Management strategy evaluation for bigeye tuna in Indian Ocean

Yuhe Tong[1,2] Yong Chen[2]

1. College of Marine Sciences, Shanghai Ocean University, 999 Hucheng Huan Road, Shanghai 201306, China
2. School of Marine Sciences, University of Maine, Orono, ME 04469, U.S.A

Abstract: In Indian Ocean, bigeye tuna (*Thunus obesus*) are ecologically and economically important. However, there is no explicit harvest policy (or harvest control rule) for the management of this resource. We used decision analysis and projections from a stochastic simulation model to aid managers in formulating a harvest policy. Our simulation model explores the medium-term implications of uncertainty in the stock–recruitment relationship, parameter uncertainty given such a relationship, stochastic process variation, and uncertainty associated with assessment and implementation errors. We used the model to project age-dynamics of the bigeye population, and thus predicted likely distributions of performance measure for 8 harvest policies, including 5 one-parameter harvest policies, 3 multi-parameter harvest policies. Performance statistics included average catch, variation in catch, remaining spawning stock biomass (SSB), as well as the frequency of how often SSB were below desirable thresholds.

Keywords: Management strategy evaluation; Harvest control rule; Bigeye tuna; Indian Ocean; Biological reference point

1 Introduction

A management strategy, often referred to as “harvest control rule” (Kell et al. 1999), and “management procedure” (Breen et al. 2003), is a fully specified set of rules for determining management actions, such as determining annual catch quotas or effort. A management strategy generally includes specifications for a monitoring system, an assessment procedure, and a decision rule. “Traditional” management strategies (see figure 1), including constant harvest rate, constant catch and constant escapement strategies, are simple HCRs with only one control parameter. However, all of these strategies have major disadvantages (Zheng and Quinn,1993), and some form of multi-parameter management strategy, also referred to as “threshold management strategy“ (Punt 2008) (see figure 1), are adopted by several fisheries jurisdictions consequently, such as “40-10” harvest strategy (PFMC,1998), MSY-based harvest strategy (Dichmont et al., 2006a,b). Threshold management strategies involve a threshold stock size below which fishing effort is set to zero, a ‘target’ stock size above which constant rate of fishing mortality above some higher (‘target’ stock size, and a zone between the ‘target’) and the threshold stock sizes within which the rate of fishing mortality is gradually reduced to zero.

Management strategy evaluation (MSE), also referred to as “Management Procedure Evaluation (MPE)”(Butterworth,2007), is the use of simulation testing with feedback to examine robustness of a management strategy in the face of uncertainty, and pre-specified, usually conflicting, management objectives. The basic MSE framework includes three key components :(a) the operating models that represents the “truth” for the evaluations; (b) the management strategies that are to be evaluated; and(c) the performance measures that reflect the management objectives (Dichmont et.al 2008).

The MSE approach has been demonstrated to be an effective way to compare and evaluate alternative management strategies. MSE has been applied to many single and multi-species fisheries (Punt, 1992; Butterworth et al., 1997; Punt et al., 2002) and to ecosystem (Dichmont et al., 2006a,b; Fulton et al., 2007). The major benefit of the MSE approach is that complete range of uncertainties can be identified and modeled so that the effects of uncertainties on performance measures and estimation performance can be quantified, and the effects of different management strategies can be evaluated by managing a"virtual" resource as operating model represents the "truth" for the evaluations.

The bigeye tuna resources in Indian Ocean are managed by the Indian Ocean Tuna Commission (IOTC) without any formal strategy, it has been in a well status in recent years, the updated stock assessment report shows that fishing mortality rate is below the F_{msy} (around 0.29), while spawning stock biomass is above the SSB_{msy} (461,477 tons) in 2008 (Shono et.al., 2009). For the sustainable utilization of this resource, specific management strategy is essential. Although a few one-parameter management strategies have been evaluated for this fishery (Shono et.al 2004), no formal management strategy has been applied. In this paper, we describe the use of decision analysis to evaluate both one-parameter and multi-parameter harvest policies for bigeye tuna in Indian Ocean. The generalized simulation framework applied allows the exploration of the performance of the harvest control rule, taking account of various sources of uncertainty. Overall, our work was designed to provide information to the IOTC to allow them to select among different harvest policies to better meet their objectives for the fishery. Despite the focus on a specific application, we believe this work provides information of general interest with regard to the performance of alternative management strategies.

2 Materials and methods

The basic approach used to evaluate a management strategy is to project a population dynamics model forward where future catches are determined using the management strategy.

2.1 operating models

The population dynamics model that forms the basis for the evaluation of alternative management strategies is age-structured, assumes that catches are taken in the middle of the year after half of natural mortality, and relates the number of 0-year-olds to spawning biomass by means of the Beverton-Holt form of the stock–recruitment relationship. The basic population dynamics are given by the equation:

$$N_{y,a} = \begin{cases} R_{y-1} & if\ a = 0 \\ (N_{y-1,a-1}e^{-M_{a-1}/2} - C_{y-1,a-1})e^{-M_{a-1}/2} & if\ 1 \le a < m \\ (N_{y-1,m}e^{-M_m/2} - C_{y-1,m})e^{-M_m/2} + (N_{y-1,m-1}e^{-M_{m-1}/2} - C_{y-1,m-1})e^{-M_{m-1}/2} & if\ a = m \end{cases}$$

where $N_{y,a}$ is the number of tuna of age a at the start of year y; m is the maximum age(treated as a plus-group); R_y is the recruitment during year y:

$$R_y = \frac{4hR_0B_y^{sp}}{K^{sp}(1-h) + B_y^{sp}(5h-1)} e^{\varepsilon_y - \sigma_R^2/2}$$

$C^{f}_{y-1,a-1}$ is the number of the fleet-specific annual catch for age a-1:

$$C^{LL}_{y-1,a-1} = N_{y-1,a-1} e^{-M_{a-1}/2} S^{LL}_{a-1} F^{LL}_{y-1}$$

$$C^{PS}_{y-1,a-1} = N_{y-1,a-1} e^{-M_{a-1}/2} S^{PS}_{a-1} F^{PS}_{y-1}$$

$$C^{total}_{y-1,a-1} = N_{y-1,a-1} e^{-M_{a-1}/2} (S^{LL}_{a-1} F^{LL}_{y-1} + S^{PS}_{a-1} F^{PS}_{y-1}) = N_{y-1,a-1} e^{-M_{a-1}/2} F^{total}_{y-1,a-1}$$

M_{a-1} is the instantaneous rate of natural mortality for animals of age a-1 (assumed to be independent of time); S^{LL}_{a-1} and S^{PS}_{a-1} are the selectivity of longline and purse seine fisheries of age a ; F^{LL}_{y-1} and F^{PS}_{y-1} are fishing mortality of longline and purse seine fisheries of year y-1; B^{sp}_{y} is the spawning biomass at the start of year y; K^{sp} is the average unfished spawning biomass; *h* is the steepness of the stock–recruitment relationship; R_0 is the virgin recruitment (number of births when the stock is at its average unfished level).

The model incorporated uncertainty associated with recruitment, stock assessment and F implementation (Table 1), and we applied following factors consistent with IOTC reports (Shono et al., 2009), including the values for the biological, fishery parameters (i.e.mass-and fecundity-at-age, natural mortality and fishery selectivity) (Table 1; Figure 2). The selectivity was same with that in Nishida and Shono (2006). We assumed the stock followed the B-H S-R relationship, Von Bertalanffy growth function (VBGF), also assumed that the ratio of F_{LL} and F_{Ps} was kept constant at 2002 level (F_{LL}/F_{Ps} =3.309)(Shono et al., 2004). All the simulations started at the fishery status at 2004 level (IOTC, 2008) (Table 1).

2.2 management strategies

11 scenarios are examined, covering a constant catch rule at 5 catch level and a status-dependent rule with 6 biological reference point (BRP) groups (Table 2).

For constant catch rule, catch is always equal to a certain level from 90000 t to 130000t with step length at 10000 t, except for fishery close when the catch object can't be achieved for low biomass.

Status-dependent rule includes target biomass (B_T) and fishing mortality (F_T), limit biomass (B_L) and fishing mortality (F_L). When biomass is between B_L and B_T, fishing mortality is changed linearly. BRPs in different groups are quoted or calculated by per-recruitment model (Table 1).

2.3 performance measures

The results of the simulations are listed in the Table 3 showing the trade-offs among the various performance measures, to capture the desire for high stable catches, and to avoid dropping stocks below the overfished threshold for bigeye tuna in Indian Ocean:

1) The average total catch
2) The extent of catch variability, as quantified by the average over simulations of the absolute annual variation in catches

3) The average spawning biomass
4) The lowest biomass during the simulation years
5) The probability that the spawning biomass was below SSB_{msy}
6) The average fishing mortality
7) The average recruitment

3 Results

3.1 Constant catch rule

Keeping annual catch at 100000 t level is most rational if we choose a constant catch rule. The result shows that the stock can be utilized sustainable when annual catch is 100000 t, maintaining SSB at around 420000 t, and above 100000 t catch will cause decline of stock. The fishery may be closed after annual catch at 130000 t for 17 years because of lower SSB. If annual catch is constant at 90000 t, the SSB will increase to nearly 500000 t after 25 years, while resulting in slightly low amount and lowest variant of catch.

3.2 Status-dependent rule

Managing the fishery under the framework of scenario SD_d can output a more appropriate result than other scenarios of status-dependent rules, as there is not big different for harvest amount among them, but both lowest catch variant is achieved for scenario SD_d, and its lowest SSB during the simulation are higher than other. Both scenario SD_b and SD_c could harvest no more than 10000 t than other scenarios, but facing higher risk of overfished for its lower SSB.

3.5 Tradeoffs between the 2 harvest control rule

Among the scenarios tested, the result shows that both scenario CC_100000 and scenario SD_d are proper choices for bigeye fishery in the Indian Ocean, their behavior are similar in terms of catch and probability of overfished. But scenario CC_100000 may be more practicable than scenario SD_d, because stock assessment are essential for enforcement of status-dependent rule, while constant catch rule is easy to be carried out.

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Table 1. Considered uncertainty and values of BRPs, indicators and parameters

Uncertainty	Value	Reference
CV_B	0.15	
CV_{SSB}	0.15	
CV_R	0.1	
CV_N	0.1	
CV_F	0.2	
BRP	**Value**	
MSY	111195 t	IOTC, 2008
SSB_{msy}	350000	IOTC, 2008
F_{msy}	0.30	IOTC, 2008
$F_{0.1}$	0.448	Calculated by per-recruit model
F_{max}	0.674	Calculated by per-recruit model
$F_{35\%}$	0.482	Calculated by per-recruit model
$F_{20\%}$	0.843	Calculated by per-recruit model
SSB_0	1150000	IOTC, 2008
Indicator	**Value**	
SSB_{2004}	430000 t	IOTC, 2008
B_{2004}	720000 t	IOTC, 2008
F_{2004}	0.29	IOTC, 2008
Parameter	**Value**	
B_0	1716600 t	Shono et al., 2009
R_0	81064400	Shono et al., 2009
h (steepness)	0.75	Shono et al., 2009
m_mat	0.25	Shono et al., 2009
L_{50}_mat	110.888	Shono et al., 2009
M (age=0,1)	0.8	Shono et al., 2009
M (age>=2)	0.4	Shono et al., 2009
L_∞(cm)	169.06	Stequert, 2003
k	0.32	Stequert, 2003
t_0	-0.34	Stequert, 2003
α_W (L<80cm)	0.0000274	Poreeyanond,1994
β_W (L<80cm)	2.908	Poreeyanond,1994
α_W (L>=80cm)	0.00003661	Nakamura and Uchiyama, 1966
β_W (L>=80cm)	2.90182	Nakamura and Uchiyama, 1966

Table 2. Scenarios specification

HCR	Scenario Abbreviation	BRP			
	CC_130000	Catch=130000t			
Constant catch rule (CC)	CC_120000	Catch=120000t			
	CC_110000	Catch=110000t			
	CC_100000	Catch=100000t			
	CC_90000	Catch=90000t			
		B_T	**B_L**	**F_T**	**F_L**
	SD_a	SSB_{msy}	$0.5SSB_{msy}$	$0.75F_{msy}$	F_{msy}
Status-dependent rule (SD)	SD_b	SSB_{msy}	$0.5SSB_{msy}$	$F_{0.1}$	F_{max}
	SD_c	SSB_{msy}	$0.5SSB_{msy}$	$F_{35\%}$	$F_{20\%}$
	SD_d	$0.4SSB_0$	$0.1SSB_0$	$0.75F_{msy}$	F_{msy}
	SD_e	$0.4SSB_0$	$0.1SSB_0$	$F_{0.1}$	F_{max}
	SD_f	$0.4SSB_0$	$0.1SSB_0$	$F_{35\%}$	$F_{20\%}$

Table 3. Result of medium-term simulations with a Beverton-Holt stock-recruitment model for the bigeye tuna in the Indian Ocean. Mean and median were estimated from 250 simulations of a 25-year fishery.

Scenarios	Mean SSB (t)	Mean C (t)	Mean R (numbers)	Lowest biomass (t)	Mean F	CV of Mean C	Porbability of SSB<SSBmsy
CC_90000	491146	88355	66755041	443510	0.195	0.002	0.000
SD_d	0.915	0.967	0.928	0.949	0.206	0.056	0.000
CC_100000	0.880	1.111	0.968	0.943	0.241	0.002	0.000
SD_e	0.850	0.991	0.905	0.855	0.224	0.083	0.000
SD_f	0.845	0.986	0.903	0.852	0.223	0.080	0.000
SD_a	0.819	1.028	0.895	0.874	0.239	0.093	0.000
CC_110000	0.744	1.222	0.921	0.687	0.308	0.002	0.000
SD_c	0.677	1.101	0.835	0.700	0.300	0.220	0.000
SD_b	0.670	1.104	0.831	0.680	0.304	0.249	0.000
CC_120000	0.579	1.335	0.831	0.281	0.453	0.002	0.120
CC_130000	0.392	1.062	0.598	0.006	0.439	0.600	0.440

Note: Optimal data are marked in frame.

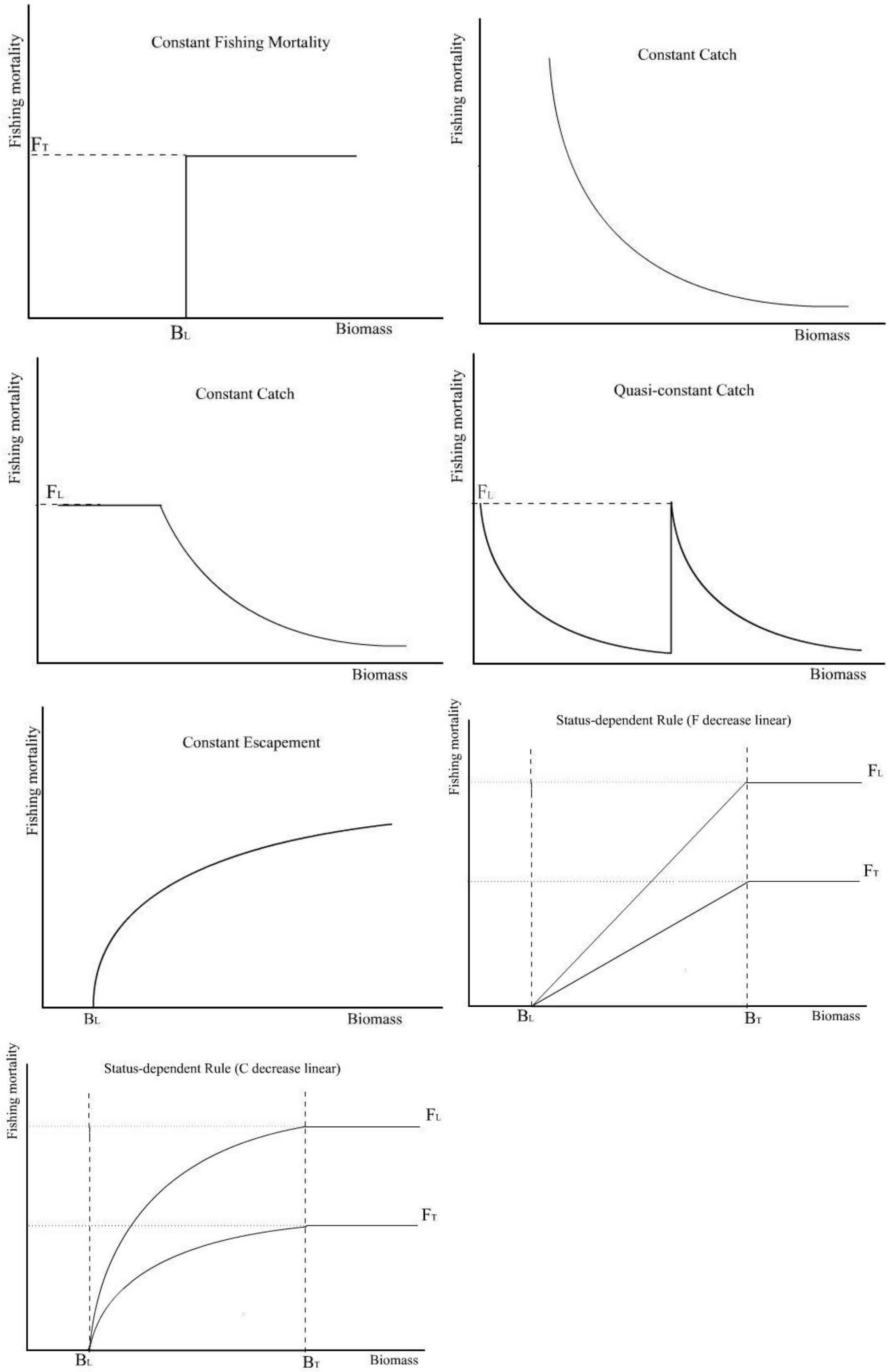


Figure 1. How fishing mortality changes with biomass for each HCR

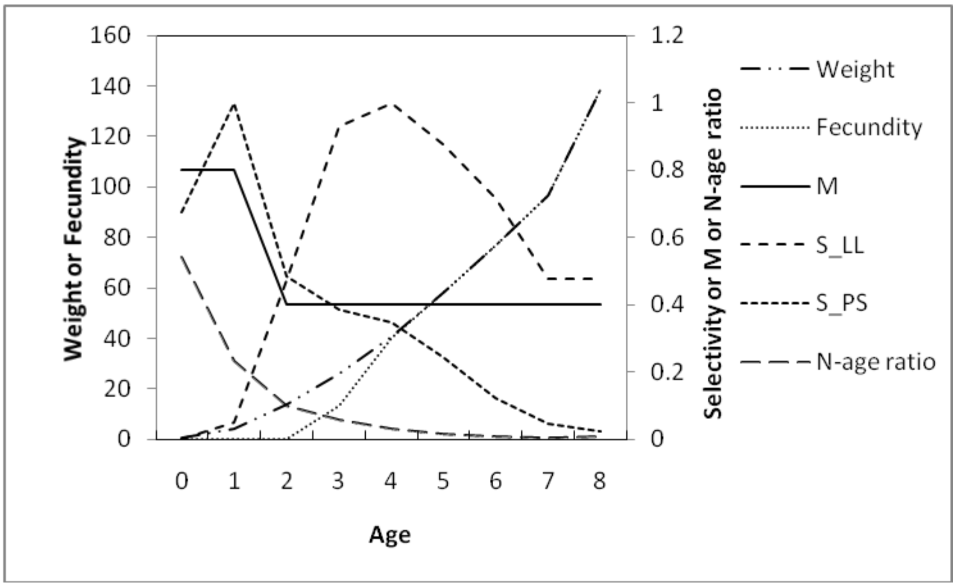
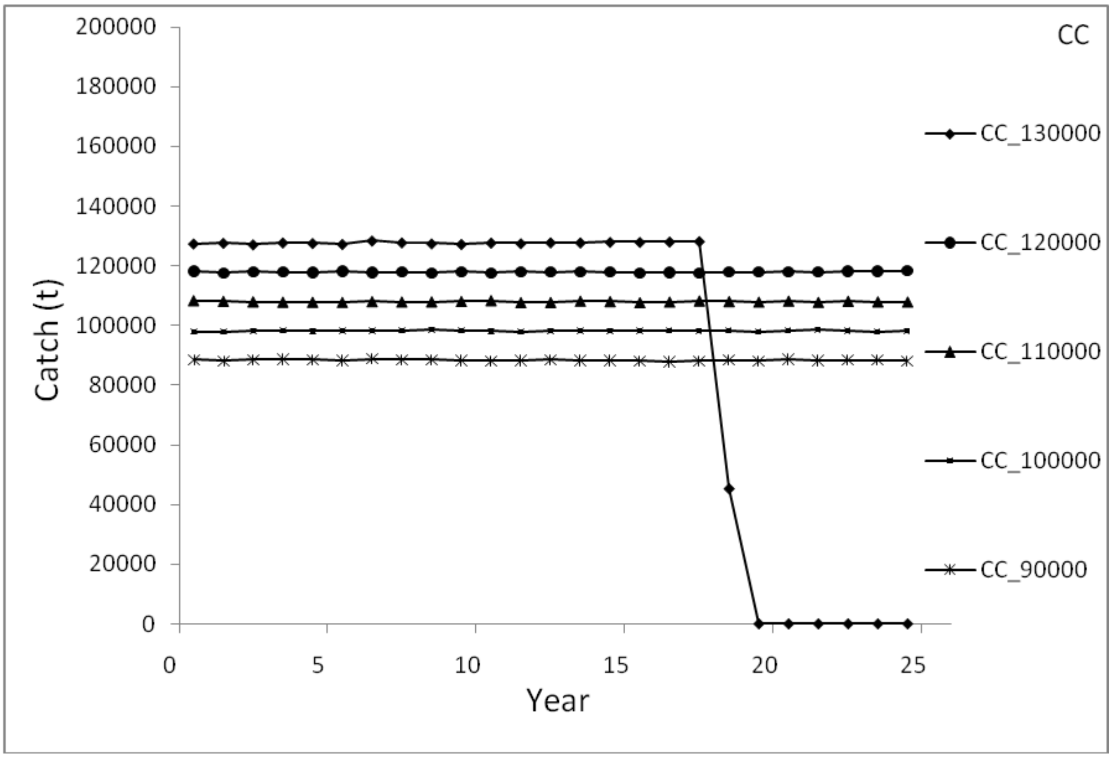


Figure 2. Biological and fishery information used to parameterize the operating model.


CC
Catch (t)
Year
CC_130000
CC_120000
CC_110000
CC_100000
CC_90000
0
20000
40000
60000
80000
100000
120000
140000
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180000
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10
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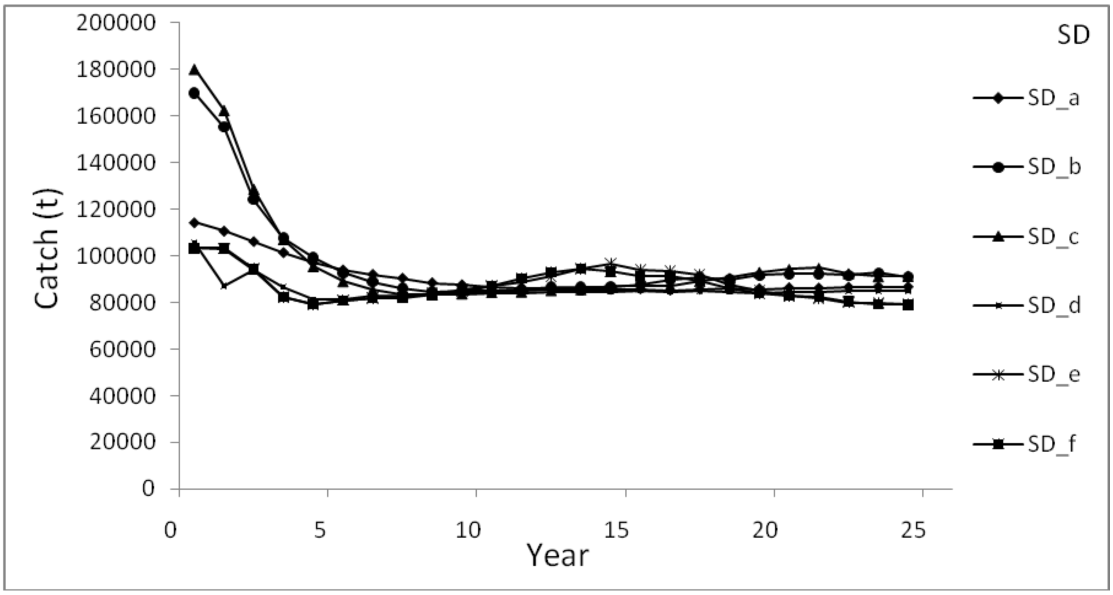
20
25


SD
Catch (t)
Year
SD_a
SD_b
SD_c
SD_d
SD_e
SD_f
0
20000
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60000
80000
100000
120000
140000
160000
180000
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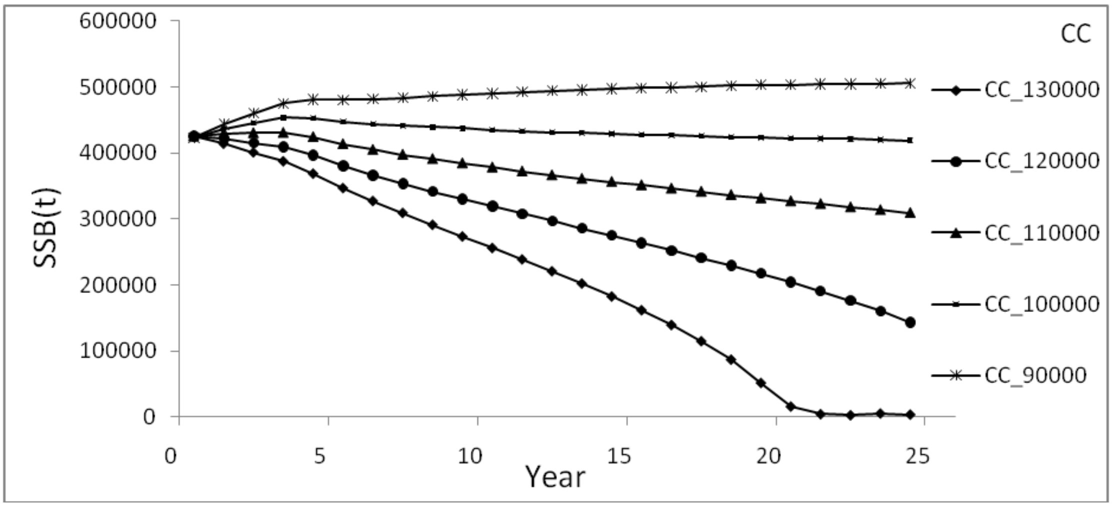


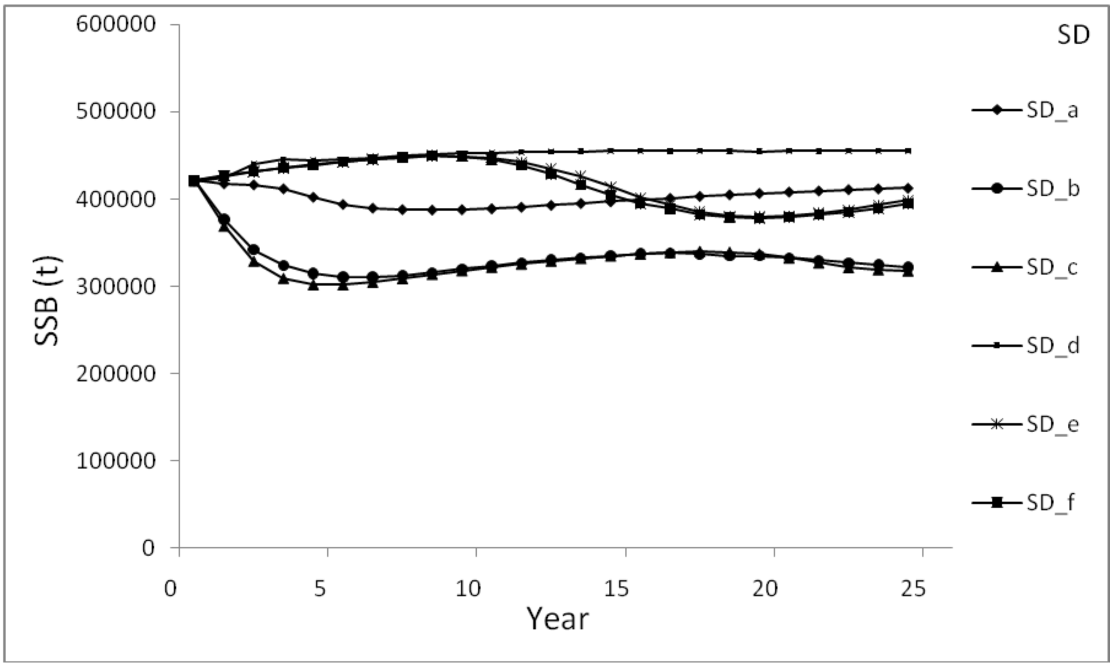
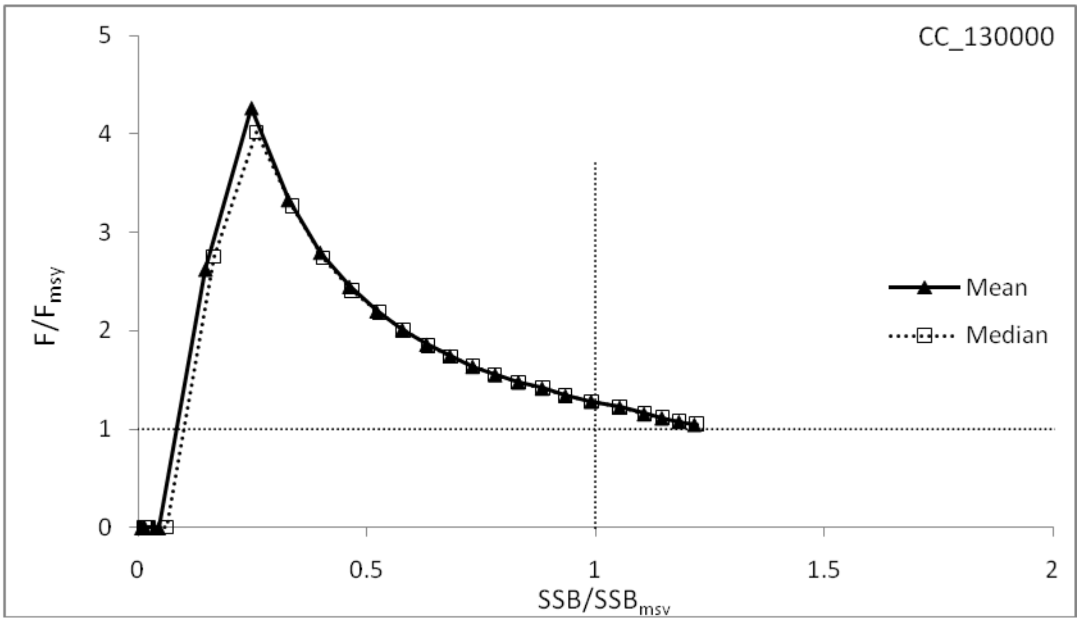


Figure 3. Year trajectories of catch and SSB


CC_130000
F/F_{msy}
SSB/SSB_{msy}
Mean
Median
0
1
2
3
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5
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0.5
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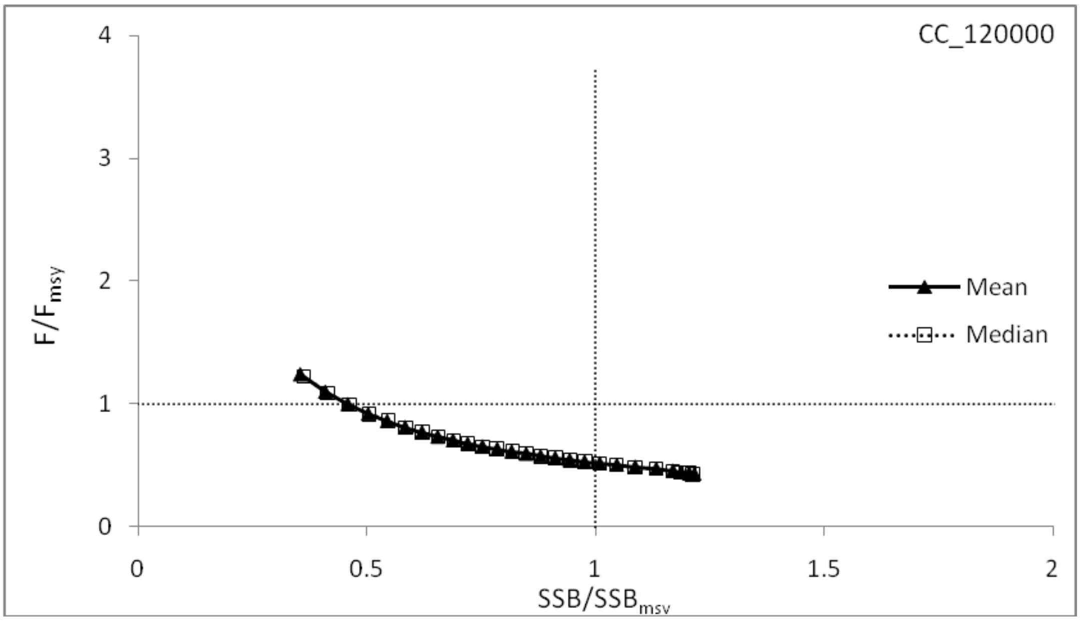
1.5
2


CC_120000
F/F_{msy}
SSB/SSB_{msy}
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Median
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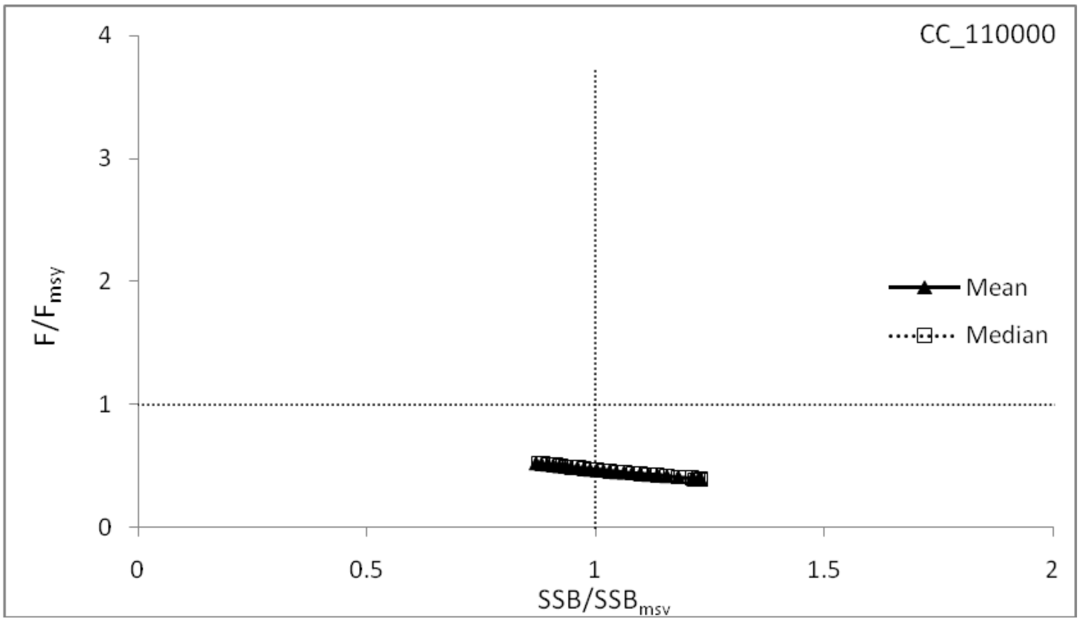
2


CC_110000
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SSB/SSB_msy
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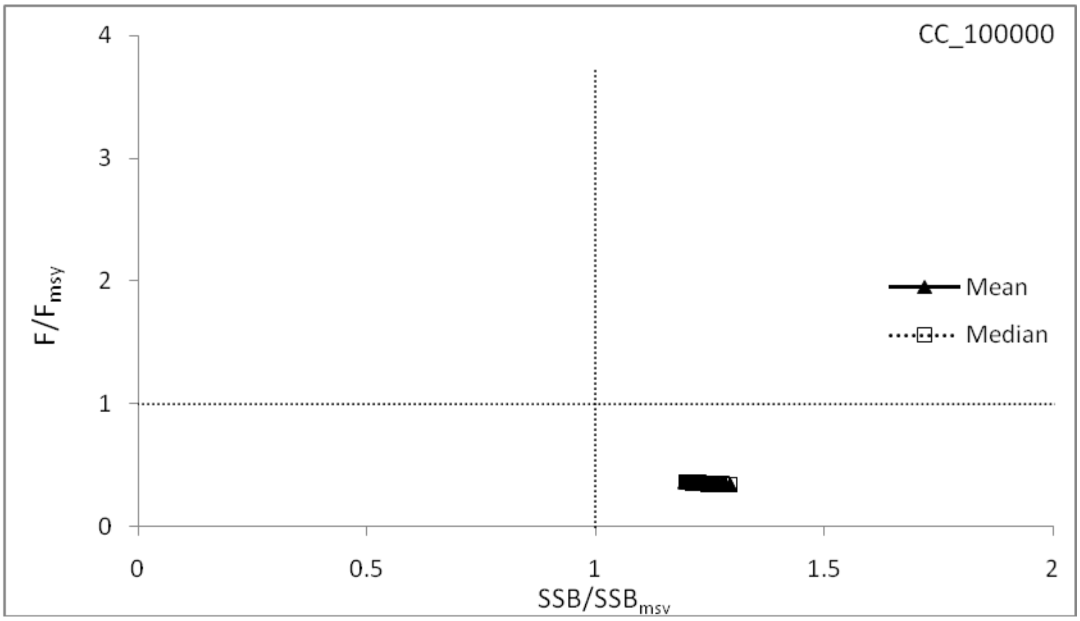
CC_100000
F/F_msy
SSB/SSB_msy
Mean
Median
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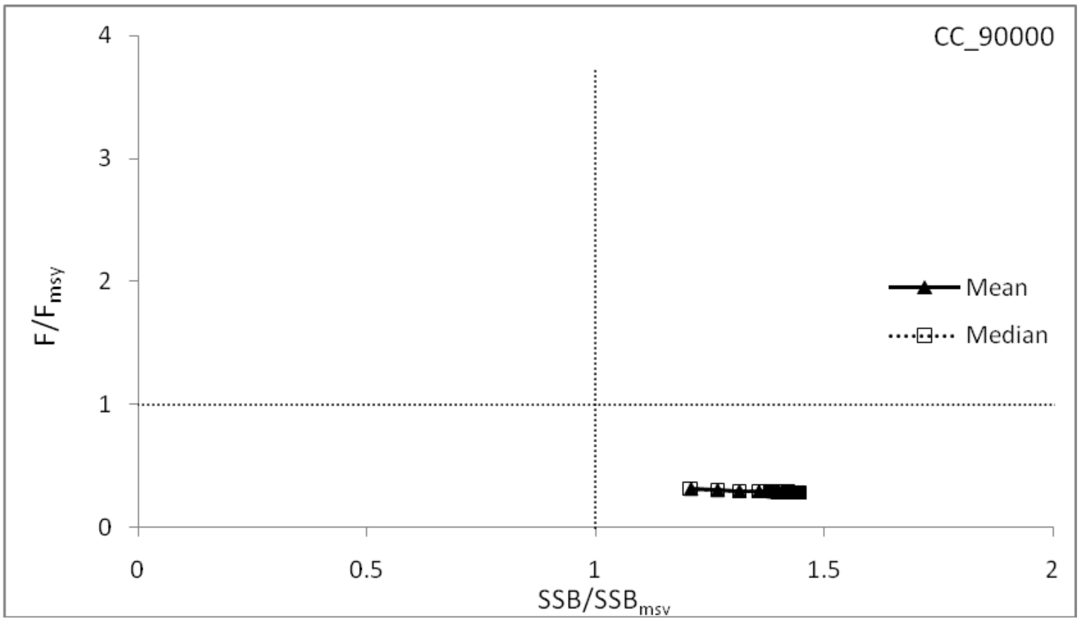
CC_90000
F/Fmsy
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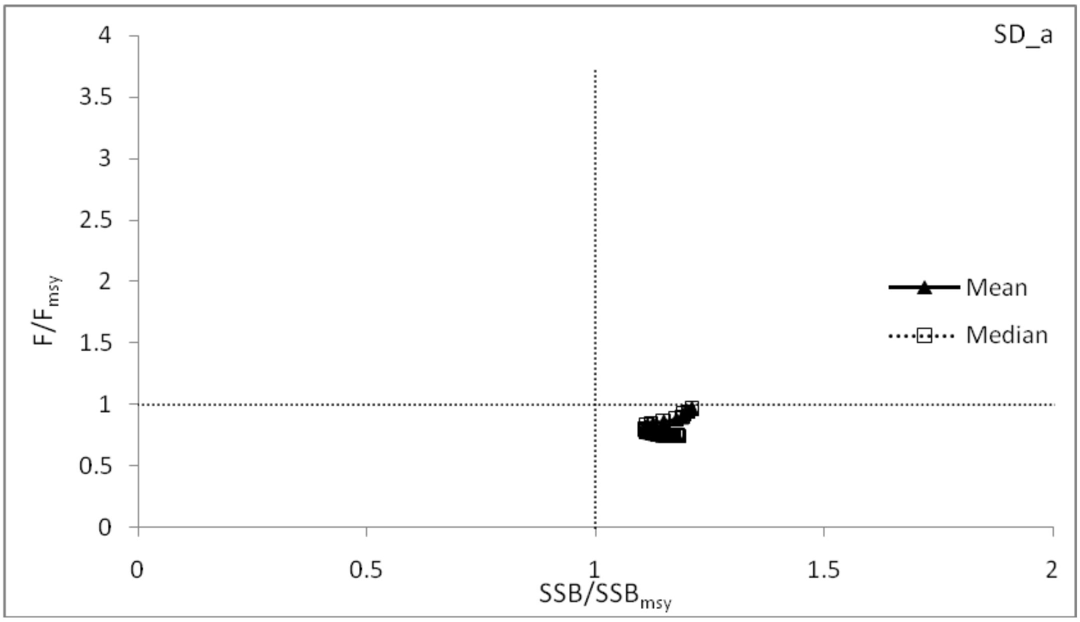
SD_a
F/Fmsy
SSB/SSBmsy
Mean
Median
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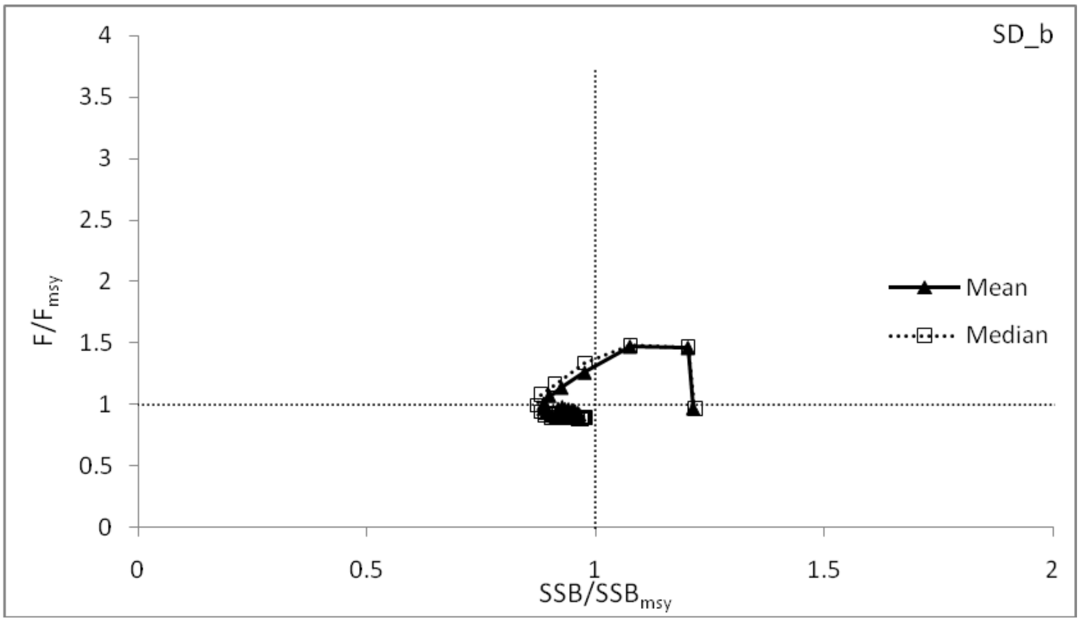
1
1.5
2


SD_b
F/F_msy
SSB/SSB_msy
Mean
Median
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2.5
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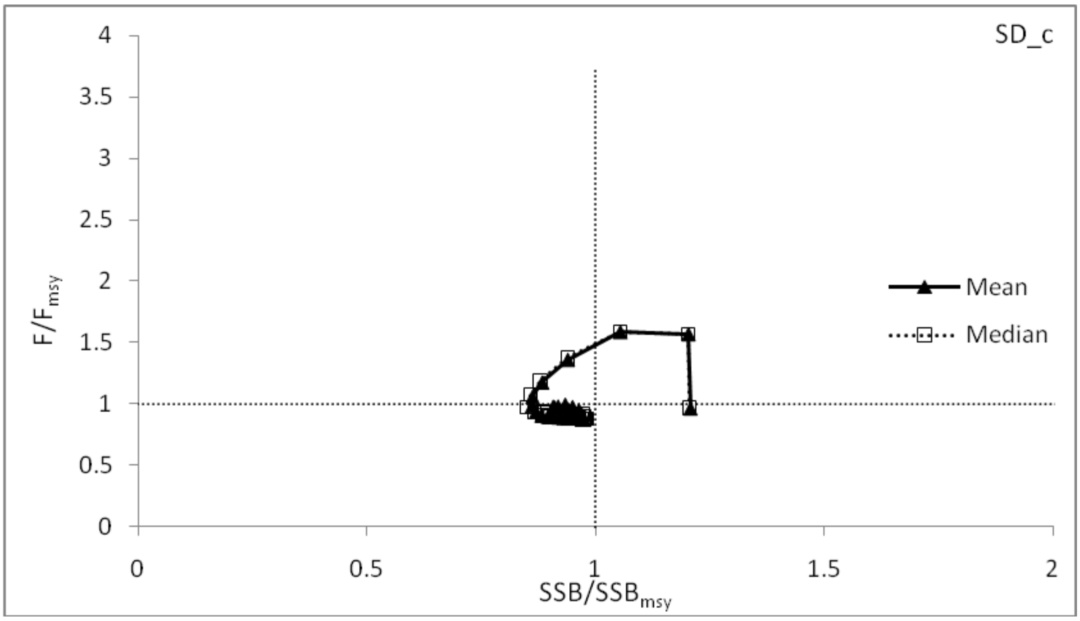
3.5
4


SD_c
F/F_msy
SSB/SSB_msy
Mean
Median
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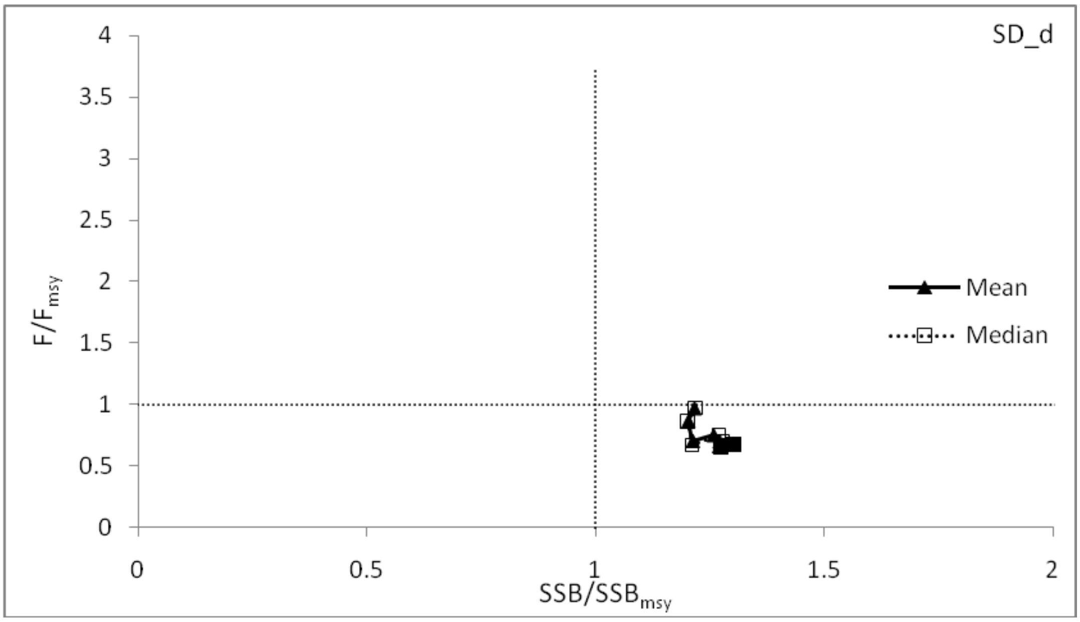
1
1.5
2
2.5
3
3.5
4


SD_d
F/F$_{msy}$
SSB/SSB$_{msy}$
Mean
Median
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0.5
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1.5
2
2.5
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3.5
4
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1
1.5
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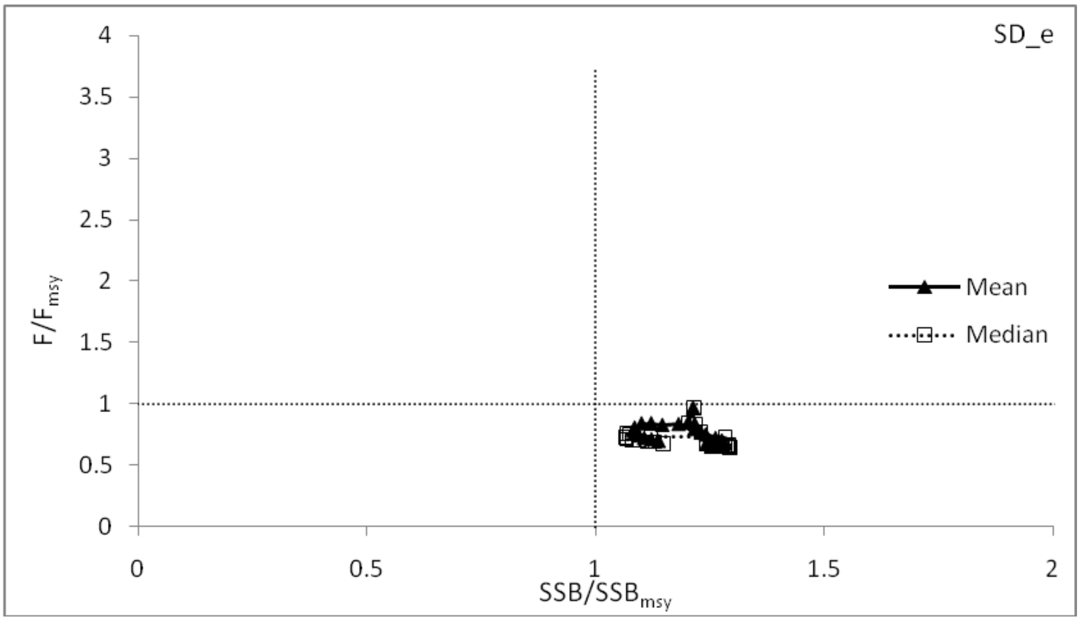
SD_e
F/F$_{msy}$
SSB/SSB$_{msy}$
Mean
Median
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1
1.5
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1.5
2

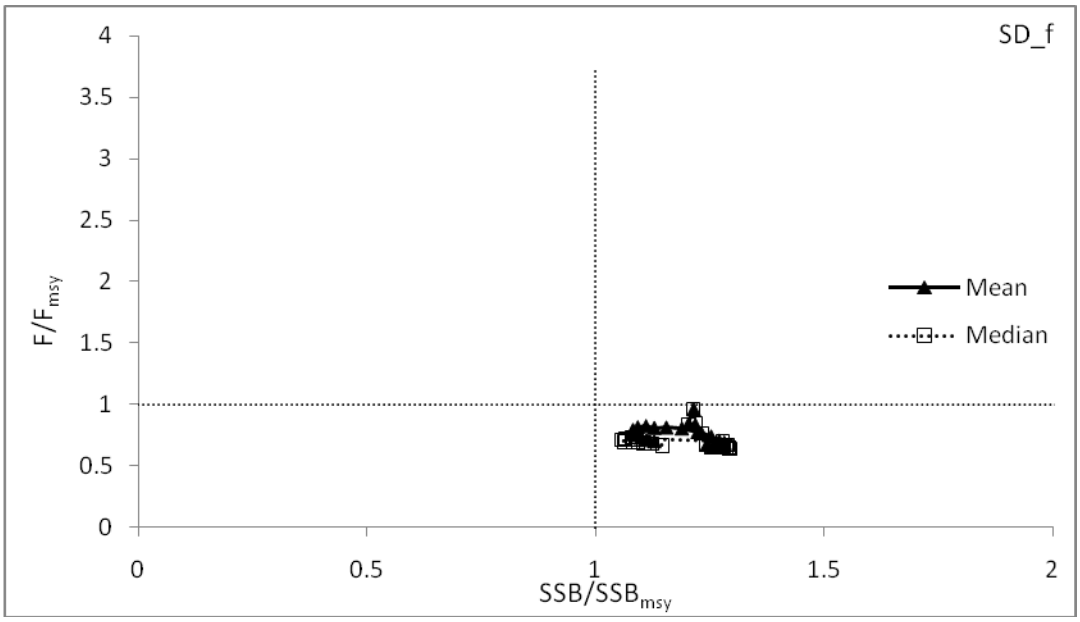

Figure 4. Year trajectories of stock status for each scenario