	167.6	377.8

S4_Y1995_FX_OE

	Mean	Median	Lower10th	Upper10th
r	1.443	1.502	0.892	1.909
K (thousand ton)	648.7	648.6	372.1	925.0
D1	1.00	1.00	1.00	1.00
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.39	0.37	0.27	0.54
q	10.34	8.64	5.52	17.54
FMSY	1.44	1.50	0.89	1.91
BMSY (thousand ton)	238.6	238.6	136.9	340.3
MSY (thousand ton)	335.2	309.9	190.0	519.4

S5_Y2008_SC_PE

	Mean	Median	Lower10th	Upper10th
r	1.240	1.195	0.827	1.764
K (thousand ton)	668.5	671.4	415.4	926.1
D1	0.39	0.35	0.23	0.61
sigma_Pro	0.19	0.17	0.04	0.35
sigma_CPUE	0.17	0.16	0.06	0.30
q	15.35	13.80	8.23	24.67
FMSY	0.62	0.60	0.41	0.88
BMSY (thousand ton)	334.2	335.7	207.7	463.1
MSY (thousand ton)	195.0	187.0	155.7	244.9

S6_Y2008_FX_PE

	Mean	Median	Lower10th	Upper10th
r	0.919	0.819	0.535	1.481
K (thousand ton)	637.6	641.4	348.2	920.6
D1	0.37	0.32	0.16	0.64
sigma_Pro	0.22	0.20	0.05	0.39
sigma_CPUE	0.18	0.17	0.05	0.33
q	20.46	16.38	8.53	38.14
FMSY	0.92	0.82	0.54	1.48
BMSY (thousand ton)	234.6	236.0	128.1	338.7
MSY (thousand ton)	194.8	178.4	150.6	258.1

S7_Y2008_SC_OE

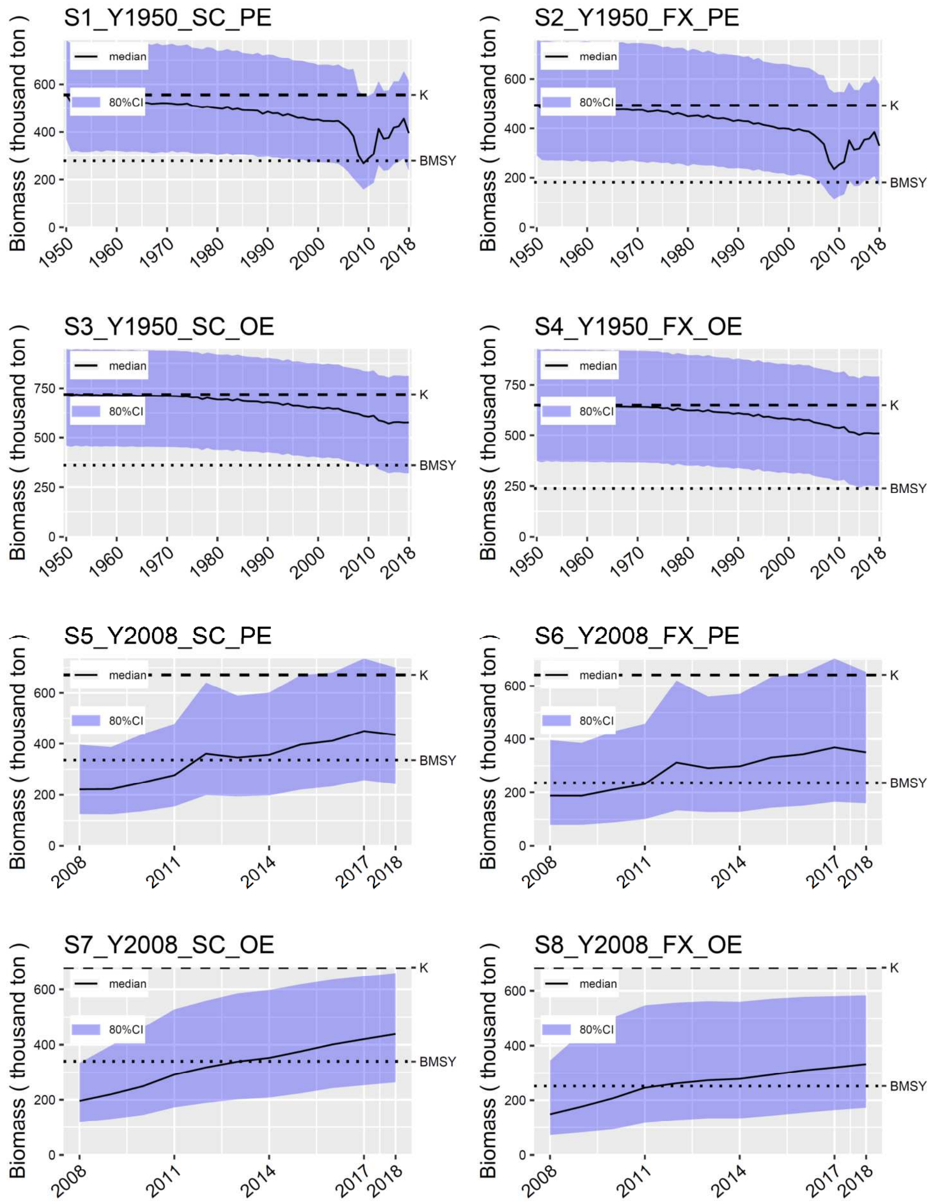
	Mean	Median	Lower10th	Upper10th
r	1.204	1.131	0.836	1.704
K (thousand ton)	679.1	679.8	420.3	938.0
D1	0.32	0.29	0.23	0.41
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.21	0.19	0.13	0.32
q	15.52	14.50	8.61	24.08
FMSY	0.60	0.57	0.42	0.85
BMSY (thousand ton)	339.6	339.9	210.2	469.0
MSY (thousand ton)	191.4	183.6	165.7	222.0

S8_Y2008_FX_OE

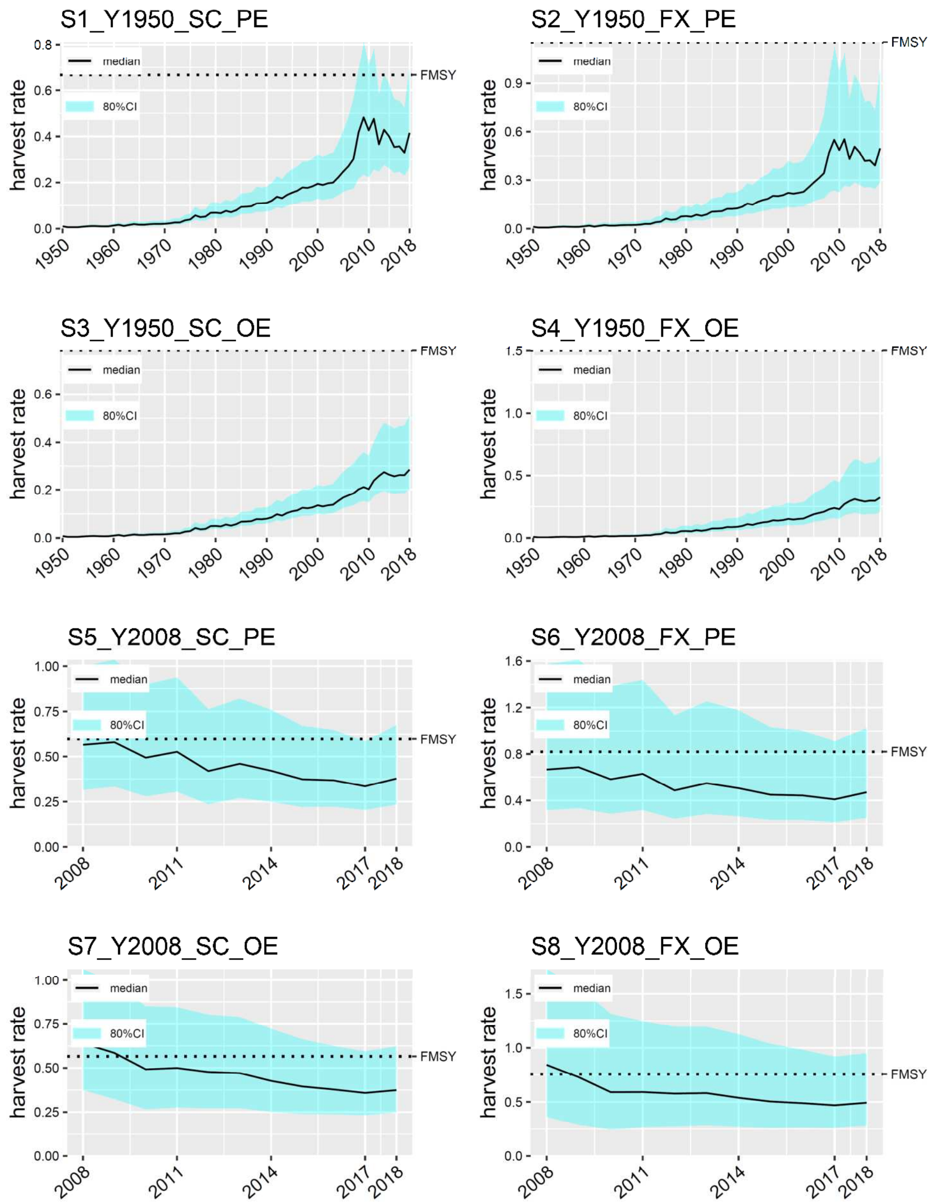
	Mean	Median	Lower10th	Upper10th
r	0.878	0.757	0.533	1.448
K (thousand ton)	670.2	685.7	375.3	935.4
D1	0.28	0.22	0.15	0.50
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.25	0.22	0.15	0.38
q	21.21	18.24	8.76	37.64
FMSY	0.88	0.76	0.53	1.45
BMSY (thousand ton)	246.5	252.3	138.1	344.1
MSY (thousand ton)	197.7	175.1	159.4	263.0

Time series plot

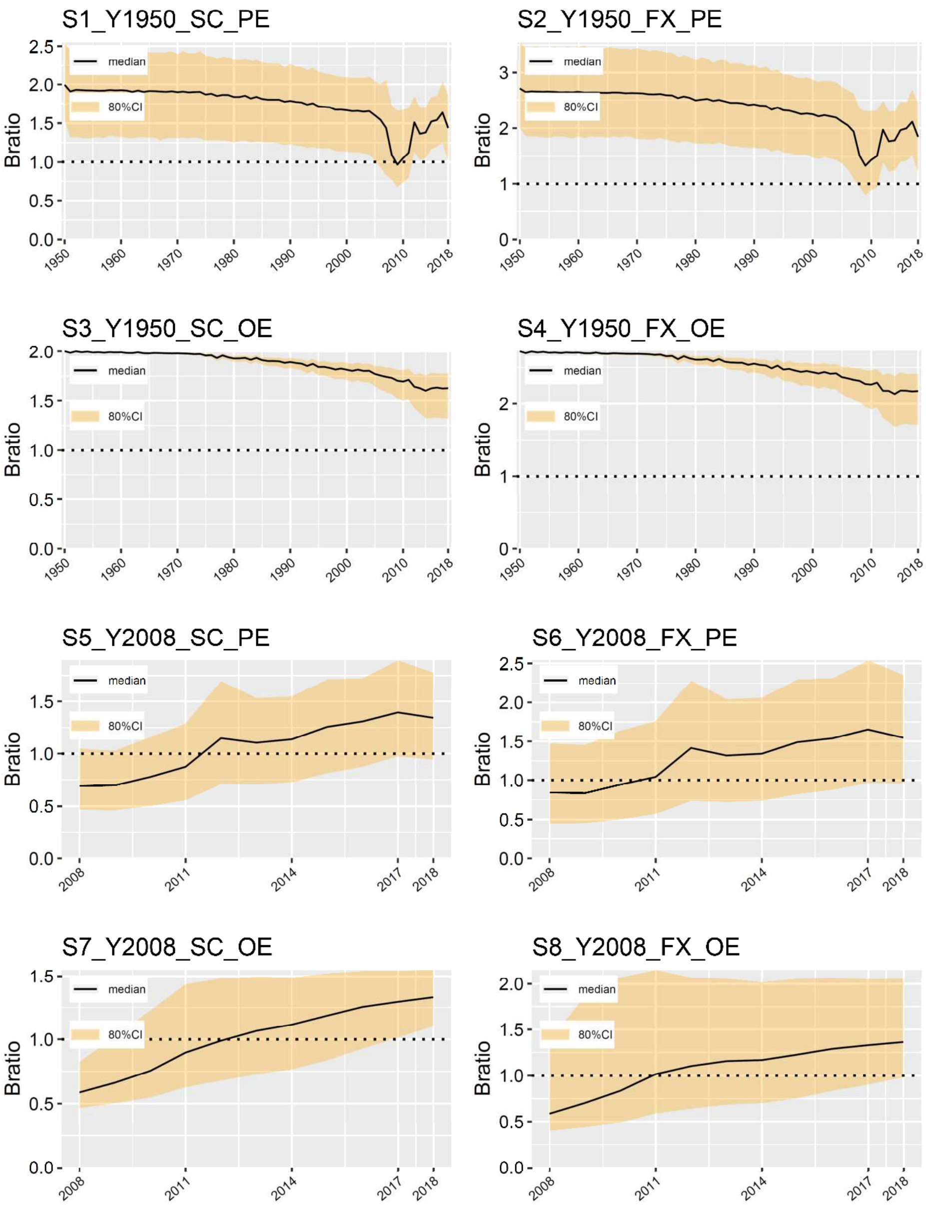
Time series Biomass



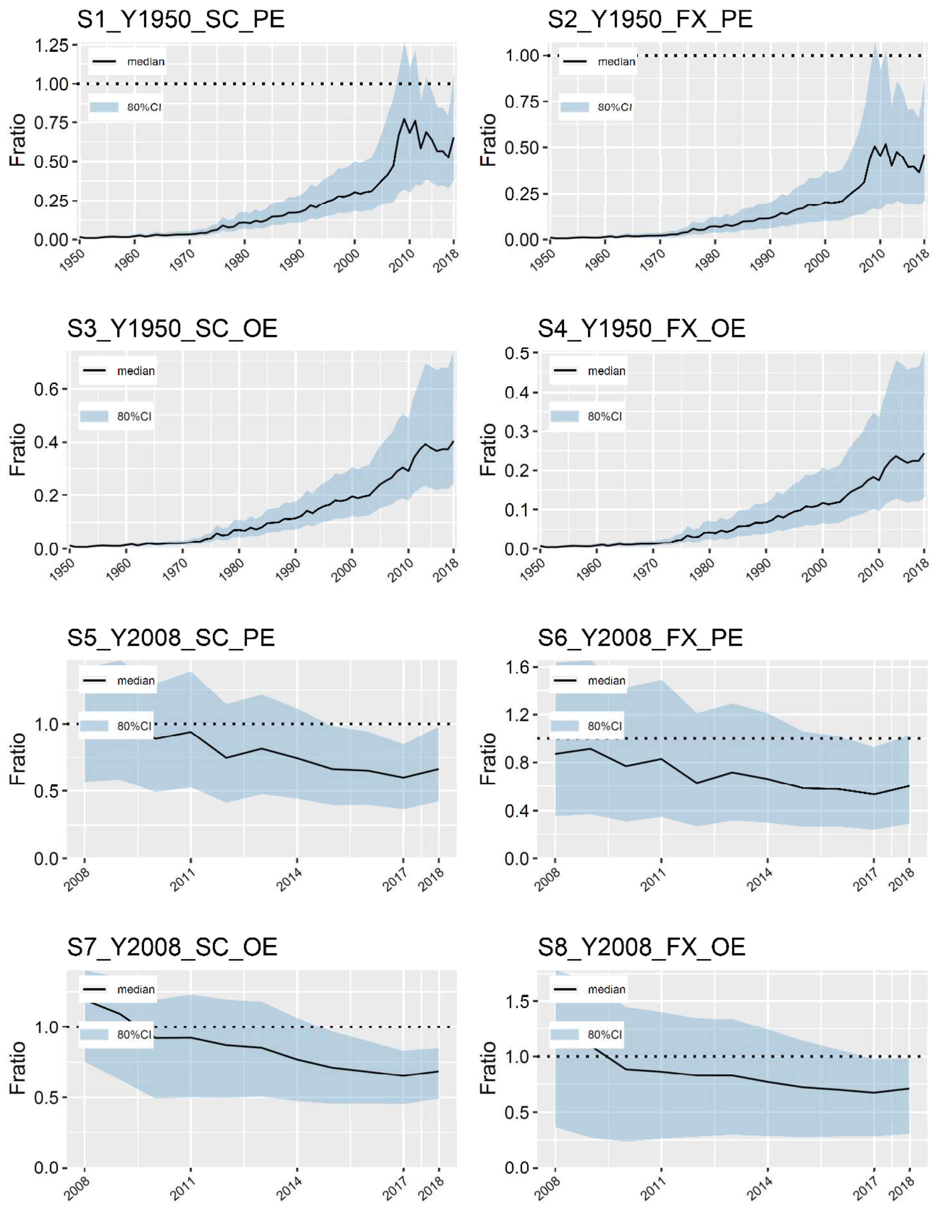
Time series Harvest rate



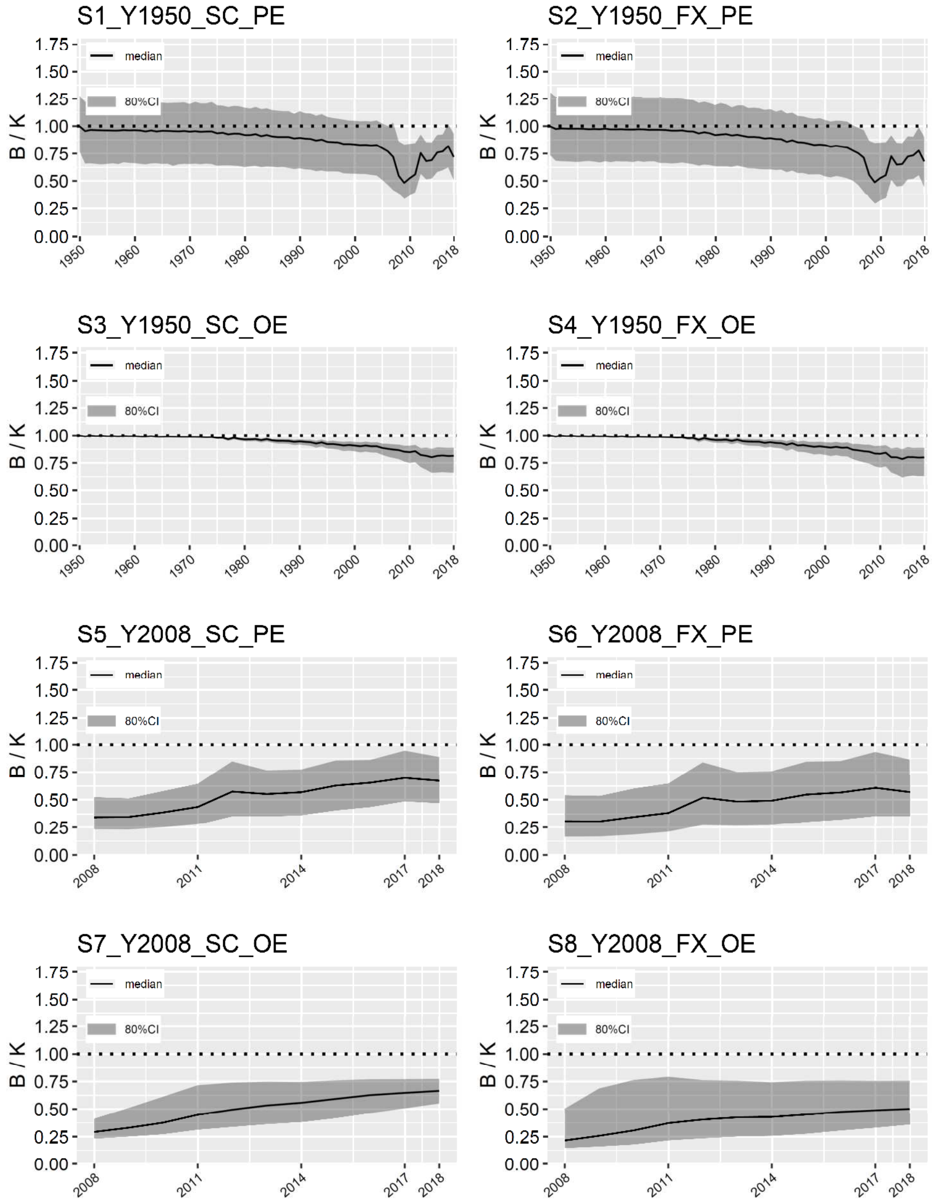
Time series Bratio



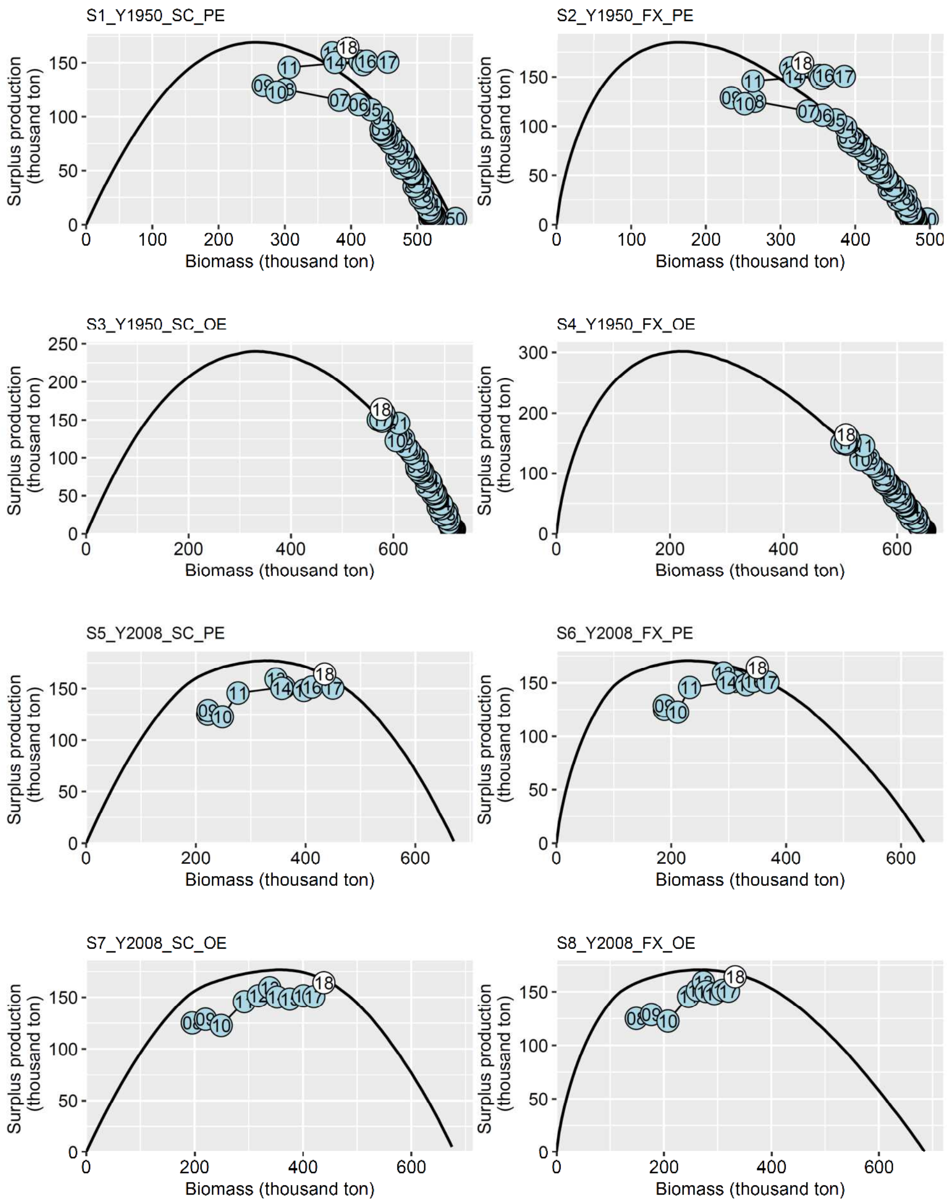
Time series Fratio



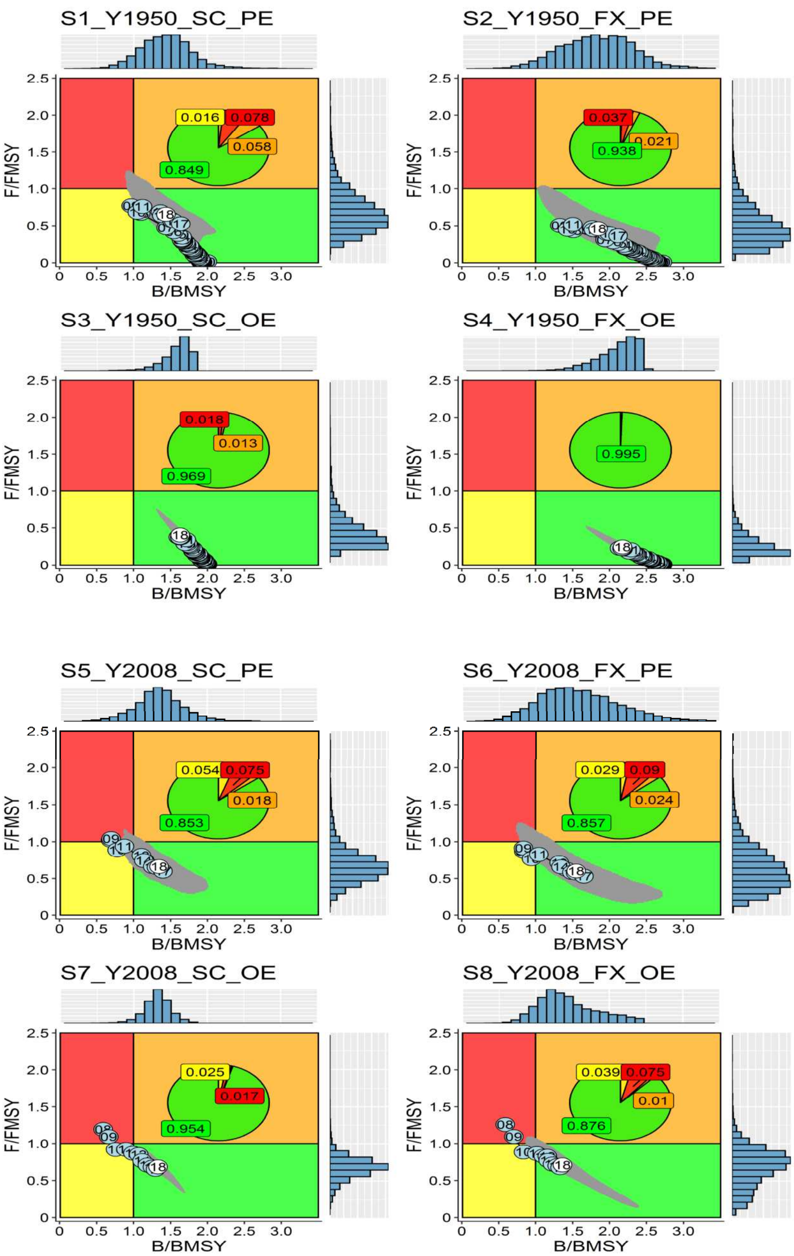
Time series B/K



Production curve



Kobe plot


S1_Y1950_SC_PE
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0.058
0.849
S2_Y1950_FX_PE
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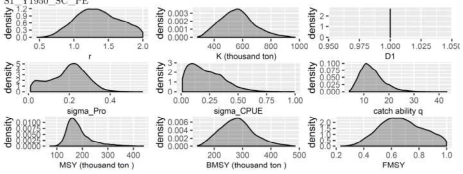
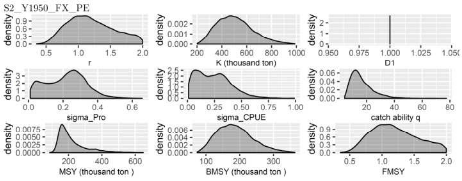
0.021
0.938
S3_Y1950_SC_OE
0.018
0.013
0.969
S4_Y1950_FX_OE
0.995
S5_Y2008_SC_PE
0.054
0.075
0.018
0.853
S6_Y2008_FX_PE
0.029
0.09
0.024
0.857
S7_Y2008_SC_OE
0.025
0.017
0.954
S8_Y2008_FX_OE
0.039
0.075
0.01
0.876
F/FMSY
B/BMSY

Posterior distributions

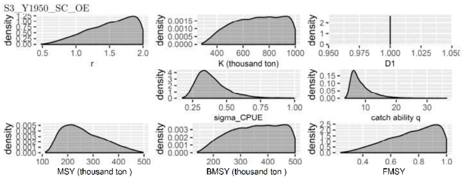
S1_Y1950_SC_PE



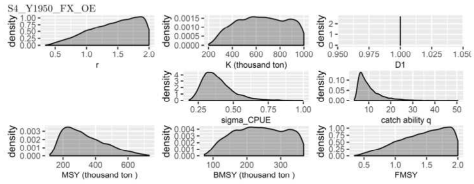
S2_Y1950_FX_PE



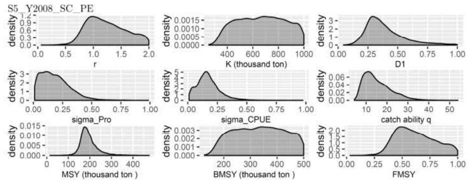
S3_Y1950_SC_OE



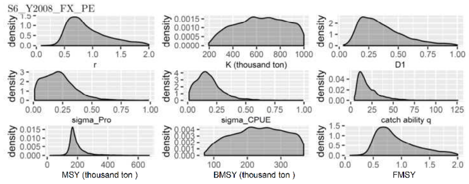
S4_Y1950_FX_OE



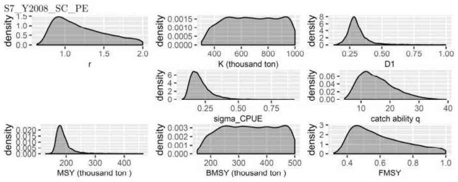
S5_Y2008_SC_PE



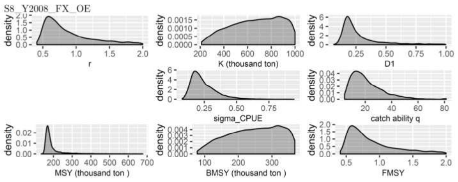
S6_Y2008_FX_PE



S7_Y2008_SC_PE



S8_Y2008_FX_OE



Appendix A-2. Results of BDM-CPUE for longtail tuna

S1_Y1995_SC_PE

	Mean	Median	Lower10th	Upper10th
r	1.421	1.423	0.967	1.874
K (thousand ton)	598.2	586.9	425.2	798.4
D1	1.00	1.00	1.00	1.00
sigma_Pro	0.14	0.13	0.03	0.27
sigma_CPUE	0.37	0.36	0.20	0.56
q	15.72	14.46	9.10	24.05
FMSY	0.71	0.71	0.48	0.94
BMSY (thousand ton)	299.1	293.5	212.6	399.2
MSY (thousand ton)	208.8	195.1	142.4	297.4

S2_Y1995_FX_PE

	Mean	Median	Lower10th	Upper10th
r	1.251	1.219	0.824	1.766
K (thousand ton)	528.9	508.6	352.5	738.1
D1	1.00	1.00	1.00	1.00
sigma_Pro	0.17	0.15	0.02	0.35
sigma_CPUE	0.39	0.36	0.14	0.69
q	20.10	18.29	9.99	32.06
FMSY	1.25	1.22	0.82	1.77
BMSY (thousand ton)	194.6	187.1	129.7	271.5
MSY (thousand ton)	239.3	210.6	151.8	374.2

S3_Y1995_SC_OE

	Mean	Median	Lower10th	Upper10th
r	1.450	1.494	0.918	1.905
K (thousand ton)	714.9	725.4	466.1	945.1
D1	1.00	1.00	1.00	1.00
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.43	0.41	0.30	0.59
q	11.93	10.50	7.22	18.82
FMSY	0.72	0.75	0.46	0.95
BMSY (thousand ton)	357.4	362.7	233.0	472.5
MSY (thousand ton)	253.6	239.3	159.8	371.4

S4_Y1995_FX_OE

	Mean	Median	Lower10th	Upper10th
r	1.396	1.446	0.819	1.893
K (thousand ton)	658.2	662.2	380.2	930.4
D1	1.00	1.00	1.00	1.00
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.43	0.41	0.30	0.59
q	14.08	11.69	7.44	24.01
FMSY	1.40	1.45	0.82	1.89
BMSY (thousand ton)	242.1	243.6	139.9	342.3
MSY (thousand ton)	328.6	303.3	182.5	517.4

S5_Y2008_SC_PE

	Mean	Median	Lower10th	Upper10th
r	1.361	1.375	0.854	1.854
K (thousand ton)	654.1	649.5	416.9	903.0
D1	0.46	0.43	0.25	0.72
sigma_Pro	0.24	0.21	0.05	0.45
sigma_CPUE	0.27	0.26	0.11	0.44
q	17.86	15.75	9.67	29.10
FMSY	0.68	0.69	0.43	0.93
BMSY (thousand ton)	327.1	324.8	208.5	451.5
MSY (thousand ton)	213.6	201.5	148.8	302.9

S6_Y2008_FX_PE

	Mean	Median	Lower10th	Upper10th
r	1.088	1.041	0.606	1.671
K (thousand ton)	603.6	599.8	330.8	884.5
D1	0.42	0.39	0.19	0.72
sigma_Pro	0.26	0.24	0.06	0.48
sigma_CPUE	0.27	0.26	0.09	0.46
q	23.97	18.90	10.29	44.62
FMSY	1.09	1.04	0.61	1.67
BMSY (thousand ton)	222.1	220.6	121.7	325.4
MSY (thousand ton)	223.7	199.8	151.2	334.4

S7_Y2008_SC_OE

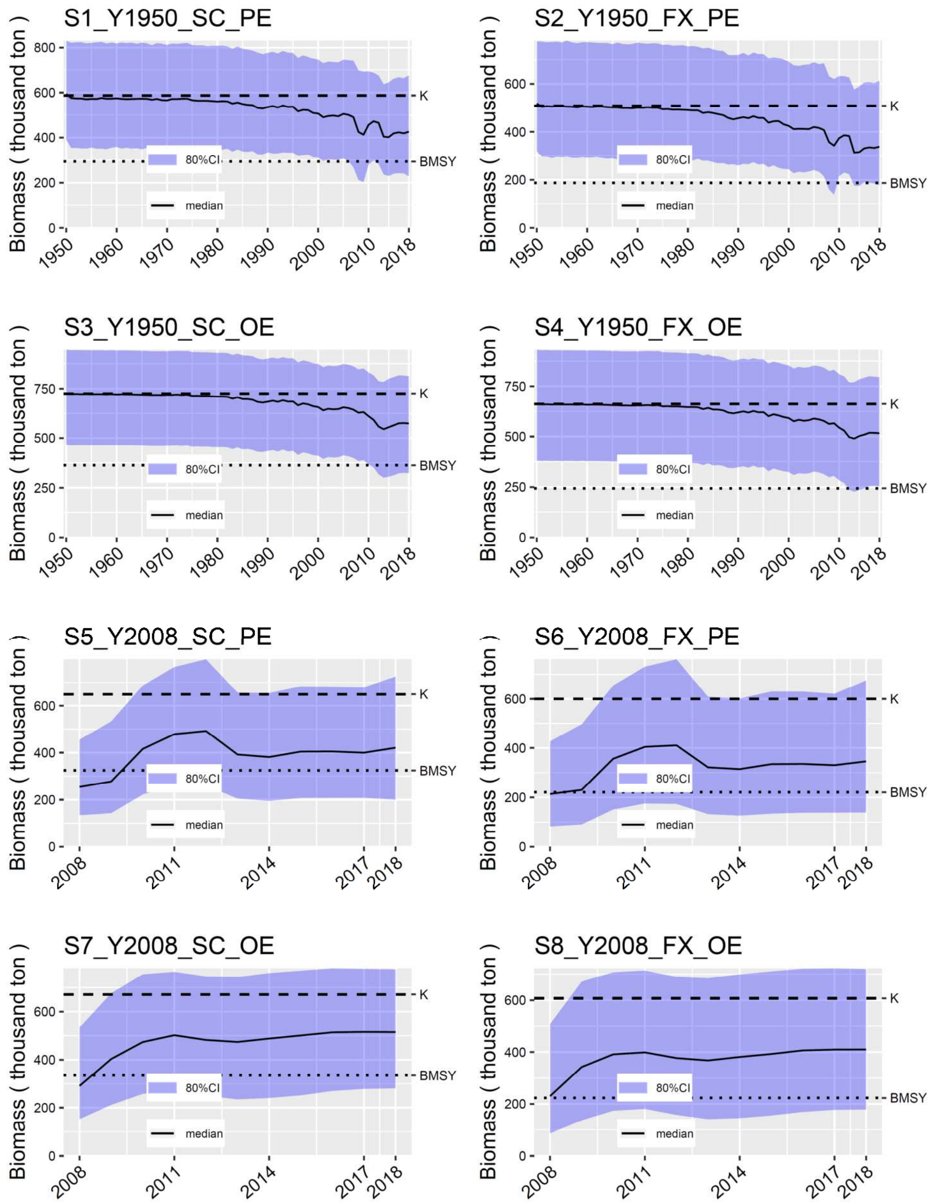
	Mean	Median	Lower10th	Upper10th
r	1.441	1.468	0.928	1.893
K (thousand ton)	673.3	671.0	425.5	928.0
D1	0.47	0.43	0.31	0.70
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.35	0.33	0.24	0.49
q	15.22	13.35	8.48	24.92
FMSY	0.72	0.73	0.46	0.95
BMSY (thousand ton)	336.7	335.5	212.7	464.0
MSY (thousand ton)	234.6	217.3	162.3	335.8

S8_Y2008_FX_OE

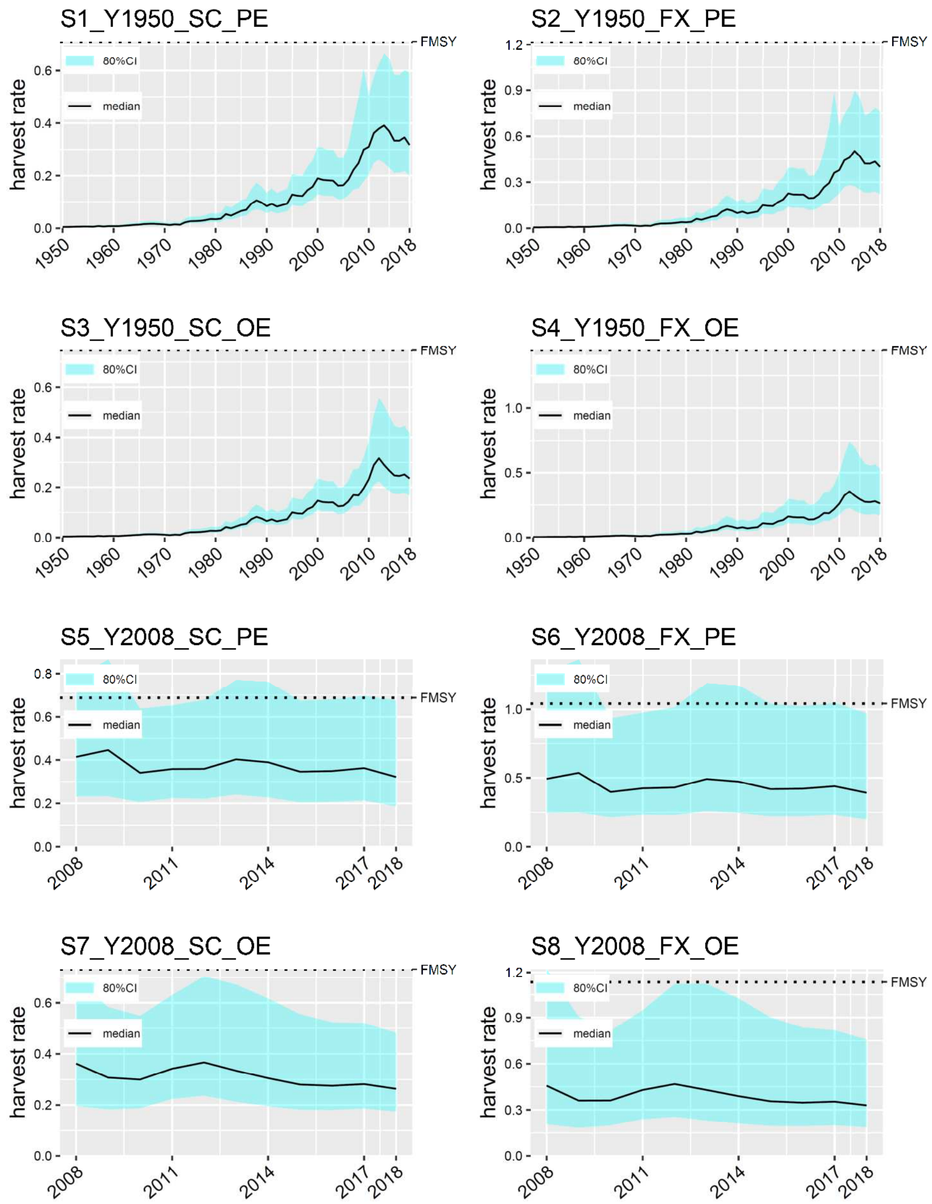
	Mean	Median	Lower10th	Upper10th
r	1.167	1.132	0.669	1.730
K (thousand ton)	617.7	607.3	339.2	906.3
D1	0.42	0.37	0.21	0.72
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.36	0.34	0.25	0.51
q	21.34	16.53	8.99	40.91
FMSY	1.17	1.13	0.67	1.73
BMSY (thousand ton)	227.2	223.4	124.8	333.4
MSY (thousand ton)	250.3	218.1	159.7	392.4

Time series plot

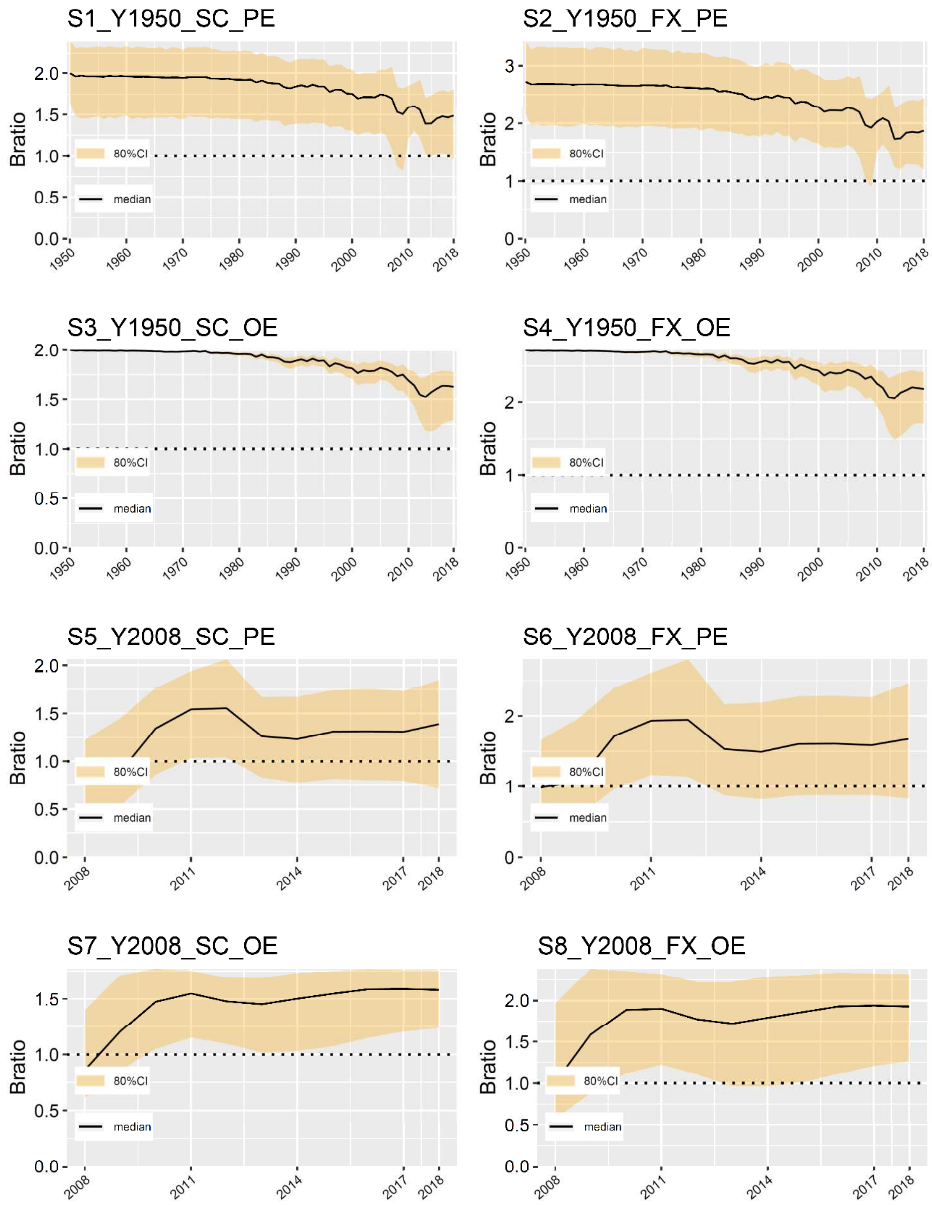
Time series Biomass



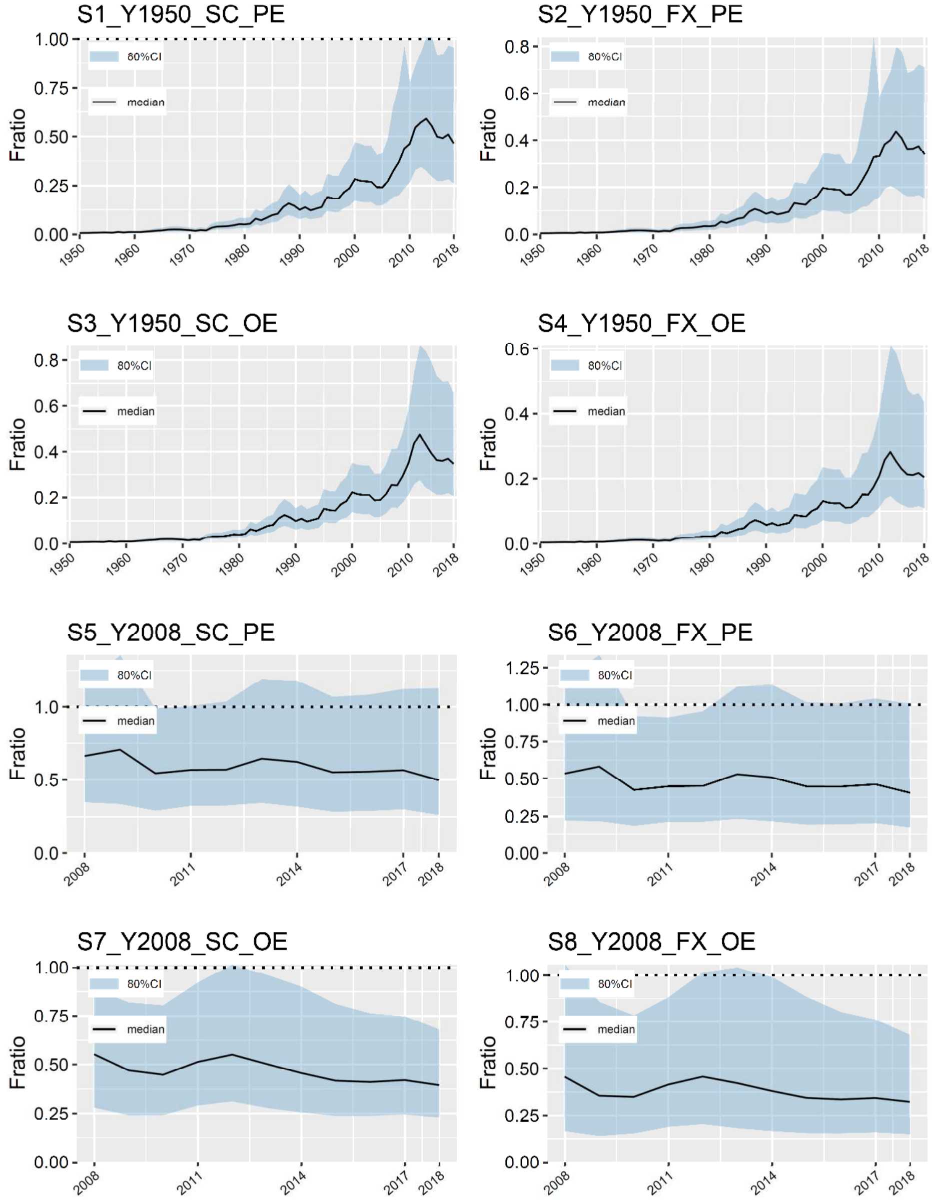
Time series Harvest rate



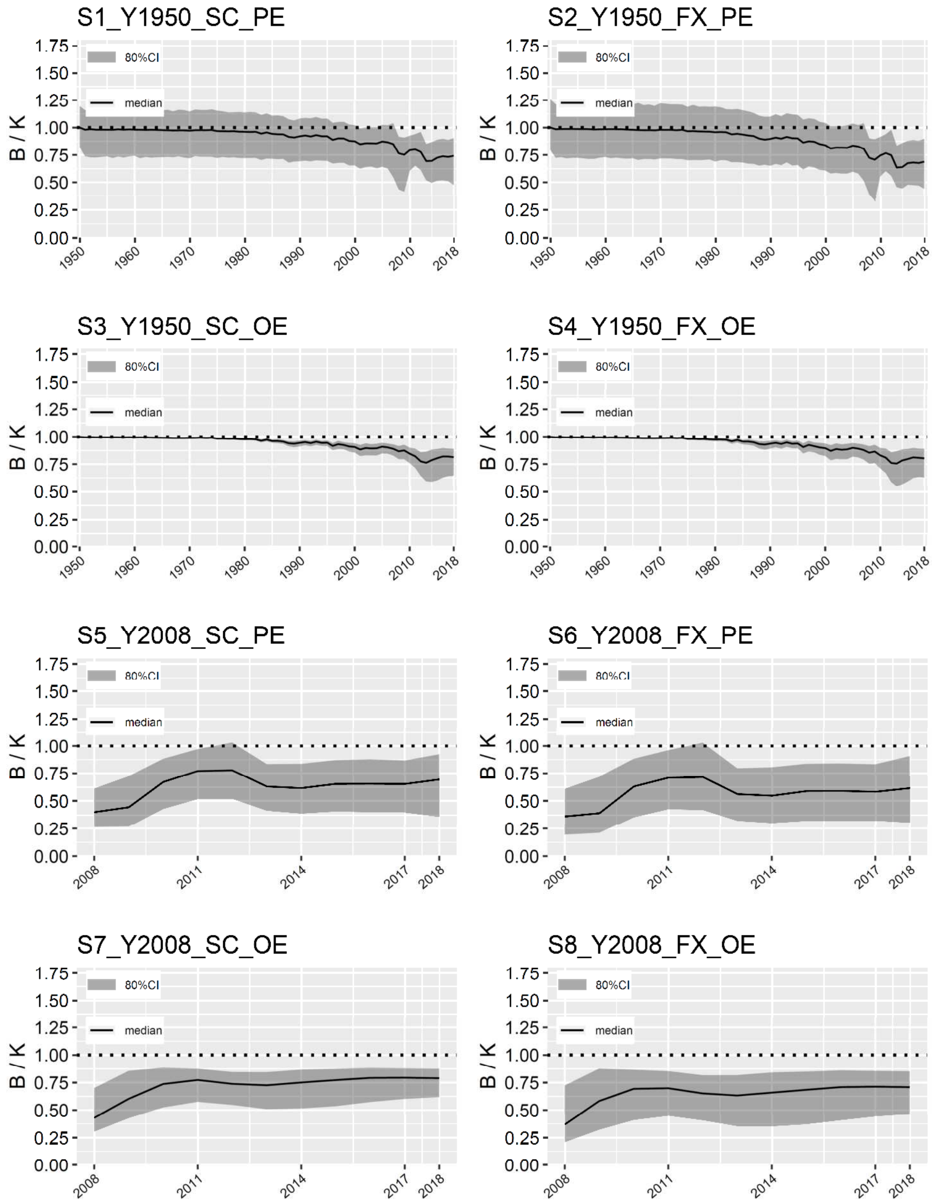
Time series Bratio



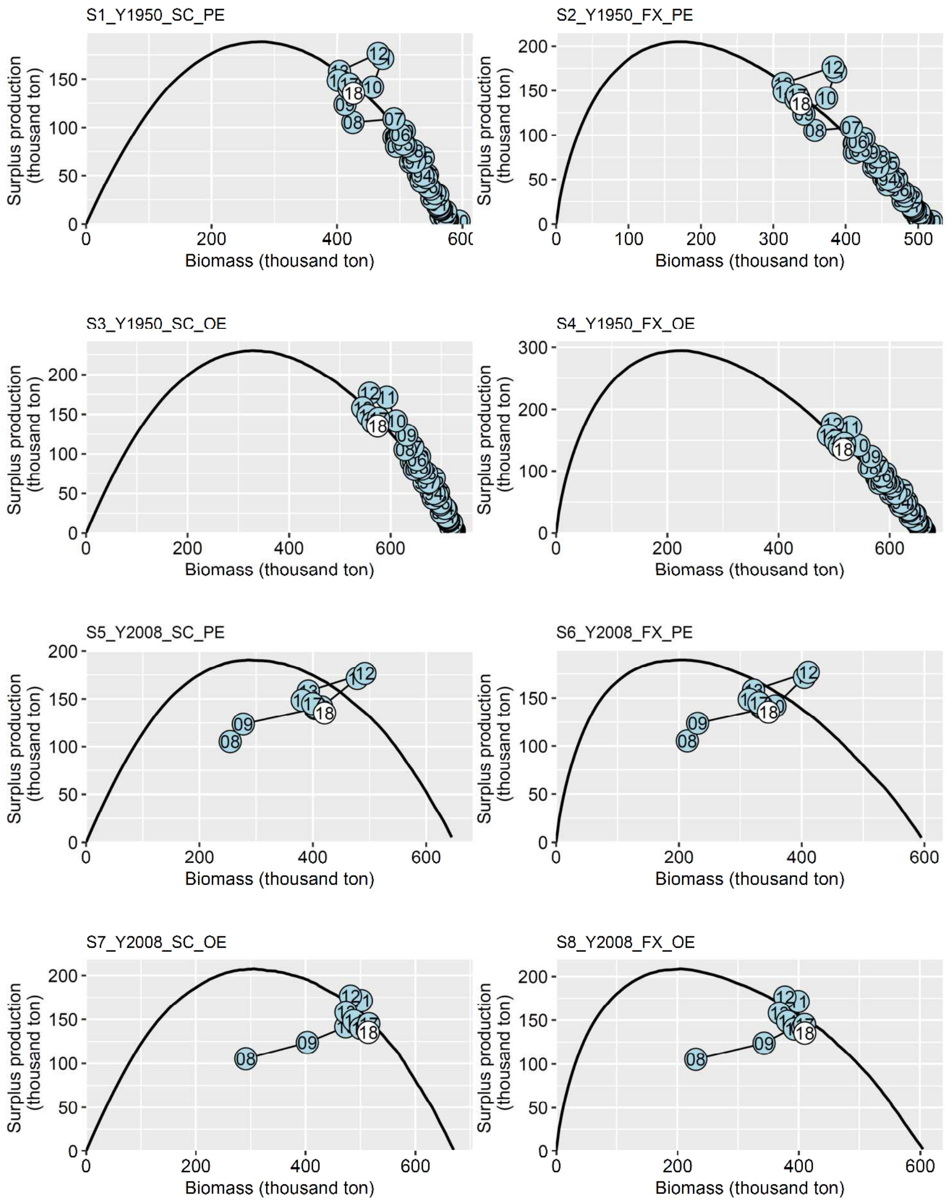
Time series Fratio



Time series B/K

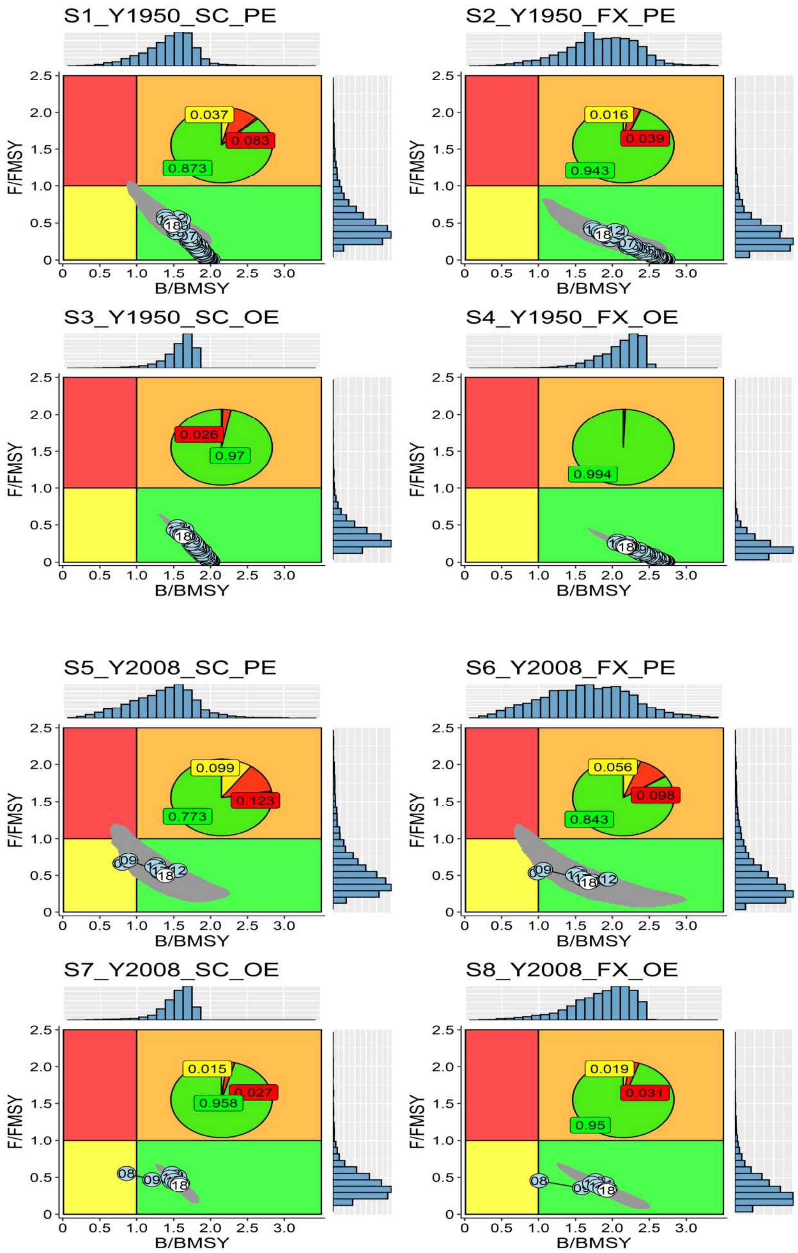


5 Production curve



15

Kobe plot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0.873
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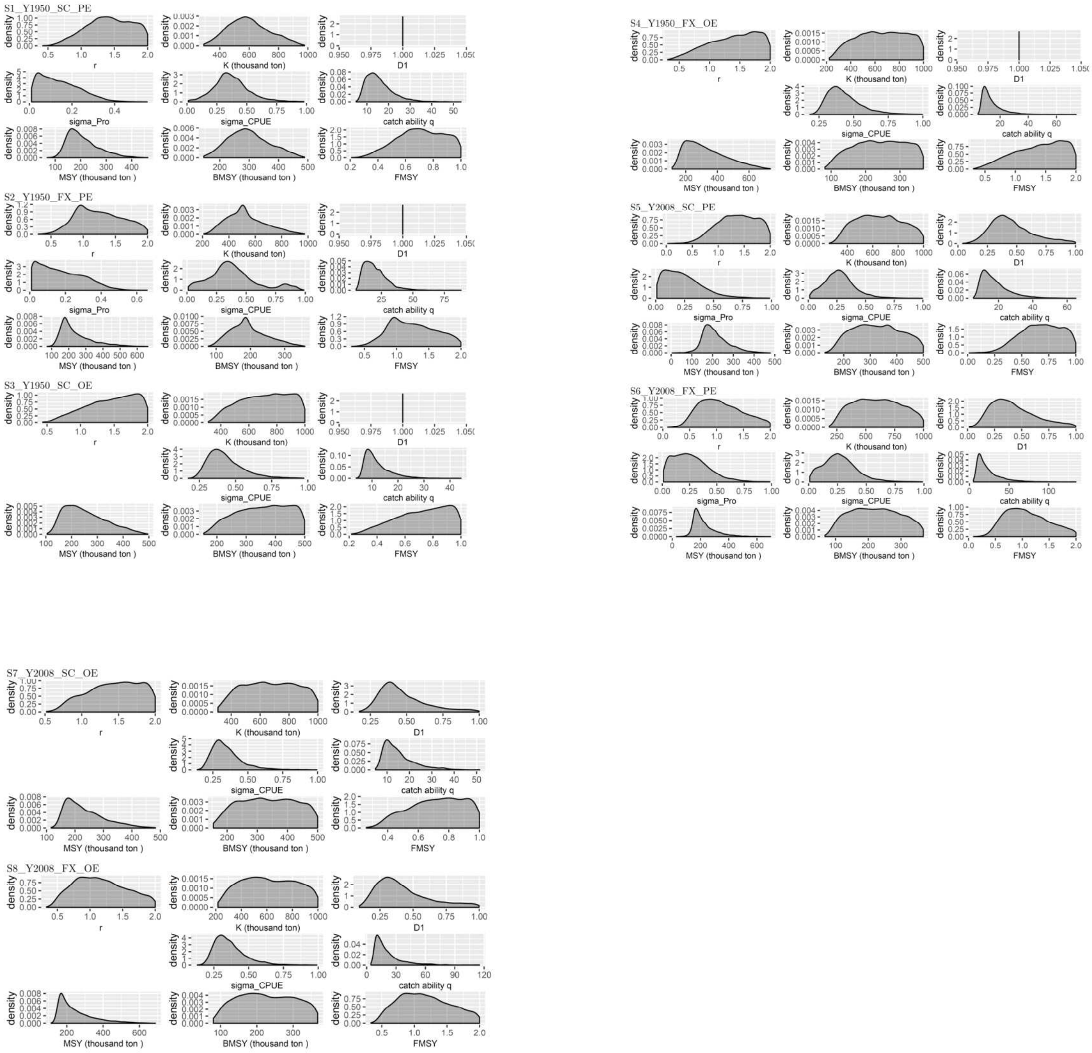
0.016
0.039
0.943
S3_Y1950_SC_OE
0.026
0.97
S4_Y1950_FX_OE
0.994
S5_Y2008_SC_PE
0.099
0.123
0.773
S6_Y2008_FX_PE
0.056
0.098
0.843
S7_Y2008_SC_OE
0.015
0.027
0.958
S8_Y2008_FX_OE
0.019
0.031
0.95
F/FMSY
B/BMSY

Posterior distributions



Appendix A-3. Results of BDM-CPUE for Spanish mackerel

S1_Y1995_SC_PE

	Mean	Median	Lower10th	Upper10th
r	1.558	1.490	1.047	2.194
K (thousand ton)	555.5	555.2	410.6	701.3
D1	1.00	1.00	1.00	1.00
sigma_Pro	0.20	0.22	0.06	0.30
sigma_CPUE	0.18	0.11	0.02	0.43
q	12.13	10.71	6.22	20.26
FMSY	0.78	0.75	0.52	1.10
BMSY (thousand ton)	277.7	277.6	205.3	350.7
MSY (thousand ton)	210.1	195.7	155.2	285.3

S2_Y1995_FX_PE

	Mean	Median	Lower10th	Upper10th
r	1.281	1.181	0.763	2.066
K (thousand ton)	509.2	502.3	325.0	708.6
D1	1.00	1.00	1.00	1.00
sigma_Pro	0.23	0.24	0.04	0.38
sigma_CPUE	0.24	0.19	0.03	0.51
q	13.59	11.43	5.93	24.83
FMSY	1.28	1.18	0.76	2.07
BMSY (thousand ton)	187.3	184.8	119.6	260.7
MSY (thousand ton)	228.8	192.3	155.5	365.1

S3_Y1995_SC_OE

	Mean	Median	Lower10th	Upper10th
r	2.917	2.901	2.882	2.955
K (thousand ton)	342.6	347.2	274.2	402.5
D1	1.00	1.00	1.00	1.00
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.36	0.38	0.29	0.41
q	12.92	11.75	9.61	17.81
FMSY	1.46	1.45	1.44	1.48
BMSY (thousand ton)	171.3	173.6	137.1	201.3
MSY (thousand ton)	249.9	256.3	196.0	291.2

S4_Y1995_FX_OE

	Mean	Median	Lower10th	Upper10th
r	2.364	2.664	1.461	2.706
K (thousand ton)	544.4	627.2	288.3	770.5
D1	1.00	1.00	1.00	1.00
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.33	0.30	0.25	0.47
q	7.14	6.32	0.18	14.28
FMSY	2.36	2.66	1.46	2.71
BMSY (thousand ton)	200.3	230.7	106.1	283.5
MSY (thousand ton)	457.8	351.4	260.4	696.5

S5_Y2008_SC_PE

	Mean	Median	Lower10th	Upper10th
r	1.455	1.333	0.947	2.172
K (thousand ton)	686.3	704.4	397.2	941.7
D1	0.26	0.23	0.15	0.40
sigma_Pro	0.17	0.15	0.05	0.29
sigma_CPUE	0.10	0.08	0.03	0.17
q	15.90	14.42	8.12	25.79
FMSY	0.73	0.67	0.47	1.09
BMSY (thousand ton)	343.2	352.2	198.6	470.8
MSY (thousand ton)	229.9	221.6	185.5	284.5

S6_Y2008_FX_PE

	Mean	Median	Lower10th	Upper10th
r	0.928	0.791	0.572	1.507
K (thousand ton)	706.7	729.4	430.2	946.6
D1	0.26	0.21	0.09	0.50
sigma_Pro	0.21	0.20	0.07	0.35
sigma_CPUE	0.11	0.08	0.02	0.25
q	19.39	15.88	7.10	36.06
FMSY	0.93	0.79	0.57	1.51
BMSY (thousand ton)	260.0	268.3	158.3	348.2
MSY (thousand ton)	219.4	203.8	171.8	273.3

S7_Y2008_SC_OE

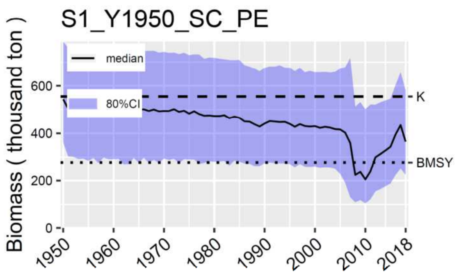
	Mean	Median	Lower10th	Upper10th
r	1.393	1.306	1.015	1.869
K (thousand ton)	722.7	750.0	457.8	947.2
D1	0.20	0.19	0.15	0.25
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.14	0.12	0.08	0.21
q	15.72	15.33	9.95	21.64
FMSY	0.70	0.65	0.51	0.93
BMSY (thousand ton)	361.4	375.0	228.9	473.6
MSY (thousand ton)	236.7	229.9	201.1	278.5

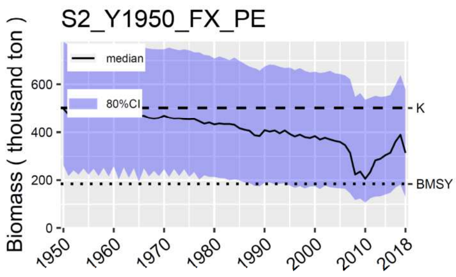
S8_Y2008_FX_OE

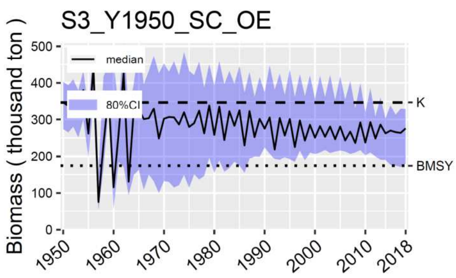
	Mean	Median	Lower10th	Upper10th
r	0.963	0.786	0.605	1.735
K (thousand ton)	747.7	785.7	480.5	958.4
D1	0.21	0.12	0.08	0.52
sigma_Pro	NA	NA	NA	NA
sigma_CPUE	0.22	0.18	0.10	0.41
q	19.65	19.84	6.82	31.77
FMSY	0.96	0.79	0.61	1.74
BMSY (thousand ton)	275.1	289.0	176.8	352.6
MSY (thousand ton)	243.2	216.7	189.5	320.6

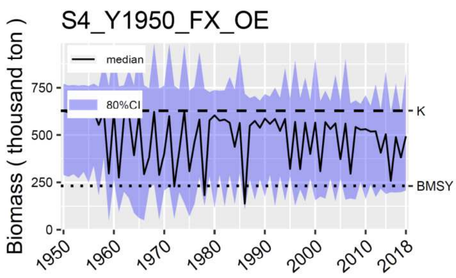
1 Time series plot

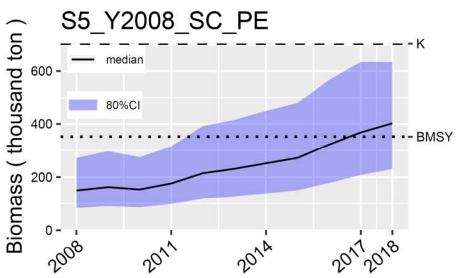
1.1 Time series Biomass

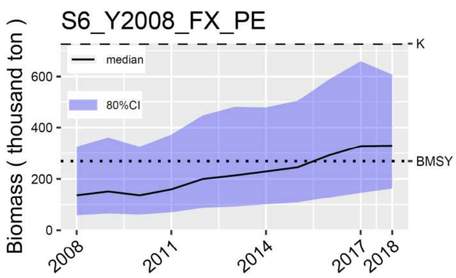


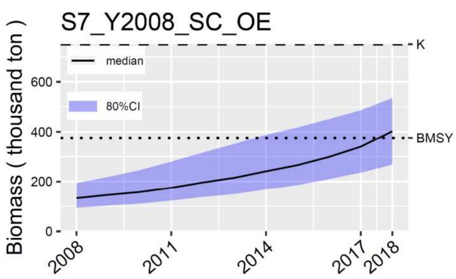


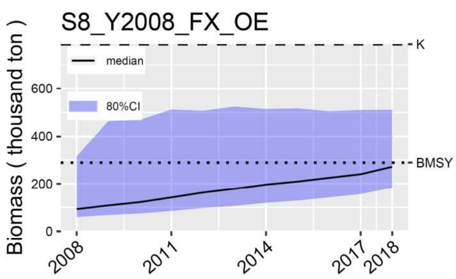




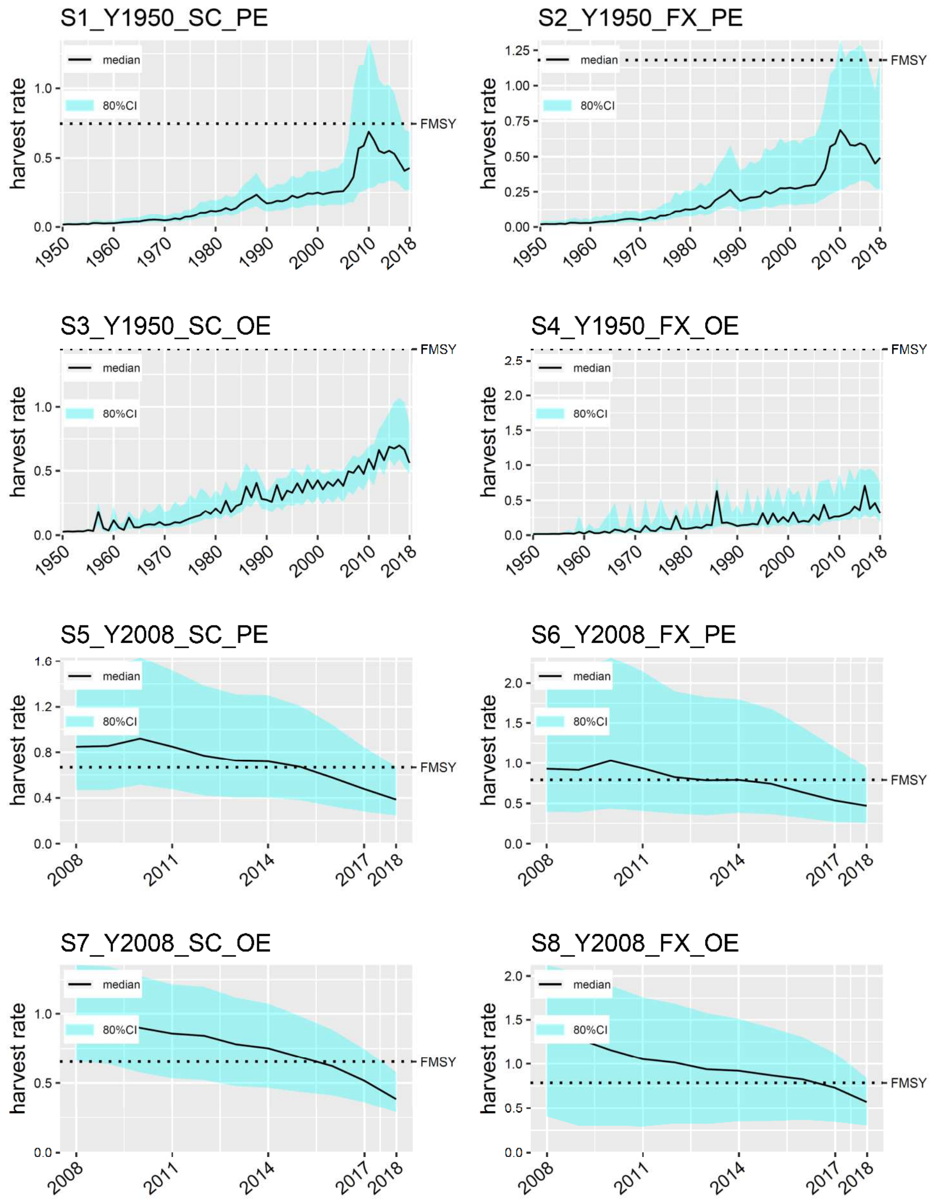




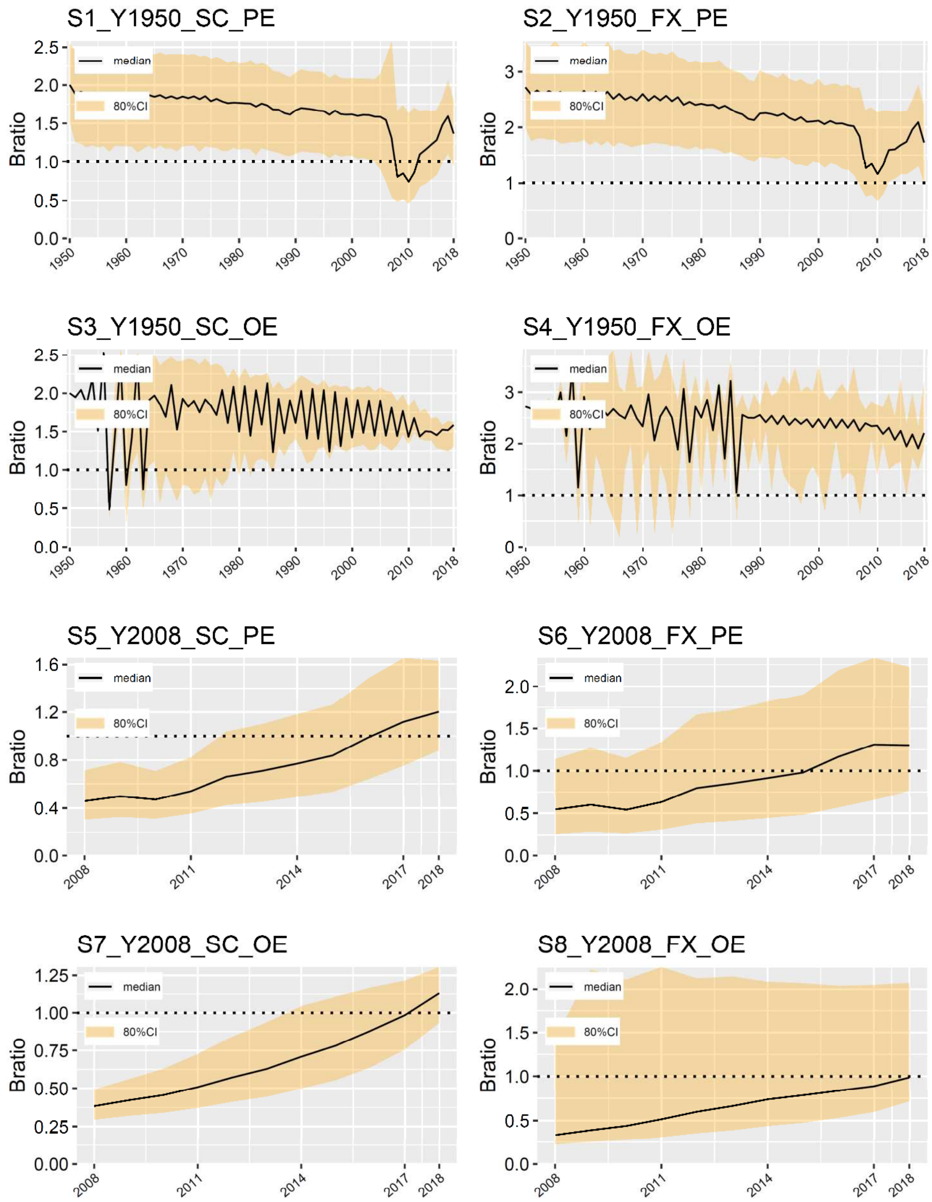




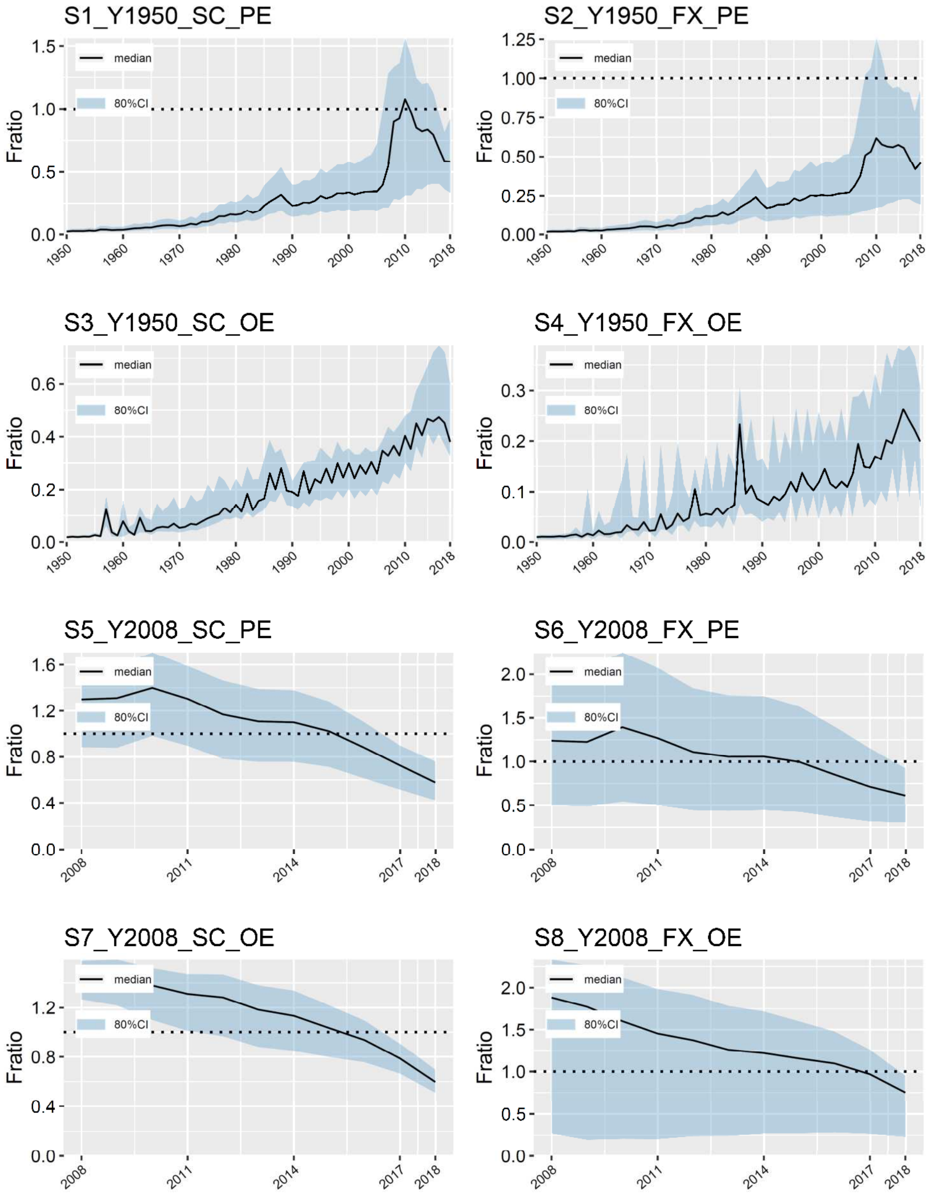
1.2 Time series Harvest rate



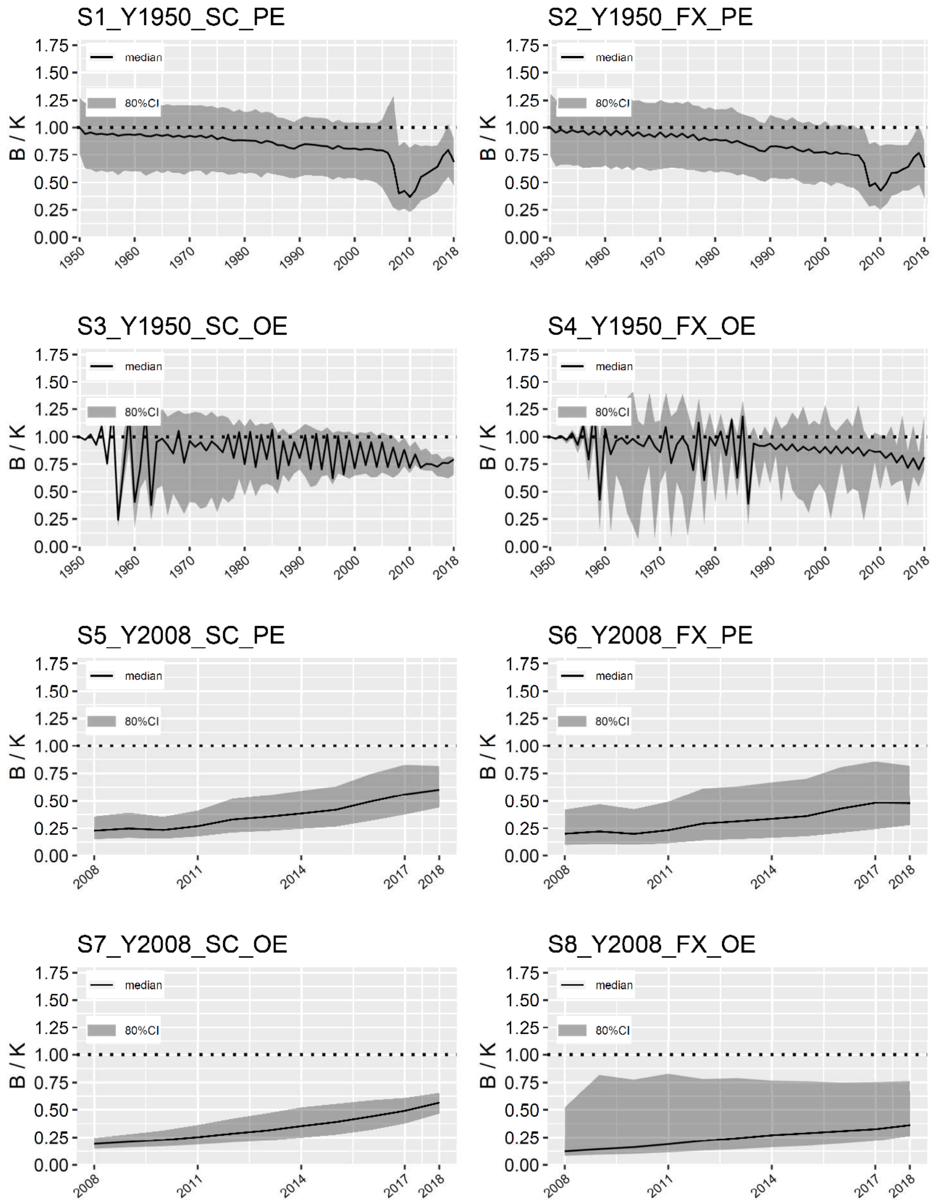
1.3 Time series Bratio



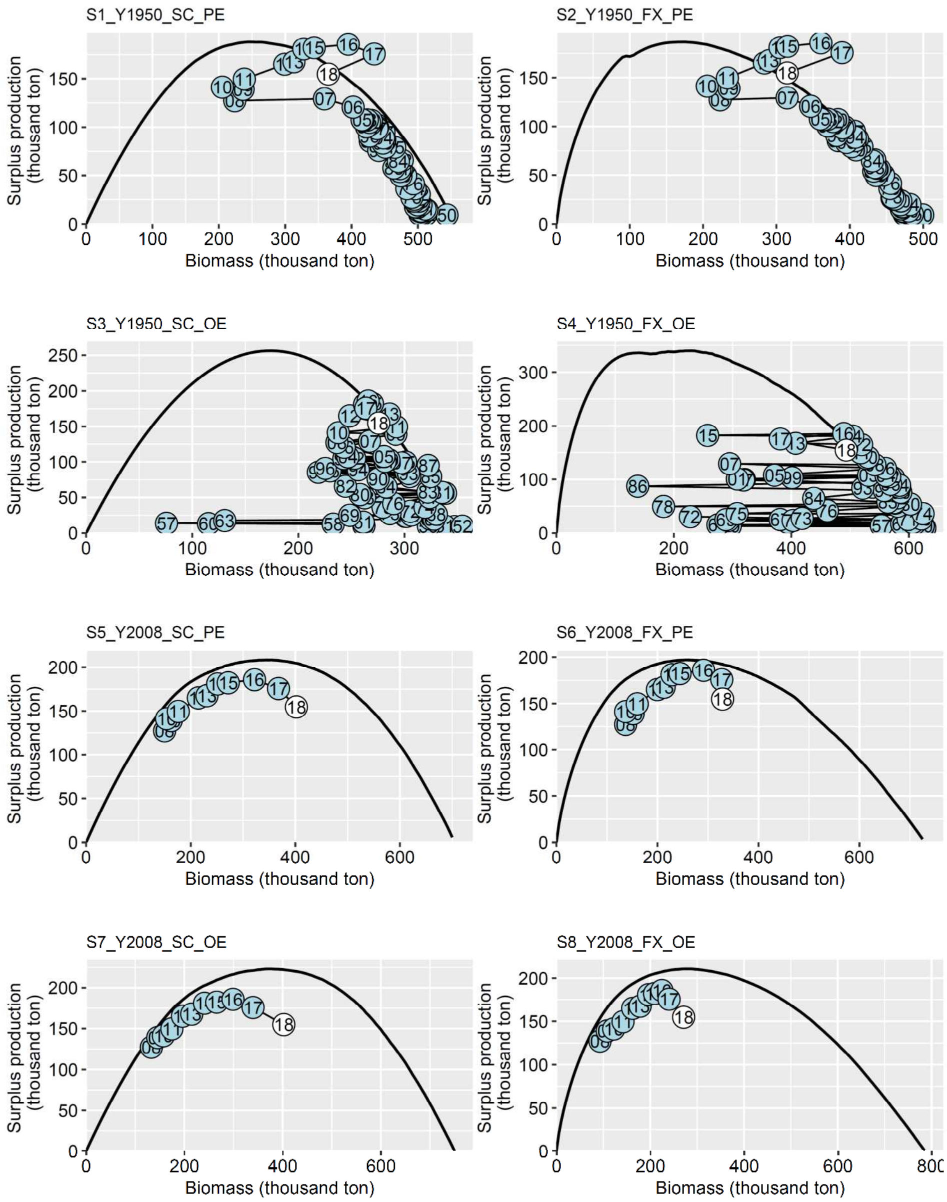
1.4 Time series Fratio



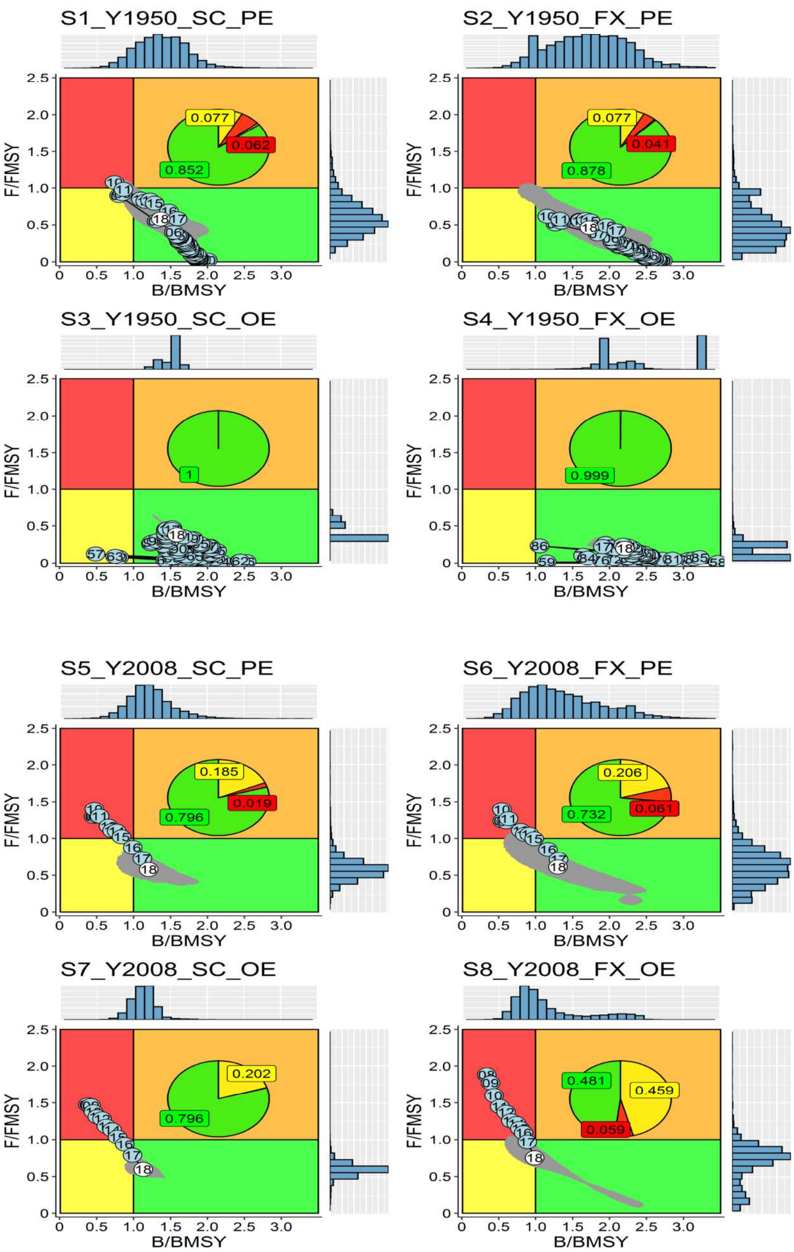
1.5 Time series B/K



5 Production curve

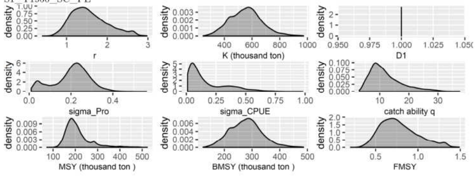


2 Kobe plot

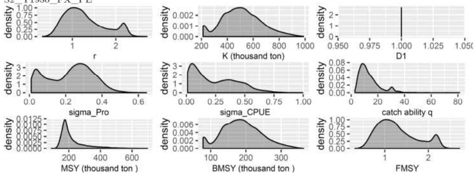

S1_Y1950_SC_PE
0.077
0.062
0.852
S2_Y1950_FX_PE
0.077
0.041
0.878
S3_Y1950_SC_OE
1
S4_Y1950_FX_OE
0.999
S5_Y2008_SC_PE
0.185
0.019
0.796
S6_Y2008_FX_PE
0.206
0.061
0.732
S7_Y2008_SC_OE
0.202
0.796
S8_Y2008_FX_OE
0.481
0.459
0.059
F/FMSY
B/BMSY

4 Posterior distributions

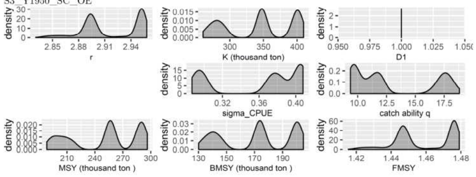
S1_Y1950_SC_PE



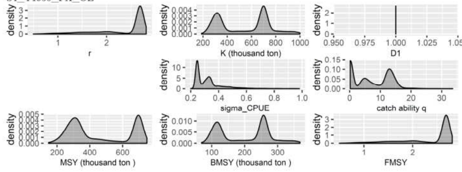
S2_Y1950_FX_PE



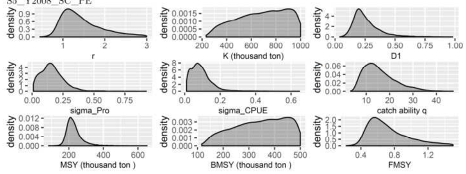
S3_Y1950_SC_OE



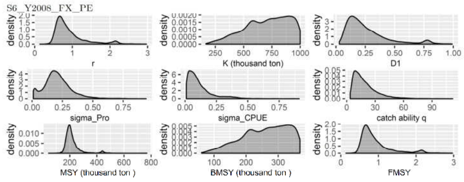
S4_Y1950_FX_OE



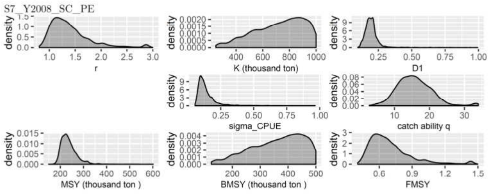
S5_Y2008_SC_PE



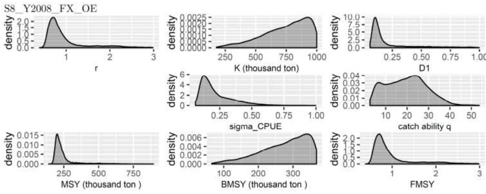
S6_Y2008_FX_PE



S7_Y2008_SC_PE



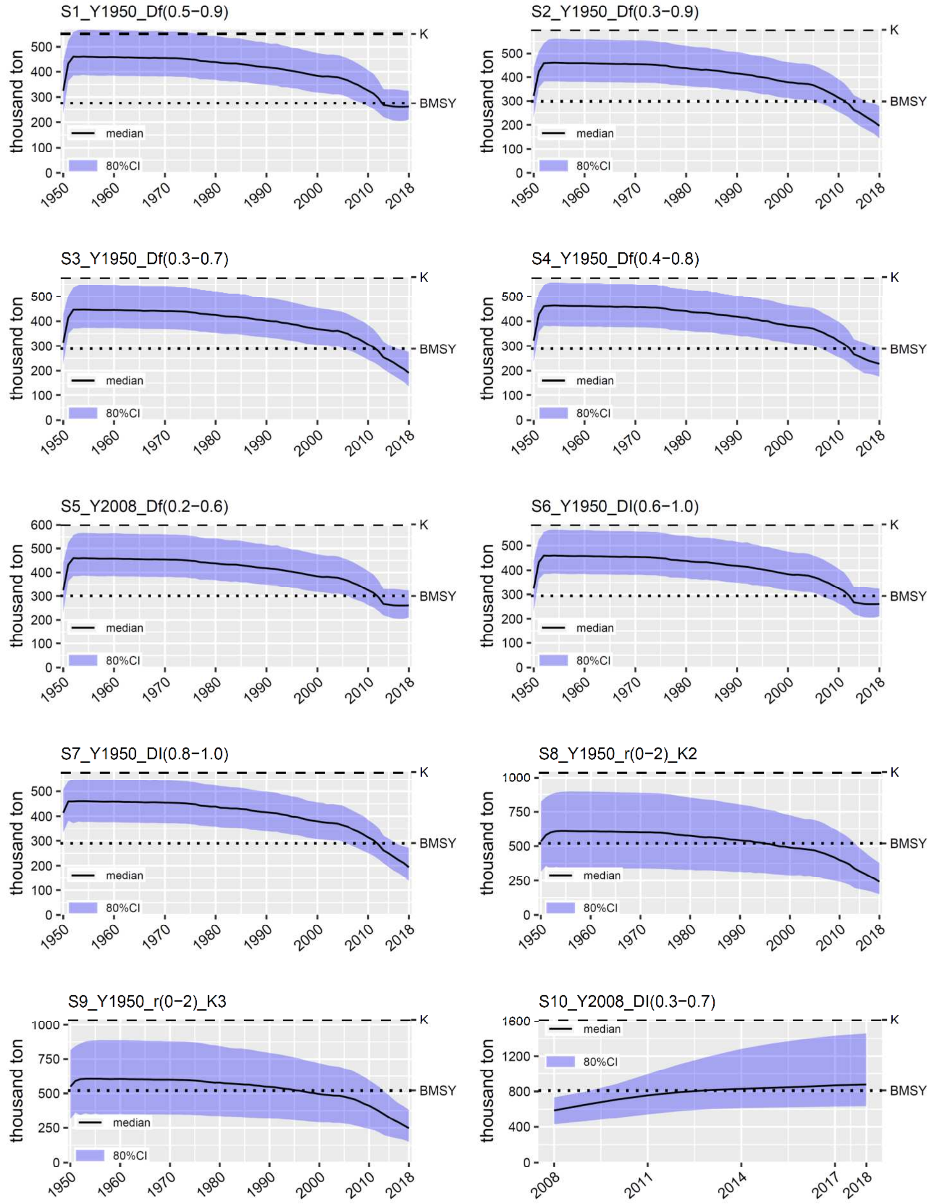
S8_Y2008_FX_OE



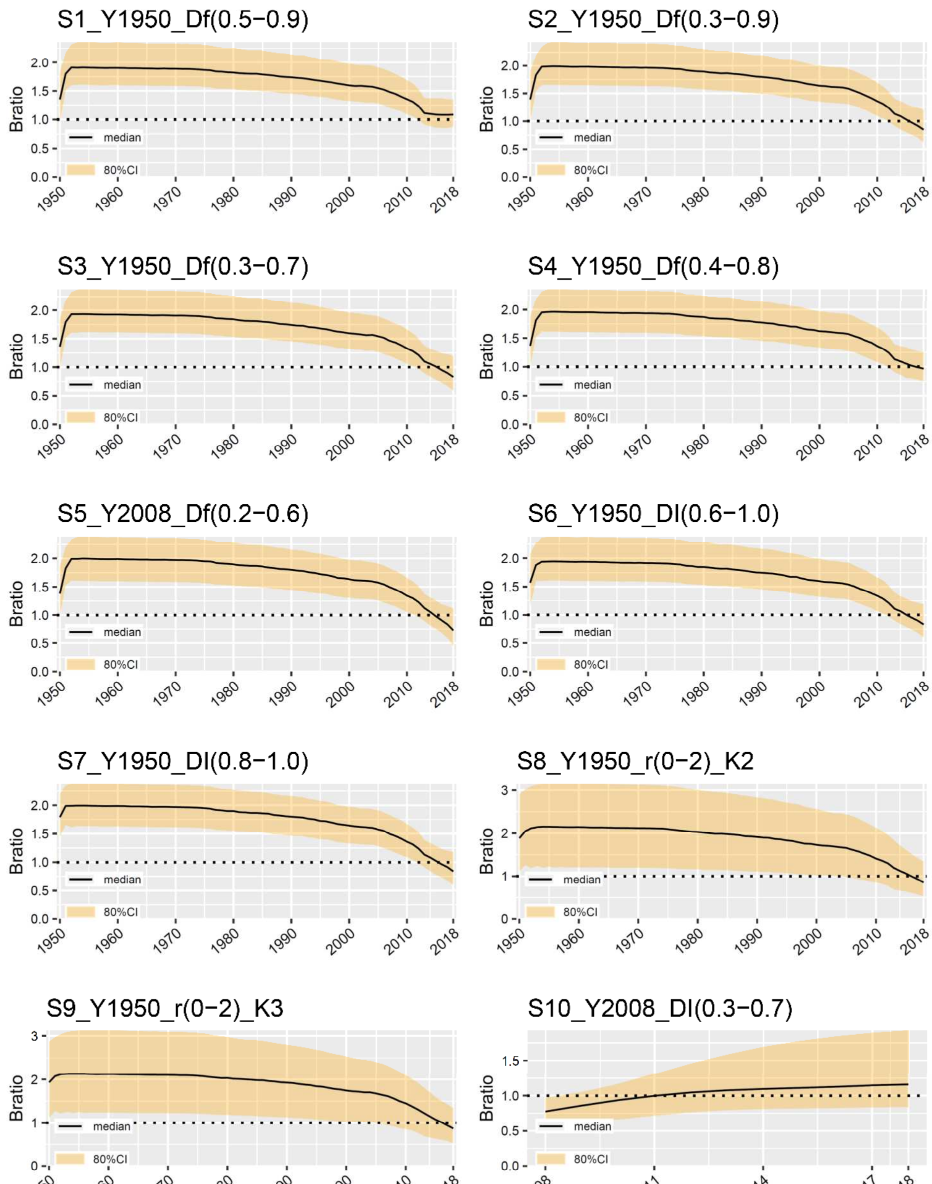
Appendix B-1. Results of BDM-CatchOnly for Kawakawa

Time series plot

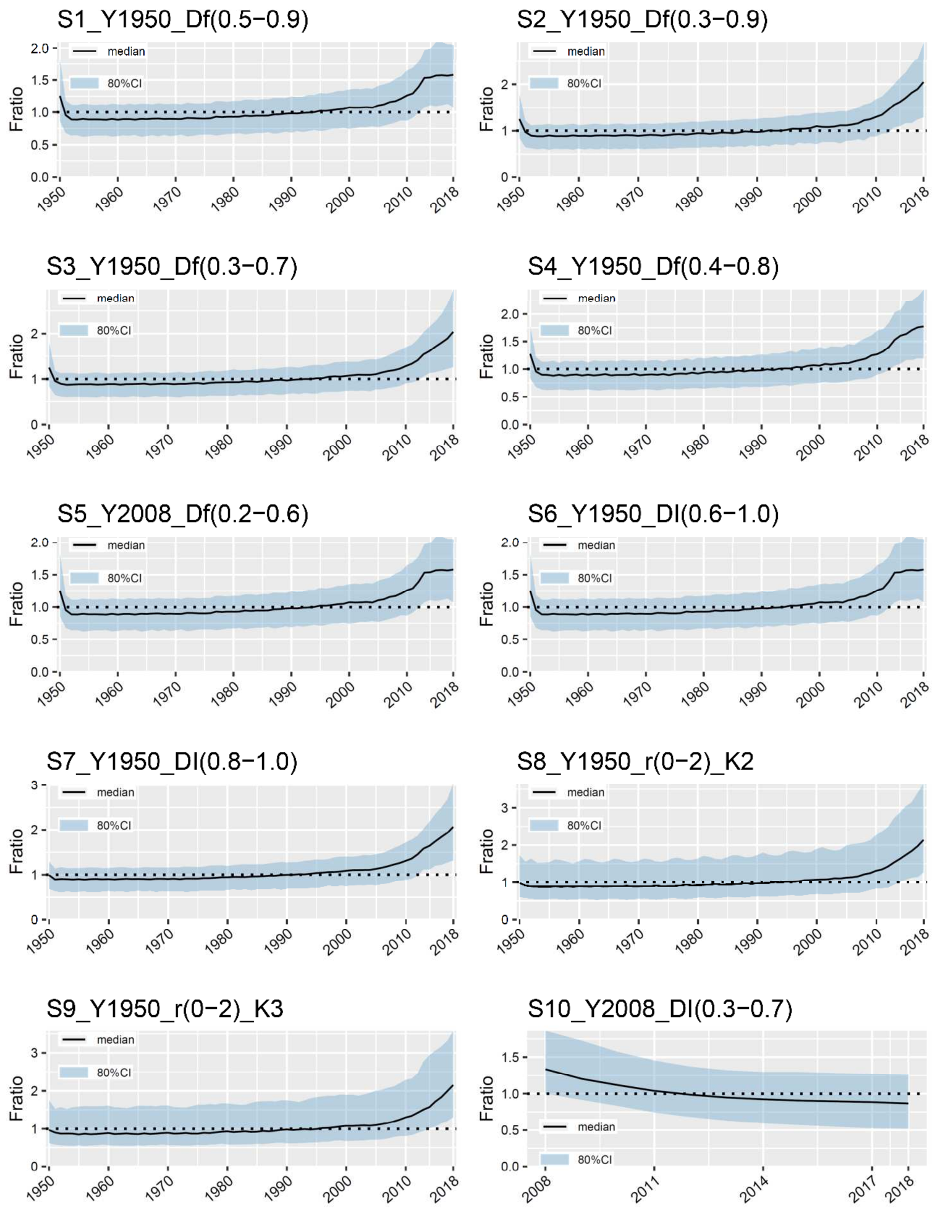
Time series Biomass



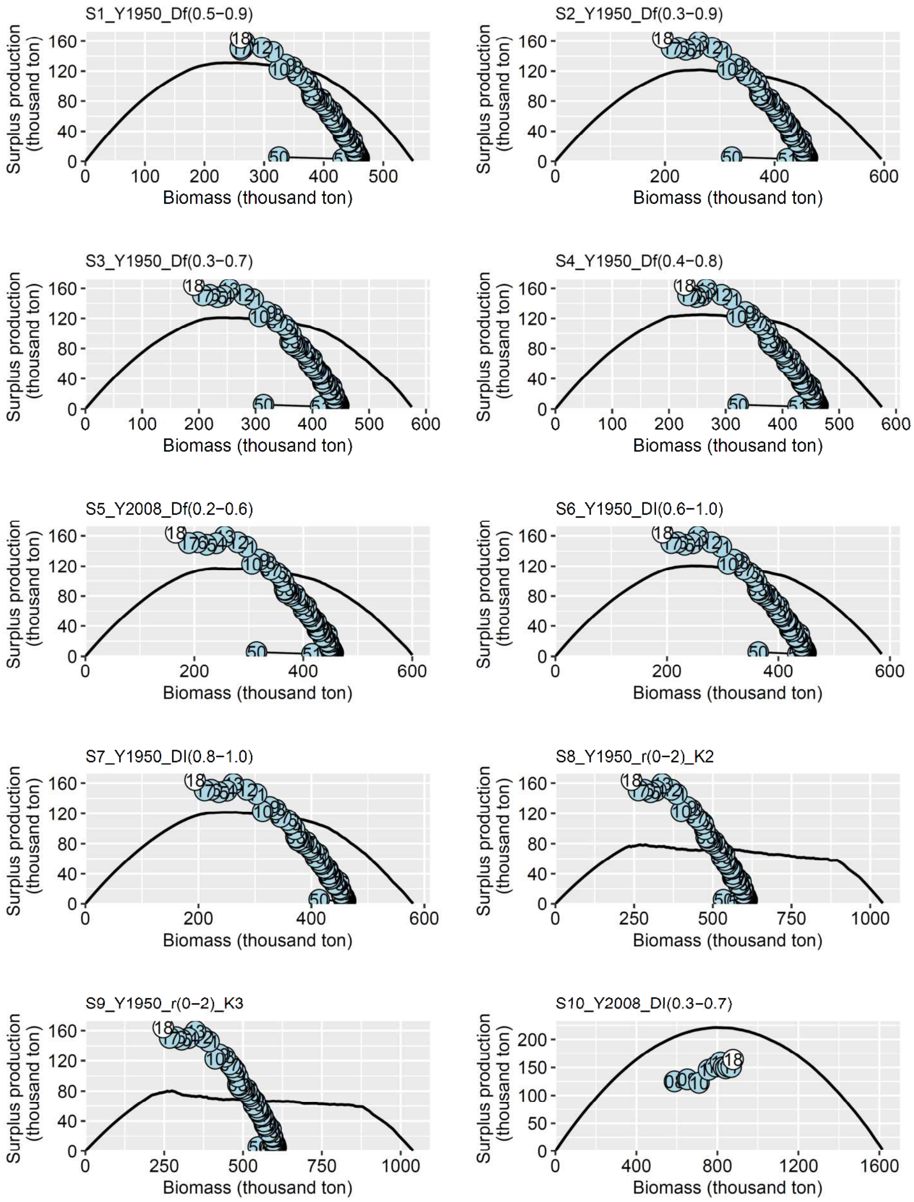
Time series Bratio



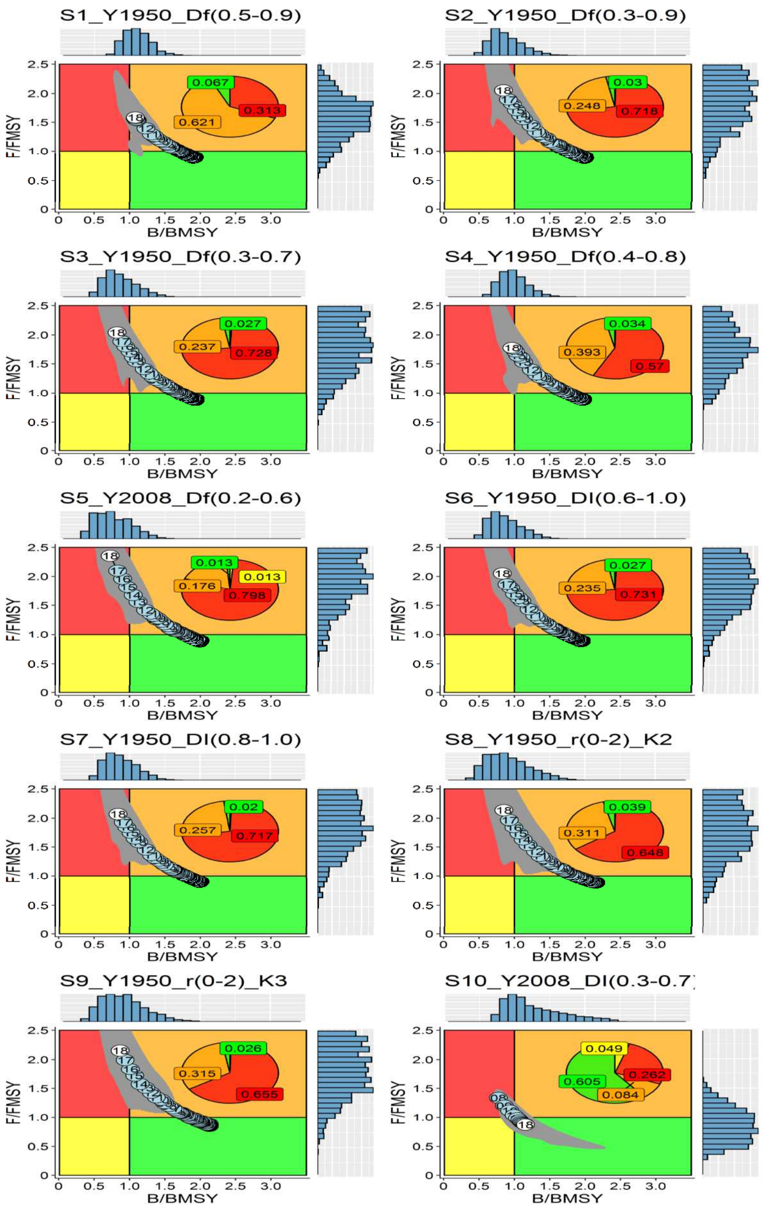
Time series Fratio



Production curve



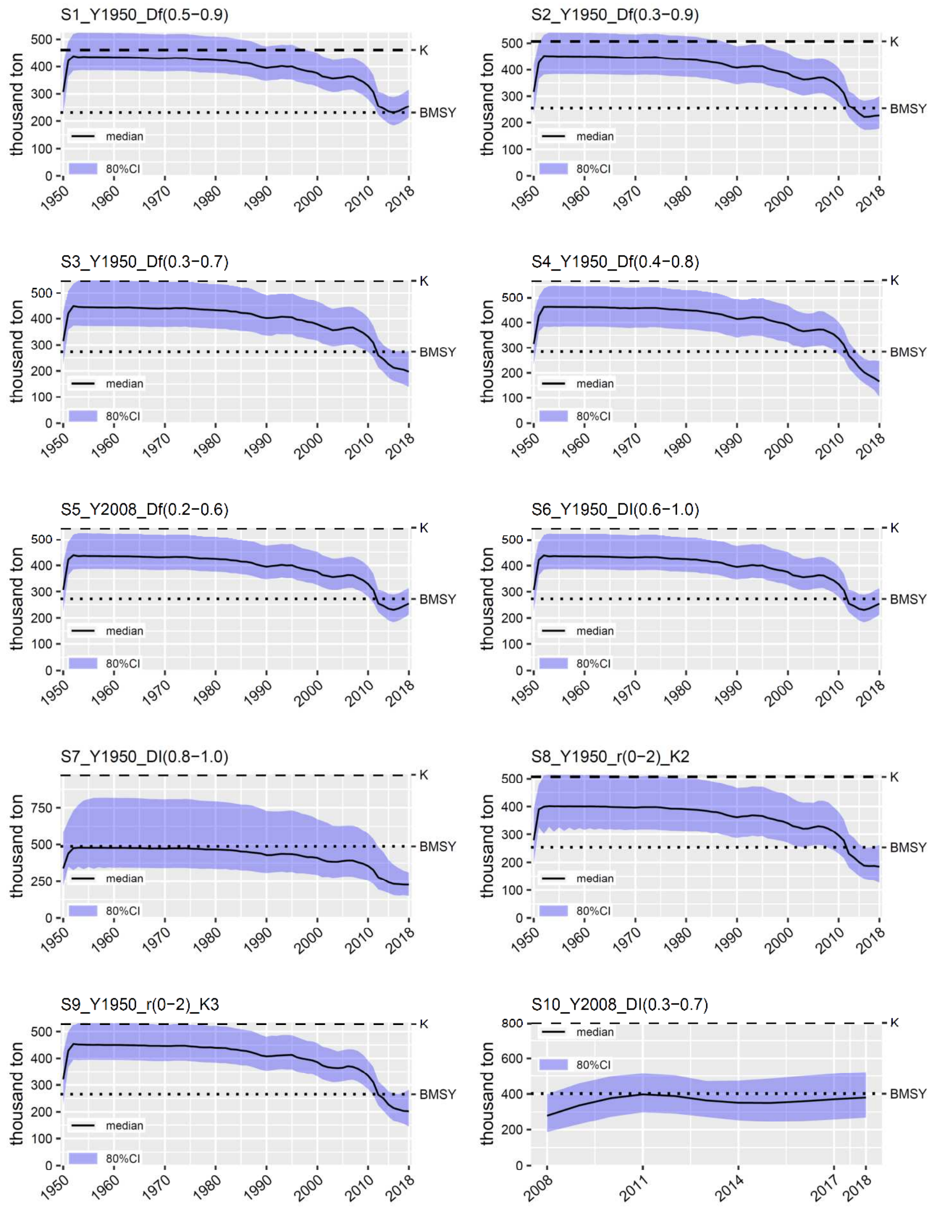
Kobe plot


S1_Y1950_Df(0.5-0.9)
S2_Y1950_Df(0.3-0.9)
S3_Y1950_Df(0.3-0.7)
S4_Y1950_Df(0.4-0.8)
S5_Y2008_Df(0.2-0.6)
S6_Y1950_Dl(0.6-1.0)
S7_Y1950_Dl(0.8-1.0)
S8_Y1950_r(0-2)_K2
S9_Y1950_r(0-2)_K3
S10_Y2008_Dl(0.3-0.7
F/FMSY
B/BMSY

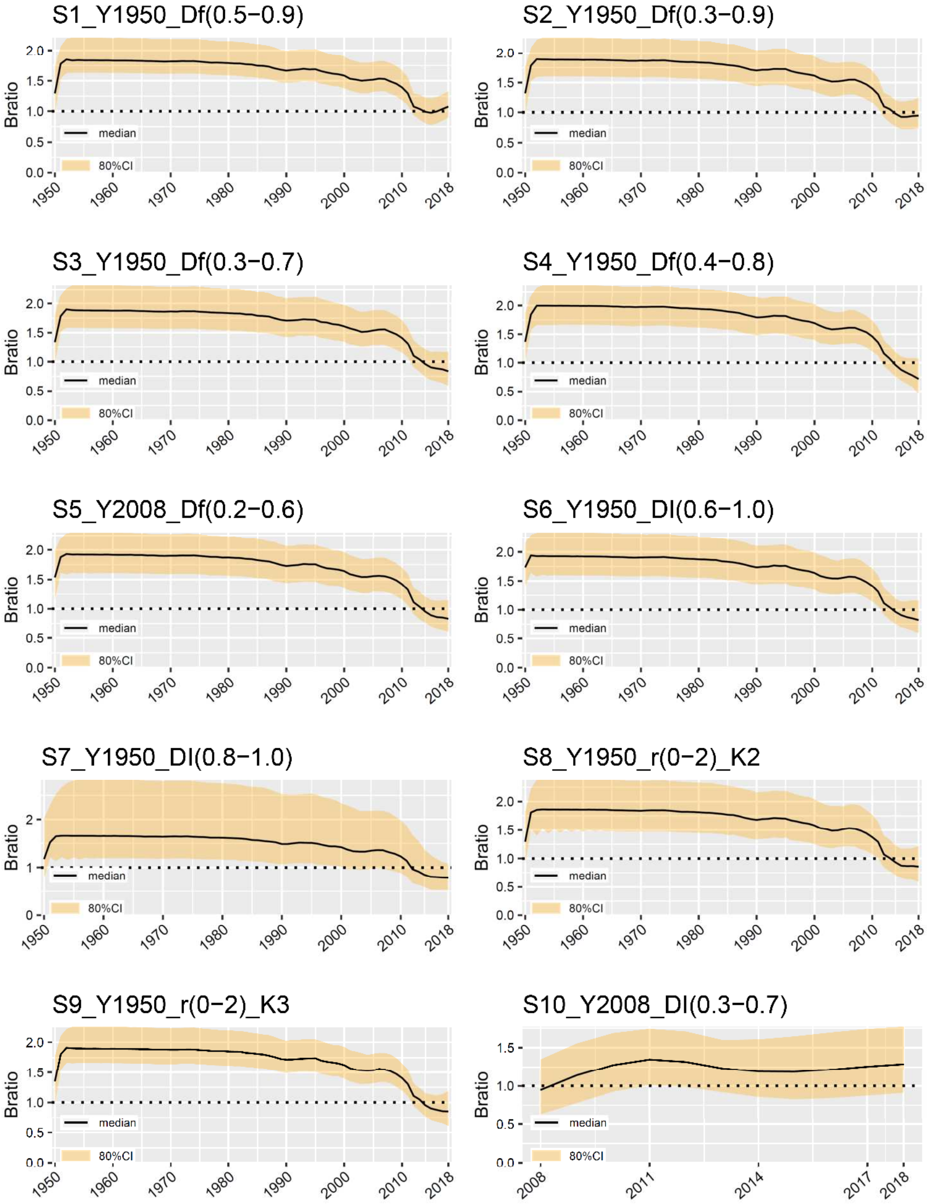
Appendix B-2. Results of BDM-CatchOnly for longtail tuna

Time series plot

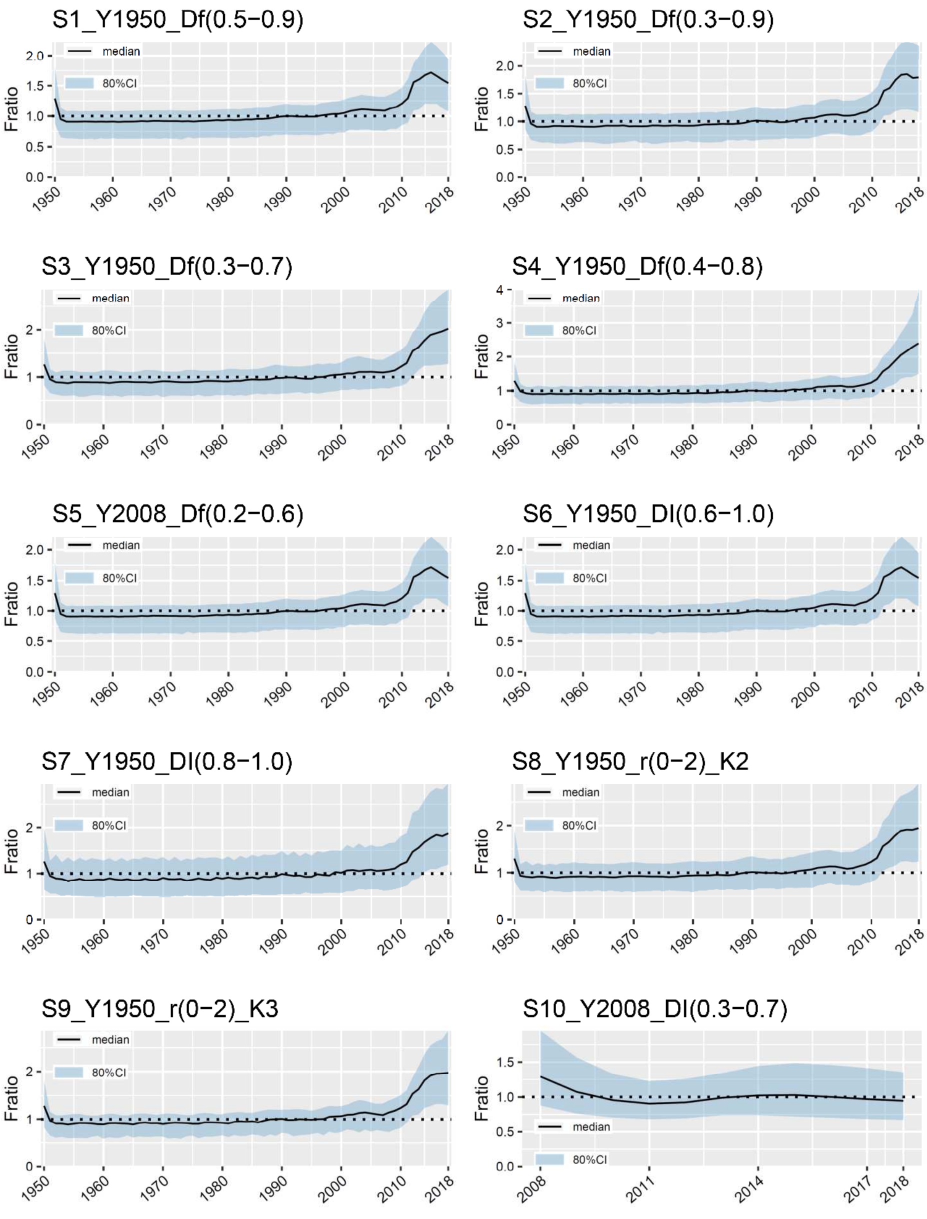
Time series Biomass



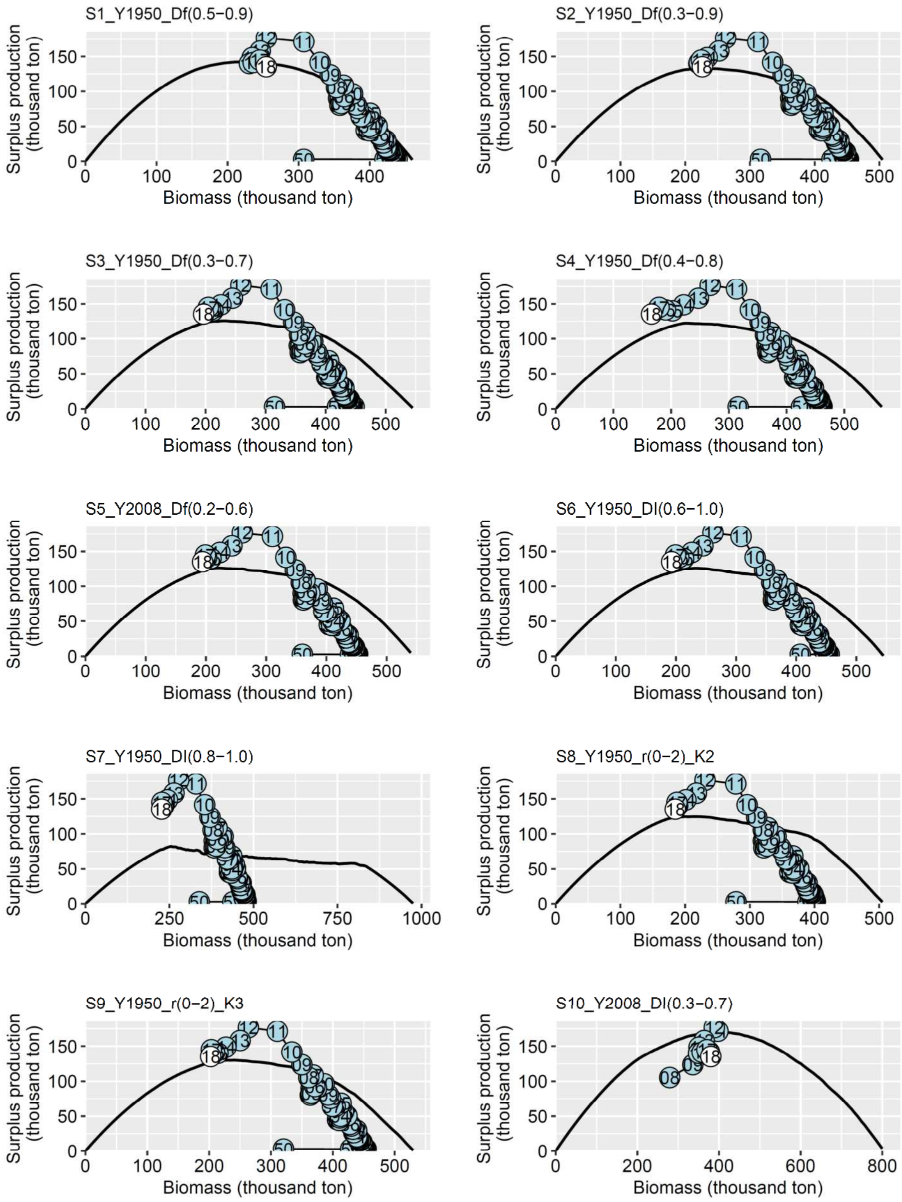
Time series Bratio



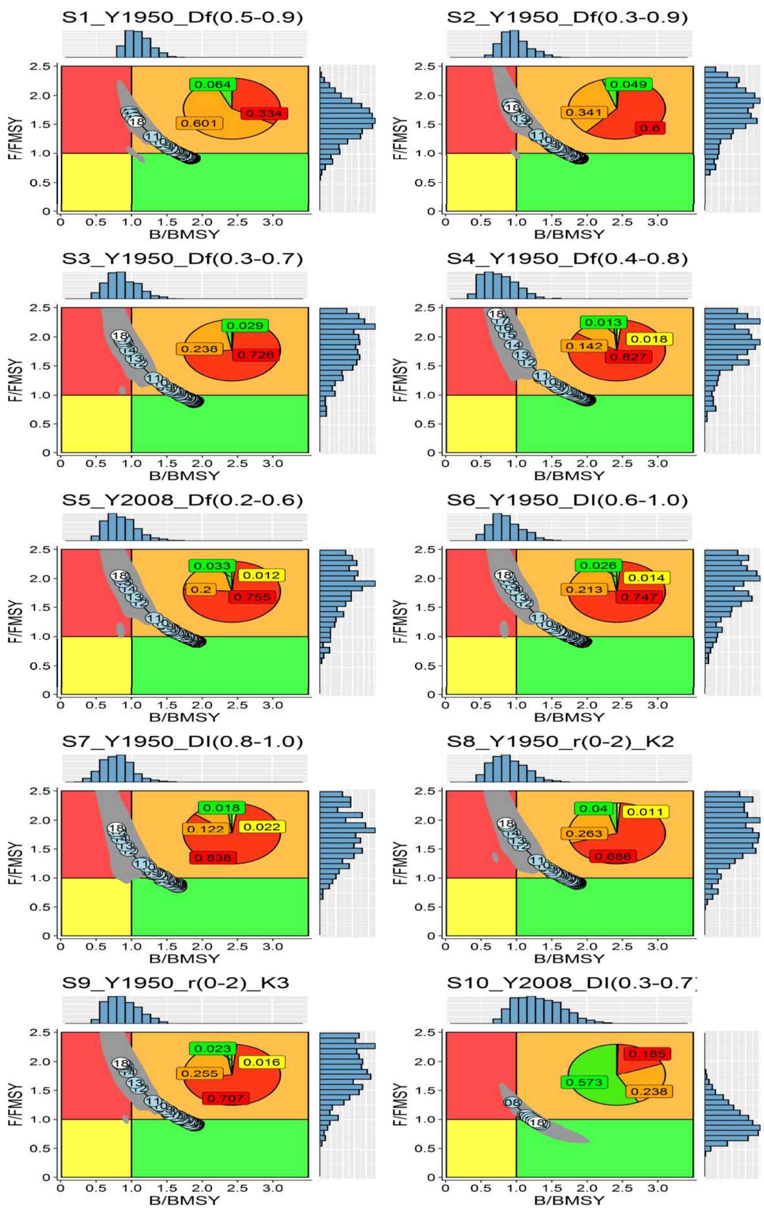
Time series Fratio



Production curve



Kobe plot

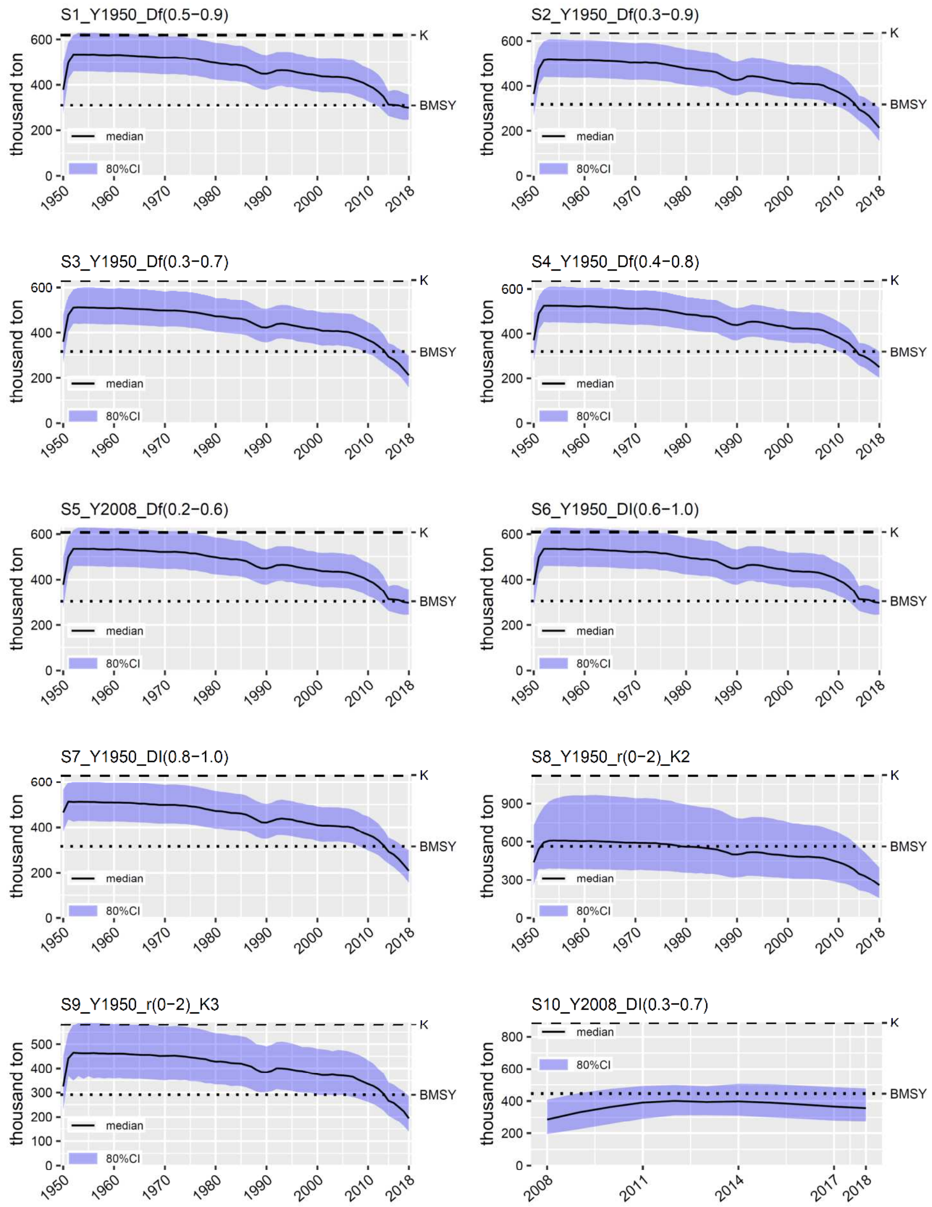

S1_Y1950_Df(0.5-0.9)
0.064
0.601
0.334
S2_Y1950_Df(0.3-0.9)
0.049
0.341
0.6
S3_Y1950_Df(0.3-0.7)
0.029
0.238
0.726
S4_Y1950_Df(0.4-0.8)
0.013
0.018
0.142
0.827
S5_Y2008_Df(0.2-0.6)
0.033
0.012
0.2
0.755
S6_Y1950_Dl(0.6-1.0)
0.026
0.014
0.213
0.747
S7_Y1950_Dl(0.8-1.0)
0.018
0.122
0.022
0.838
S8_Y1950_r(0-2)_K2
0.04
0.011
0.263
0.686
S9_Y1950_r(0-2)_K3
0.023
0.016
0.255
0.707
S10_Y2008_Dl(0.3-0.7
0.185
0.573
0.238
F/FMSY
B/BMSY

v

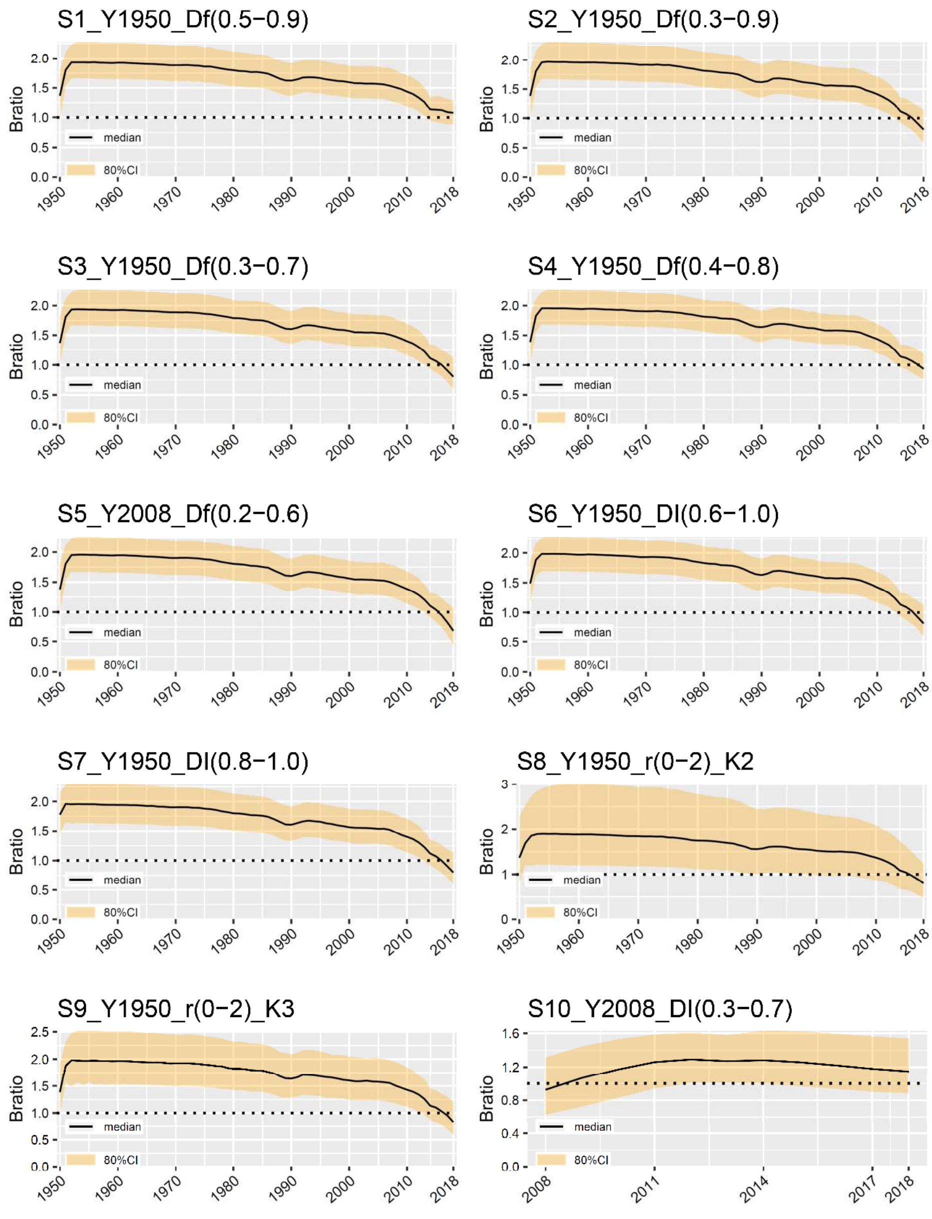
Appendix B-3. Results of BDM-CatchOnly for Spanish mackerel

Time series plot

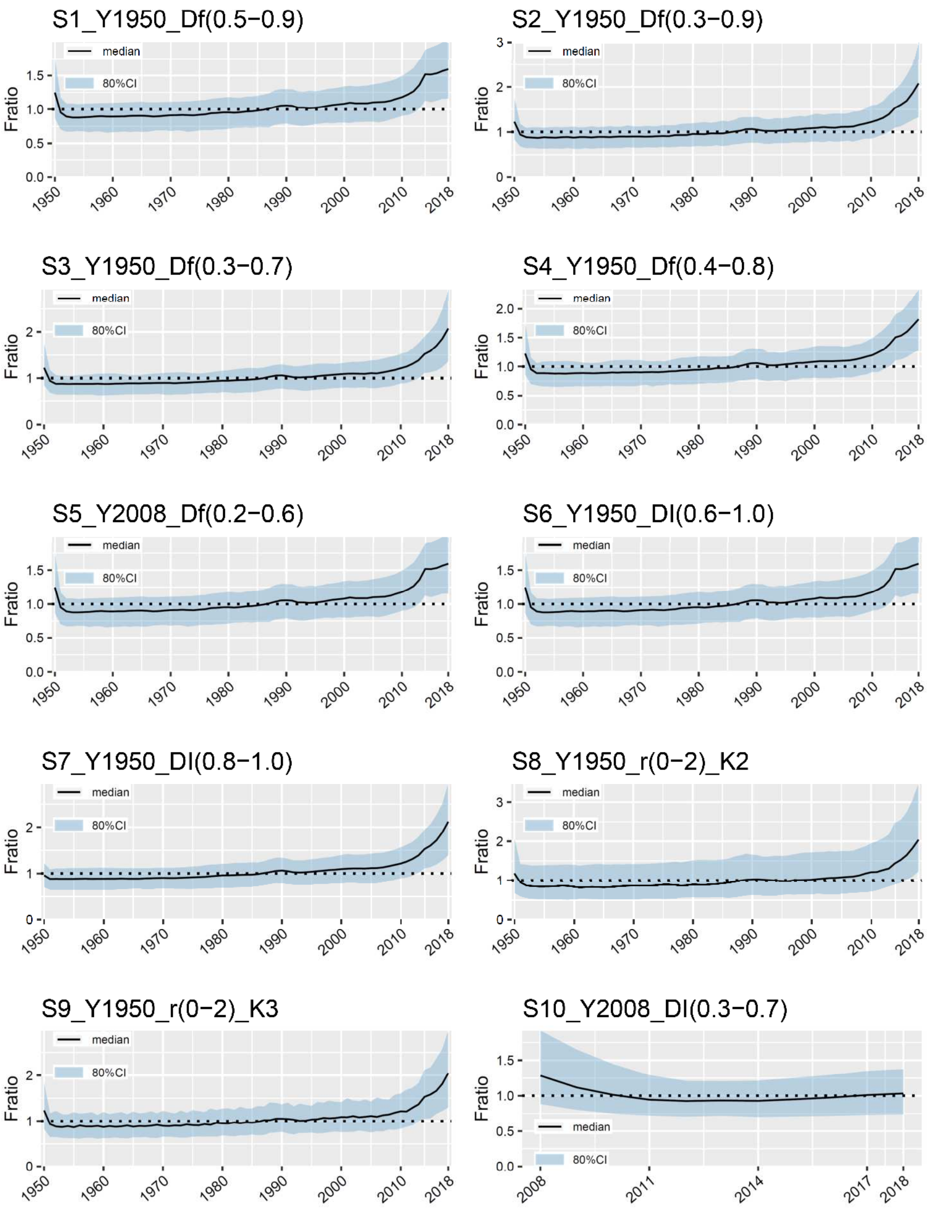
Time series Biomass



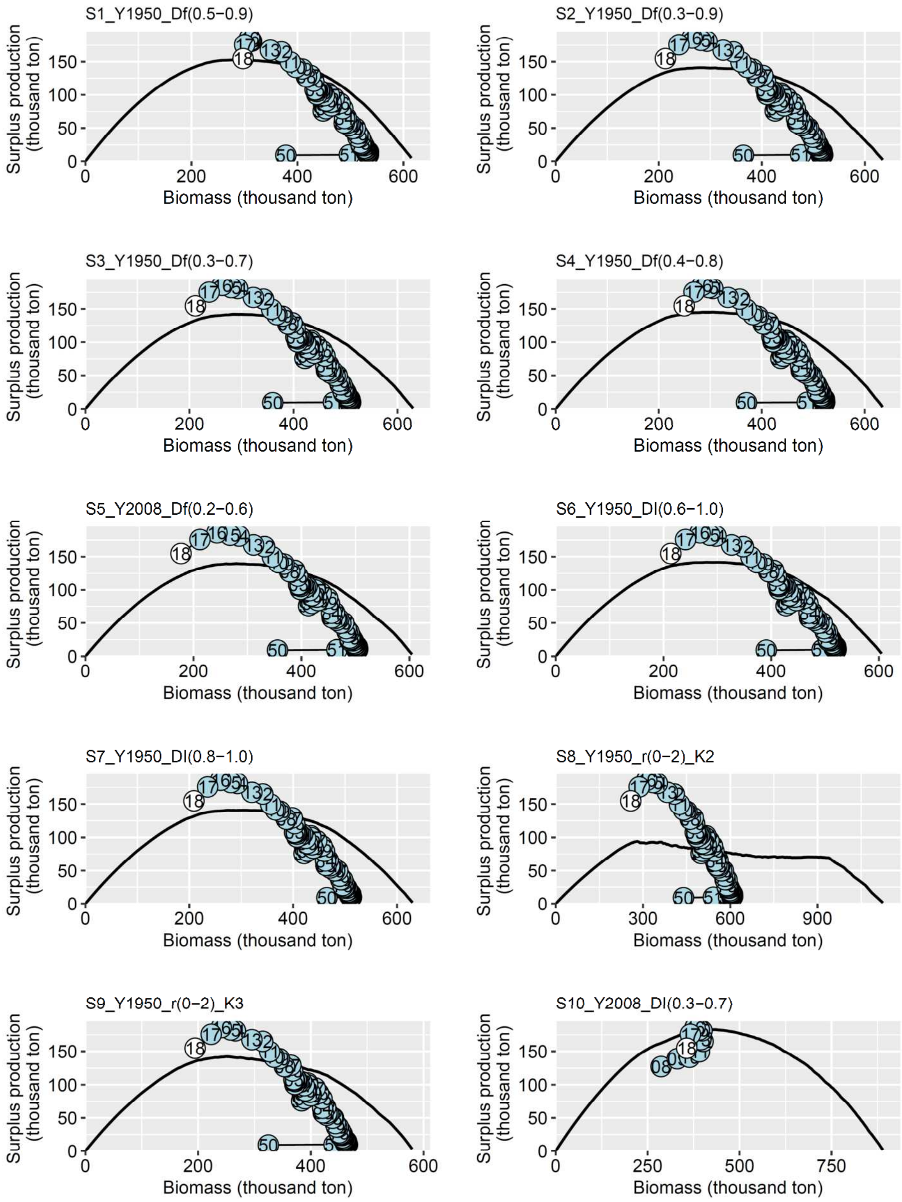
Time series Bratio



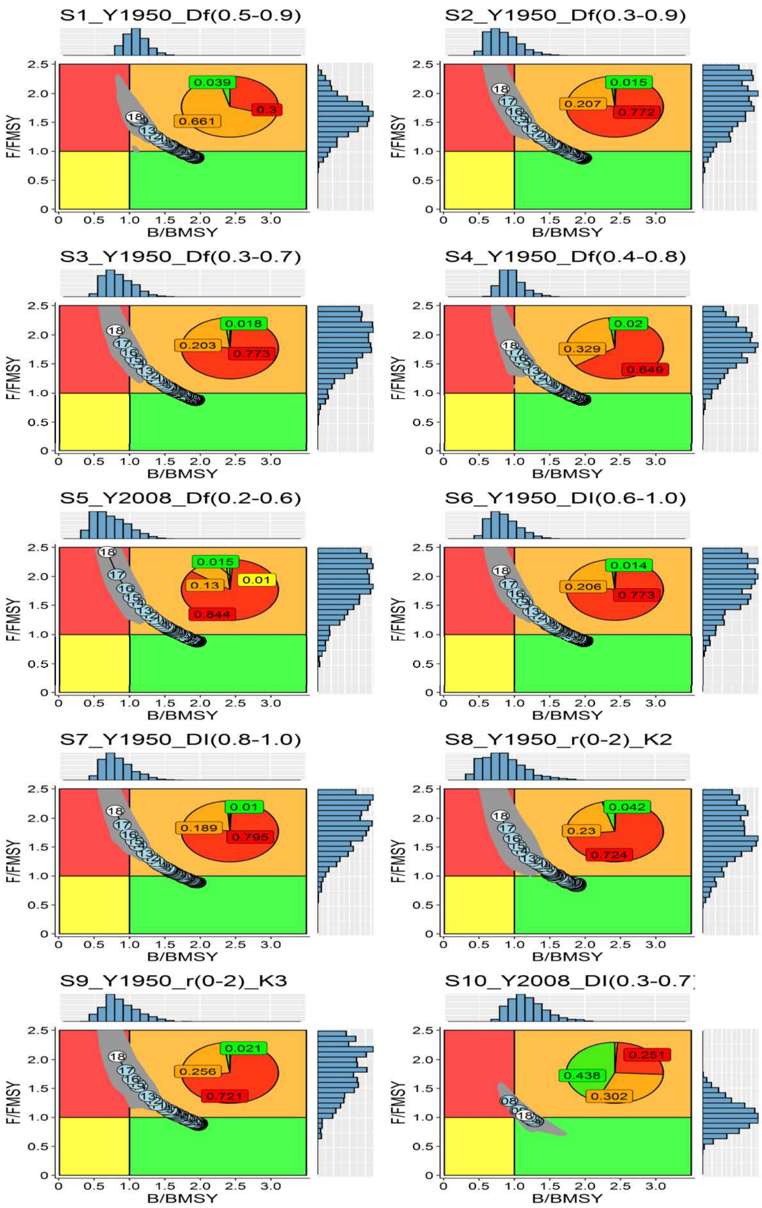
Time series Fratio



Production curve



Kobe plot


S1_Y1950_Df(0.5-0.9)
0.039
0.661
0.3
S2_Y1950_Df(0.3-0.9)
0.015
0.207
0.772
S3_Y1950_Df(0.3-0.7)
0.018
0.203
0.773
S4_Y1950_Df(0.4-0.8)
0.02
0.329
0.649
S5_Y2008_Df(0.2-0.6)
0.015
0.13
0.01
0.844
S6_Y1950_Dl(0.6-1.0)
0.014
0.206
0.773
S7_Y1950_Dl(0.8-1.0)
0.01
0.189
0.795
S8_Y1950_r(0-2)_K2
0.042
0.23
0.724
S9_Y1950_r(0-2)_K3
0.021
0.256
0.721
S10_Y2008_Dl(0.3-0.7)
0.251
0.438
0.302
F/FMSY
B/BMSY