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Final Report --- Risk Assessment Modeling of a Potential Red Abalone Fishery at San Miguel Island to Examine Sustainability

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Prepared for

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Oct 27, 2012

To: Ian Taniguchi, California Department of Fish and Game (CDFG)
From: Yan Jiao, Associate Professor, Virginia Tech (VT)
Cc: Office of Sponsored Programs, Virginia Polytechnic Institute and State University

Introduction: This report represents the key work product and draft deliverable completed for Basic Subcontractor Agreement P1070004 between the Office of Sponsored Programs of VT and CDFG dated November, 2011.

Activities and Completion of Tasks by Modeler Yan Jiao

After the proposal was funded, I worked closely with CDFG in the following ways:

- Contacted CDFG to update data and re-explore the appropriateness of the usage of the data based on the peer reviewer's comments
- Developed models and approaches based on the Tasks in the contract and the peer reviewer's report.
- Communicated (both written reports and phone calls) research progress to the CDFG.
- Revise the draft report based on the comments from the external reviewers.

Consistent with the Tasks in the contract, I completed the following:

- Revised SCA model (3 model scenarios were explored and the following one is recommended)
    - use of survey abundance 2006-2008 with their variances; multinomial pdf of length frequency but effective sample size is used; logistic selectivity,
- Conducted risk assessment
    - Explored appropriated recruitment models based on recommended model above
    - Projected population based on the selected SCA model hybrid with the recommended Recruitment and Selectivity submodels

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Risk assessment of reopening the San Miguel Island red abalone (*Haliotis rufescen*) fishery

Abstract

Red abalone has historically been an important natural resource in southern California. Currently, all commercial and recreational abalone fisheries in southern California, including San Miguel Island (SMI), have been closed for over 10 years. There are questions about the recovery of the stock and the possibility of opening an abalone fishery at SMI. A systematic stock assessment is needed to better understand the status of the stock and to better manage this region. We assessed the risk of reopening SMI red abalone fishery using a Bayesian statistical catch-at-age model to estimate fishing mortality, population size, and biological reference points (BRPs) based on survey abundance, and length frequency. The population abundance estimation from a geostatistical analysis of fishery-independent surveys in 2006 to 2008 done by the California Department of Fish and Game (CDFG) were used as informative priors in the Bayesian analysis. Potential Total Allowable Catches (TACs) given different *F*-based BRPs were calculated. The risk of the population's decline and risk of overfishing were assessed under different *F* and TAC management strategies. Based on the data available, our model comparison suggests a Bayesian statistical age-structured model with selectivity following a logistic curve to be used for SMI stock assessment. Three types of recruitment models, random, Beverton-Holt (B-H) model, and Ricker model were explored outside of the Bayesian statistical age-structured model. The population projection used in the risk assessment started from the joint posterior distribution of population size in 2008 and then projected based on the recommended Bayesian statistical age-structured model and the B-H recruitment model. Our risk assessment based on the recommended model suggests that the population can undergone some fishing and the fishing level may be determined based on the risk and population size levels that stakeholders would like to accept. This work is critical to successful management of SMI red abalone. Precautionary management strategies need to be considered because of the high uncertainty of the data and the stock assessment results. This analysis enables better understanding of the red abalone dynamics at SMI and helps develop further fishery monitoring/survey programs and fishery management goals as well as future studies.

Introduction

San Miguel Island (SMI) is one of the islands located in the Southern California Bight. The SMI red abalone fishery, like many other abalone fisheries, was depleted in the early 1990s, and the fishery has been closed since 1997. Recent surveys suggest possible signals of recovery for this important fishery; however, formal stock assessment on this population is needed. We developed a stock assessment which was peer reviewed in 2009 (Jiao 2009). The present study was conducted to restructure the recommended stock assessment model based on the reviewers' comments and do a further risk assessment to investigate the risk of reopening this fishery.

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There are many sources of data for the SMI red abalone fishery including commercial and recreational catches and current and historical (back to 1983) statistics on abalone density and relative abundance: the CDFG recreational survey (RS), CDFG fishery-independent surveys (FIS), the Channel Island National Park (CINP) fishery-independent survey, CDFG fishery-independent swim surveys (FISS), Jack Engle swim survey (JEngle), and the Partnership for Interdisciplinary studies of Coastal Oceans (PISCO) survey data. The FIS surveys also sampled the lengths of abalone observed. This study followed the recommendation from the last peer review in 2009 in selecting data to calibrate the stock assessment model (see section of data sources).

A statistical catch-at-age model fitting to length frequency observation, survey abundance and catches, was developed for stock assessment and population dynamics modeling of this fishery. F_{msy} was estimated as one of the biological reference points for management purposes, consistent with the Magnuson-Stevenson Act. $F_{40\%}$ and $F_{50\%}$ were also estimated and considered as the F_{msy} proxies. Length-specific selectivities for commercial and recreational fisheries were modeled as a truncated shape for red abalone according to their management strategy on size limits: i.e., selectivity for the commercial fishery is zero if abalone size is under 178 mm and one if not; selectivity for the recreational fishery is zero if abalone size is under 197 mm and one if not (CDFG 2006, 2007). Red abalone populations have shown large variation in recruitment/cohorts according to observations on this species and many other abalone species (Bartsch 1940; McShane 1995; Braje et al. 2009). Process error is important to consider in the variability of these situations (de Valpine and Hasting 2002; Jiao et al. 2008). Red abalone data are restricted because of limited efforts allocated towards collecting data from both fishery-dependent and fishery-independent sources. Recent survey data have helped us to understand the basis of population size, and are especially useful when appropriate time series of abundance indices are lacking. Survey information on population size was used to calibrate the population size in a Bayesian framework to help us better simulate the population dynamics of red abalone.

The model was implemented in a Bayesian framework to estimate vital parameters of population dynamics and analyzed using Markov Chain Monte Carlo (MCMC) simulation (Jiao et al. 2012). The estimated joint posterior distributions were further used for forward simulation to evaluate population response under different hypothesized fishing mortalities (Jiao et al. 2009). The objective of this study was to develop an appropriate stock assessment and evaluate the possibility of reopening the fishery through a risk assessment.

Material and Methods

Data sources and their usage in this stock assessment based on the previous TP and peer review panel's comments

Catch. Commercial landings were obtained from CDFG, which collects landing data directly from seafood dealers located in the state of California. Recreational catch estimates were obtained from Commercial Passenger Fishing Vessels (CPFV) logbook data, which are administered by the CDFG. CPFVs are the charter boats that take recreational fishers out fishing. The CDFG has been sampling recreational fishing charter

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boats operating since 1978 (Figure 1). Both commercial and recreational harvest were used to calibrate the model (see Eq 1 and Table 1)

Relative abundance or survey abundance. Time series of relative abundance were available from six sources: the CDFG recreational survey (RS), CDFG fishery-independent surveys (FIS), Channel Island National Park (CINP) fishery-independent survey, the CDFG fishery-independent swim surveys (FISS), JEngle swim survey (JEngle), and the PISCO survey data. Because of the short time series and/or low spatial coverage of the FISS, JEngle, and PISCO, these were not used in this study after discussion with scientists John Butler and Paul Crone from SWFSC and Ian Taniguchi and Laura Rogers-Bennett from CDFG. The RS was also not used because the fishery was regulated on a small daily bag limit (two or four abalone per day) causing the CPUE to not truly and directly reflect abundance. The bag limit was furthermore reduced from four abalone per day to two per day during the time frame of the data collection, so the drop in CPUE was artificial. The CINP Kelp Forest Monitoring data were eliminated because abalone abundance dropped to zero around 1990 in many locations and most importantly, the survey spatial scale is very limited so that the relative abundance from this survey is inappropriate to represent the overall SMI population changes. The population abundance surveys from CDFG FIS have been used by CDFG to develop the estimate of population abundance from 2006-2008 (CDFG 2007). The estimated survey abundance was used to calibrate population abundance from 2006-2008.

Length frequency. Length-frequency (LFQ) data from the fishery independent surveys (FIS) were used (Figure 2).

The statistical catch-at-age model fitting to length frequency data (SCAAL)

A statistical catch-at-age model calibrated by the length frequency data (SCAAL) (Hilborn and Walters 1992; Quinn and Deriso 1999) based on the available red abalone fishery data was written as,

$$
\begin{aligned}
&N_{a+1,y+1} = N_{a,y} e^{-F_{a,y}-M} \\
&C_{i,a,y} = \frac{F_{i,a,y}}{F_{i,a,y}+M} N_{a,y}(1-e^{-F_{i,a,y}-M}) \\
&C_{i,y} = \sum_a C_{i,a,y}) \\
&F_{i,a,y} = F_{i,y} S_{i,a} \\
&N_y = \sum_a N_{a,y} \\
&N_{L,y} = N_{a,y} P_{L|a} \\
&N_y^{visable} = \sum_L N_{L,y} S_L \\
&P_{L,y} = \frac{N_{L,y} S_L}{\sum_L N_{L,y} S_L} \\
&N_{a=1,y} = R_y \text{ and } Ln(R_y) = Ln(\bar{R}) + \varepsilon_R
\end{aligned}
\tag{1}
$$

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where a is age, y is year, i is the ith fishery (commercial or recreational; i = 1 or 2), $N_{a,y}$ is the population size of age a abalone in year y, $C_{i,a,y}$ is the catch of age a in year y by the ith fishery, $F_{i,a,y}$ is the fishing mortality rate of age a in year y by the ith fishery, and M is the natural mortality rate. $S_{i,a}$ is the selectivity of the ith fishery for age a abalone, s_L is the selectivity for the fishery independent survey (FIS). An age-length relationship was used to calculate $N_{L,y}$ from $N_{a,y}$ (Sullivan et al. 1990, Quinn and Deriso 1999, Jiao 2009). Here, $N_{a,y}$ is a matrix of $[\ ]_{y\times a}$, and $P_{L|a}$ is a matrix of $[\ ]_{a\times k}$, and k is the total length intervals used in this study. So, $[\ ]_{y\times a}[\ ]_{a\times k} = [\ ]_{y\times k}$ which is the $N_{L,y}$, the length frequency of the Lth length interval in year y.

To quantify the uncertainty in this model, we used a Bayesian estimator, which considers both the prior probabilities and the likelihoods of survey population size ($N_y^{visable}$), observed catch ($C_{i,y}$) and observed length frequency from the survey ($P_{L,y}$). We assumed normal error structures for survey population abundance, lognormal distribution for commercial fishery catch, normal distribution for recreational catch, and multinomial distribution for length frequency. Calculation of effective sample size of the observed length frequency followed McAllister and Ianelli (1997).

The time series of population size was estimated by projecting the abundance forward from the start of the annual catch series with the initial abundance $N_{a,1980}$, recruitment, and $F_{i,y}$ and S_L as parameters (Quinn and Deriso 1999). Appropriate selectivity and recruitment submodel selections in Eq 1 were explored. Three alternative selectivity scenarios for the FIS survey were used in the model exploration: logistic selectivity (MS1R1), double logistic selectivity (MS2R1), and age-specific selectivity that was modeled as a random walk process (MS3R1) (Table 1). Because annual recruitments of red abalone were observed to fluctuate dramatically over time, recruitment each year was assumed to follow a stochastic distribution that is built in the SCAAL (see Eq 1). After the 3 models with 3 selectivity curves and recruitment modeling as shown in Eq 1 was compared, estimated recruitment based on the posterior mean of recruitment were further analyzed. Five Ricker based stock recruitment (SR) models and 5 B-H based SR models (Table 2) used in Jiao et al. (2009) were used in the recruitment modeling based on the posterior mean of spawning stock and recruitment, the best recommended SR model was used to in the risk assessment when projecting the population from year of 2008 for another 30 years. The recommended SR model is a B-H model although its model goodness-of-fit is not the best but we did not found any mechanical factors that can be used to explain the parameters that are autocorrelated (See Table 2 and Figure 8).

We explored the estimation of F_{msy} and N_{msy} by combining SPR and SR models (Shepherd 1982). We also considered the application of $F_{x\%}$ developed from the SPR analysis, and $F_{0.x}$ developed from the YPR analysis, as the proxies of F_{msy} instead of the F_{msy} because of the weak relationship between spawning stock size and recruitment as shown in the result (Caddy and Mahon 1995; FAO 1995; Jiao 2009). Only abalone ≥

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100mm were considered in both *SSN* and SSN_{msy} estimations. Because abalone mature at length 100mm, we treated abalones $\geq$ 100mm as the spawning stock. However, fecundity at size varies largely, but we do not have estimates of % mature abalones in different length groups so far.

Bayesian approaches

A Bayesian approach was used to fit the model to data collected from different sources which included commercial and recreational catches, survey population abundances and observed length frequency from the surveys. Bayesian methods are computationally feasible for time-series models, including fisheries catch-at-age models (Millar and Meyer 2000; Calder et al. 2003; Carroll et al. 2006; Jiao et al. 2012), and have been increasingly recommended in fisheries stock assessment. The Bayesian approach uses a probability rule (Bayes' theorem) to calculate a posterior distribution from the observed data and a prior distribution that summarizes prior knowledge of the parameters (Patterson et al. 2001; Gelman et al. 2004).

Determining when random draws have converged to the posterior distribution is a critical issue when using Markov Chain Monte Carlo methods (including Metropolis-Hasting within Gibbs sampling). We used three methods: monitoring the trace for key parameters, diagnosing the autocorrelation plot for key parameters, and Gelman and Rubin statistics (Spiegelhalter et al. 2002; 2004). Three chains were used. After several sets of analysis, the first 30,000 iterations with a thinning interval of five were discarded from each chain and another 25,000 iterations with a thinning interval of five were used in the Bayesian analysis.

Prior specification in the Bayesian analysis

The Bayesian approach to estimate parameters requires specification of prior distributions on all unobserved quantities (Gilks 1996). Detailed prior specification can be found in Table 1. Non-informative priors (here, wide uniform distribution) were used for precision parameters, defined as the reciprocal of the variance of the error terms in the process and observation equations. Wide non-informative uniform distributions were used for recruitment, age-specific abundance, and fishing mortality. Informative priors were used for *M* and $N_y^{visable}$. Natural mortality (*M*) was assumed to follow a uniform distribution between 0.11 and 0.23 per year, which is from a study based on life histories of northern California red abalone (Rogers-Bennett et al. 2007). A previous study found a natural mortality of 0.15 per year for red abalone in southern California (Tegner et al. 1989). Considering the uncertainty of natural mortality in the previous estimate, the consistency of the mean estimate of 0.15 in the southern area, and the range of 0.11-0.23 in the northern area, the range seems a reasonable approximation of natural mortality with uncertainty. Because of a lack of direct data on natural mortality, we assumed *M* is unknown with a prior of uniform distribution between 0.11 and 0.23 when a Bayesian approach was used in solving the SCAAL model. Log transformed recruitment of year 1980, abalone of age 1, $Ln(R_{y=1980})$, was assumed to be between 1 and 12. Upper bound of 12 has been tested to make sure that it is not informative and do not influence the results. Abalone abundance of 1980 cross other ages were assumed to have an upper

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bound $R_{y=1980}e^{-M_{low}}$ (M_{low} is the lower bound of M). The estimated survey abundance was used to calibrate population abundance from 2006-2008 (CDFG 2007). Priors for other parameters were specified and listed in Table 1. Sensitivities on the priors of the variances and boundaries of uniform distributions were analyzed and specified in Table 1 also.

Risk assessment: framework and simulation studies

Risk assessments were done based on the recommended stock assessment models developed in the Model Section. The estimated joint posterior distribution shown as the recorded posterior runs were used in the forward simulation study, which include the population size of 2008 (SSN_{08}), the historical stock and recruitment and the parameters in the recruitment model of abalone, the estimated natural mortality, and parameters in the selectivity submodel (Hilborn et al. 1993; Patternson et al. 2001). Because there is no clear SR relationships for this population (see Figure 8), $F_{0.1}$, $F_{60\%}$ and $SSN_{60\%}$ and $F_{80\%}$ and $SSN_{80\%}$ together with F_{msy} and SSN_{msy} were estimated. The following measurements were estimated as a probabilistic way: $P(F > F_{msy})$, $P(F > F_{X\%})$, $P(F > M)$, $P(SSN < SSN_{X\%})$, $P(SSN < SSN_{msy})$, $P(SSN < SSN_{08})$, P(D < 2000/hec) etc. $P(F > F_{msy})$ and $P(SSN < SSN_{msy})$ et al., were estimated in the number of iterations where the posterior value of $F > F_{BRP}$ and the number of iterations where the posterior value of $SSN < SSN_{BRP}$ in the Bayesian analysis of the SCAAL described above.

When risk was evaluated based on the abalone density, density in the simulated years were assumed to be proportional to population abundance and mean density of 2006 was used to calibrate the density in the simulated years. Also density is measured as the observable density (cryptic considered). When density of the abalone was used as an indicator of the population status, mean density and density uncertainty were also estimated from the survey (CDFG 2006, 2007).

Management scenarios were only designed to be varying on F and the minimum harvestable length strategy followed historical policy on commercial and recreational fisheries. The corresponding total catches (total allowable catch, TAC) under different F values were also estimated.

The Bayesian model was solved using both MATLAB (Mathworks 2012) and WinBUGS (Spiegelhalter et al. 2004). The risk assessment was done in MATLAB.

Results

The population dynamics history was calibrated by historical catch, length frequency data, and the survey abundance from 2006-2008. The model fits and the parameter estimates using data from 1980 to 2008 showed that the fits and parameters estimated were very close to each other among the 3 model scenarios although differences were still observed in recruitment patterns over time (Figures 2-7). The fits were mainly dominated by the LFQ even when the effective sample sizes other than the real sample sizes were used (Figure 2).

The estimated selectivity patterns were different (Figure 4), and they did influence

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the estimates of recruitment but not on the results of *M* and *F* (Figures 5 and 6). The model goodness-of-fit (DIC here) supported the logistic selectivity (Table 1). The uncertainty when age-specific selectivity were modeled as a random walk process was much higher than the other 2 model scenarios, but no clear dome shaped curvature was supported through this model exploration. Also the double logistic model did not show a dome shaped curve. Both the dome shaped selectivity and the random walk selectivity showed higher selectivity at length less than 50 mm, which is apparently caused by the observed higher LFQ for abalones less than 50 mm in the surveys of 1993 and 1994 (Figure 2).

Natural mortality estimates tended to be small, and the posterior modes were all close to 0.12-0.14 (Figure 5). However, because the prior for the natural mortality was based on many previous studies on red abalone, so no extra sensitivity analysis were used but the prior apparently influenced the results largely. Posterior mean estimate of *M* would be lower if the lower bound of the prior was decreased.

The SR relationship was weak, and no clear relationships were found between S and R, and between South Oscillation Index (SOI) and R (Figure 7 and 8). Recruitment was high in the early 1990s, but was very low in the 2000s (Figure 6a). Recruitment relationships with SOI were also explored for each model scenario but no strong relationships were found (Figure 7). The five models fitted to the top SCAAL model (MS1R1) indicated that the SR autoregressive models worked the best for the SR data (only results for MS1R1 were shown in Table 2 and Figure 8). However, because of lack of explanation on the autoregressive patterns, the autoregressive models were not used in the risk assessment. Risk propagates much faster for these nonstationary time series models than their corresponding stationary time series models.

Population size was low in the 1980s and then increased in 1990s but then decreased in 2000s again (Figure 6a). The high fishing mortality period occurred from the early 1980s to mid 1990s. After the moratorium, there was no clear increasing trend in population size (Figure 5). Fishing mortalities were high before 1995 but the estimates were of high uncertainty in all the three model scenarios (Figure 6b).

The selection of recruitment model influence the $F_{X\%}$, and $F_{0.1}$ and F_{msy} dramatically (Figure 9). The abalone individual growth was estimated based on data that were in a El Nino period, which indicated that the individual growth of abalone estimated based on the data in this period tend to have a slow growth. This resulted in high $F_{X\%}$ and low $F_{0.x}$ estimates. Estimated F_{msy} were always high, which implied that the current minimum catchable size used in the fishery is large enough and the fishery is not sensitive to F values in theory.

The risk assessment shown as probabilities higher or lower than specified *F* measurements indicated the risk of overfishing under different *F* values (Figure 10). The corresponding population size and population growth rate and TACs over time given different *F* levels were shown in Figure 11. Because the selection of recruitment model is of high uncertainty, results of using 3 types of recruitment models were shown in Figure 11. B-H and Random recruitment implied that the population would reach equilibrium over time under different *F* levels (Figure 11), while Ricker recruitment model implied that the population would oscillate because the strong density dependent SR relationship. B-H is recommended in this case given the reality that historical high oscillation was not observed and the biological reference points based on Ricker model is

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unreasonably high. The risk assessment shown as probabilities higher or lower than specified measurements of spawning stock size indicated the risk of the population being overfished (Figure 12). The probability of a population lower than 2000 abalone per hectare was always high even when *F* was 0 (Figure 12).

Discussion

F_{msy} and SSN_{msy} estimated by combining YPR and SR models (Shepherd 1982) tends to be high. Considering that spawning stock size is hard to define and that there was a weak relationship between recruitment (age-1 abalone) and spawning stock size (size of population ≥ 100mm in length), reference points from this approach are not recommended. However, the use of F40%, SSN40% etc., is a conservative measurement and we do not meant to use them to measure the risk of increase of decrease of the fishery. They may be used temporarily as a measurement of spawning stock size that we want to keep.

The stock recruitment relationship of this species is weak, so the biological reference points $F_{x\%}$ from the SPR model, and $F_{0.X}$ from the YPR model, are usually suggested rather than an F_{msy} from the age structured models and YPR model (Shepherd 1982). However, in this study the estimated BRPs from SPR analyses were much higher than historical *F* when Ricker model was used (Figure 9b), which suggests a possible bias of using these estimated BRPs (Jiao 2009). An empirical biological reference point such as natural mortality (Patterson 1992) is therefore suggested as a temporal proxy of F_{msy} based on this study. $F_{50\%}$ and $F_{0.1}$ etc., may be considered as alternatives in the future when more data were collected to validate their uncertainty and usefulness. With more high quality data collected, it may be possible to calculate better BRPs in the future.

Modeling recruitment is critical for future management strategy evaluation. The recruitment of SMI abalone is weakly explained by spawning stock size and SOI. This is common for an abalone species (McShane 1995; Braje et al. 2009). However, it is still beneficial if more causal factors combining with patterns cross space and time can be explored in the future. Such analysis should improve the recruitment prediction in the future stock assessment. Sensitivity of the risk assessment results to alternative recruitment models as we did here is useful and needed before a better recruitment model is found.

The overall mean population density of this fishery was 1200 abalone/hectare in 2006, with standard error ranging from 50 to 170. In high density locations (identified as possible management zones), densities of red abalone ranged from 1500 to 2400/hectare, with standard errors ranging from 200 to 300. A hierarchically structured distribution can further be used to simulate the density in the next step.

Survey abundances were only available in 3 years, and the length frequency sampling had very limited years of collection and spatial coverage. These results and the high data uncertainty suggest that the results need to be carefully considered when managing this fishery.

This study is intend to evaluate the risk of reopening this SMI abalone fishery, but NOT to evaluate alternative management strategies (MSE) as done in fisheries and conservation biology (Butterworth 2007; Butterworth et al. 2010; Milner-Gulland et al. 2010; Bunnefeld et al. 2011). If the decision made by CDFG is to reopen this fishery

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after this study, a full MSE is suggested to search for management strategies that are robust to recruitment stochasticity, low predictability and high data uncertainty.

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Table 1: Priors used in the models (catches are in 1000 abalone in the models). See text for the justification of the priors.

Models	Distributions of variables, Parameters and their priors	Selectivity	Recruitment	Sensitivity analysis to priors
MS1R1 (DIC= 153.73)	$C_{1,y} \sim \ln N(Ln(\bar{C}_{1,y}), \sigma_{c1}^2)$; $C_{2,y} \sim N(\bar{C}_{2,y}, \sigma_{c2}^2)$; $N_y \sim N(\bar{N}_y, \sigma_{N_y}^2)$; $y = 2006$, 2007 and 2008; $N'_{L,y} \sim MN(P_{L,y}, N'_y)$, N'_y is the effective sample size =80 $F_{i=1,y} \sim U(0,4)$; $F_{i=2,y} \sim U(0,3)$; $M \sim U(0.11, 0.23)$; $\sigma_{c1}^2 \sim U(0.001,1)$; $\sigma_{c2}^2 \sim U(0.001,10)$; $\ln N_{a=1,y=1980} \sim U(1,12)$ $\ln N_{a>1,y=1980} \sim *U(l_a, l_b)$	$S_L = \frac{1}{1+e^{-a_0(L-b_0)}}$; $a_0 \sim U(0,0.5)$; $b_0 \sim U(50,150)$	$Ln(R_y) \sim N(Ln(\bar{R}), \sigma_R^2) I(0.001,12)$ $\sigma_R^2 \sim U(0.001,10)$	$N'_y = 40$; $\sigma_{c1}^2 \sim U(0.001,10)$ $\sigma_{c2}^2 \sim U(0.001,5)$ $\sigma_R^2 \sim U(0.001,5)$ Lower l_b by minus 0.5
MS2R1 (DIC= 223.22)	Same as above	$S_L = \frac{\frac{1}{1+e^{-a_0(L-b_0)}} + \frac{1}{1+e^{a'_0(L-b'_0)}}}{\max[\frac{1}{1+e^{-a_0(L-b_0)}} + \frac{1}{1+e^{a'_0(L-b'_0)}}]}$ $a'_0 \sim U(0,0.001)$; $b'_0 \sim U(10,180)$	Same as in MS1R1	Same as in MS1R1
MS3R1 (DIC= 156.16)	Same as above	$Ln(S_L) = Ln(S_{L-1}) + \varepsilon_S$; $\varepsilon_S \sim N(0, \sigma_s^2)$	Same as in MS1R1	Same as in MS1R1 $\sigma_S^2 \sim U(0.0001, 0.2)$

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		$\sigma_S^2 \sim U(0.001, 0.1)$; $S_L \sim U(0,1)$		

*Abalone abundance of 1980 cross other ages were assumed to have an upper bound $R_{y=1980}e^{-M_{low}}$ (M_{low} is the lower bound of M).

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Table 2: Models used to fit the SR (posterior means of S and R)

SR models (Ricker model and its alternations)	DIC	SR models (Beverton-Holt (BH) model and its alternations)	DIC
M_R1 (Ricker model)	362.11	M_R1 (BH model)	361.38
M_R2 (Residual Autoregressive model)	358.79	M_R2 (Residual Autoregressive model)	360.91
M_R3 (Random Walk model)	352.45	M_R3 (Random Walk model)	341.32
M_R4 (Autoregressive model)	338.73	M_R4 (Autoregressive model)	331.39
M_R5 (Hierarchical Ricker model)	358.75	M_R5 (Hierarchical BH model)	338.45

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Figure 1: Catch (in number of abalone from commercial and recreational fisheries).

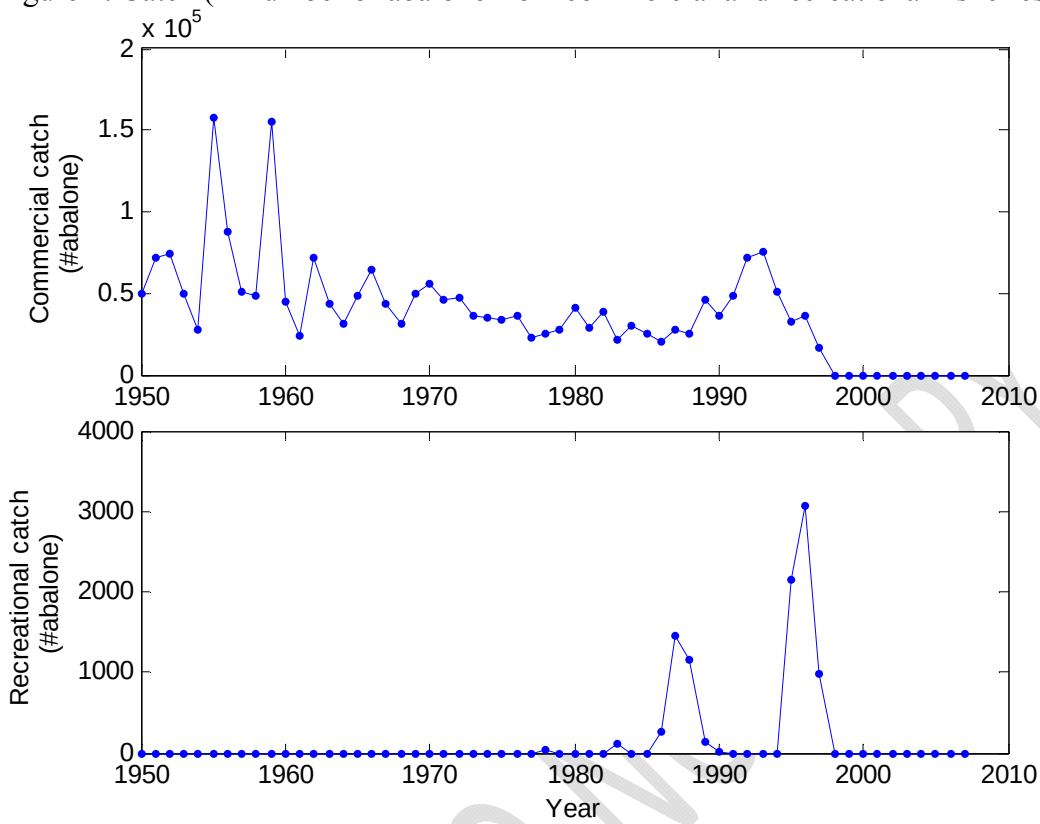

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Figure 2: Length frequency (LFQ) from fishery independent surveys on the population. Yellow car are the original observed length frequency.

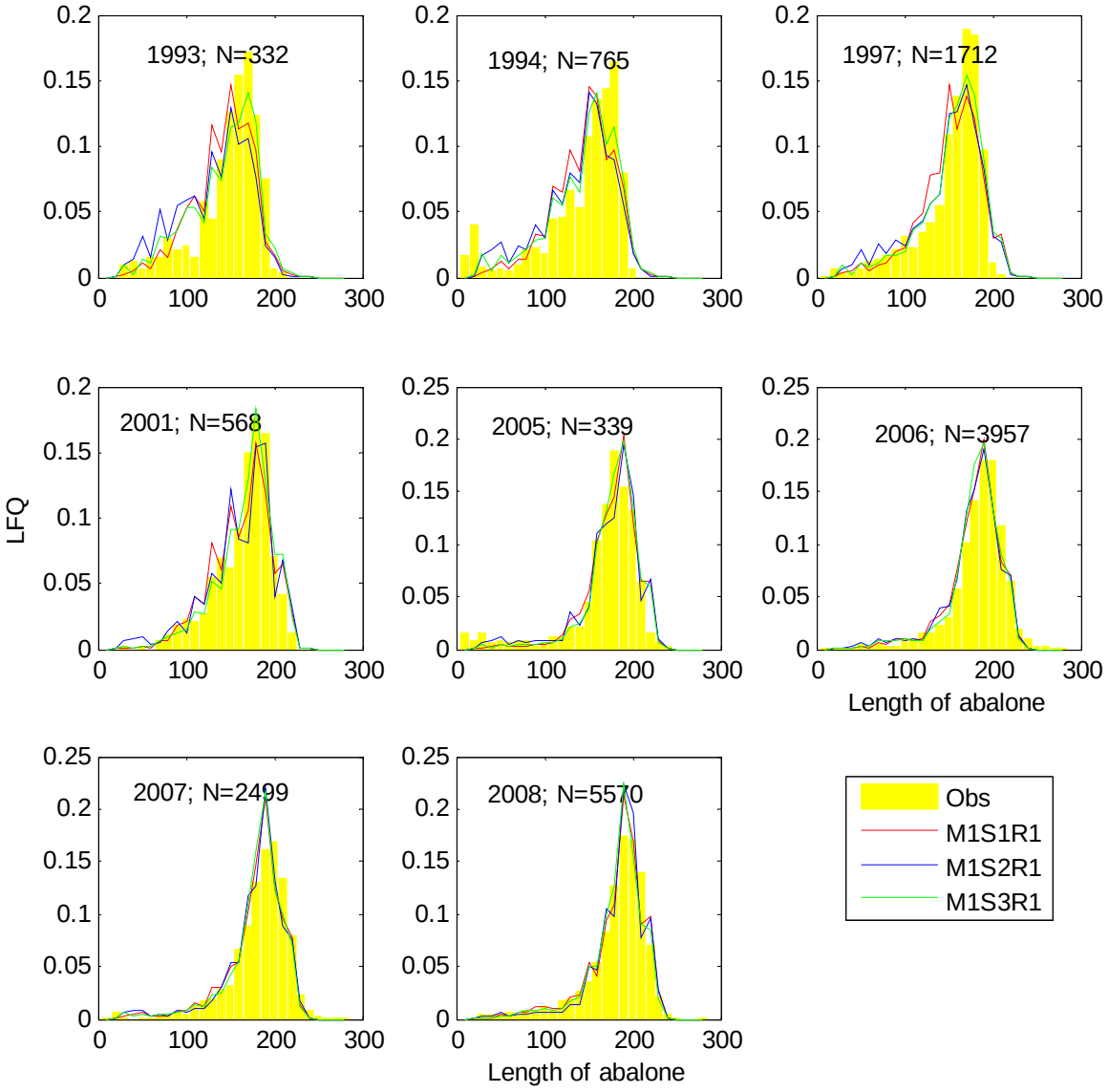

Figure 3: Fit of Catch from 1980 to 2008.

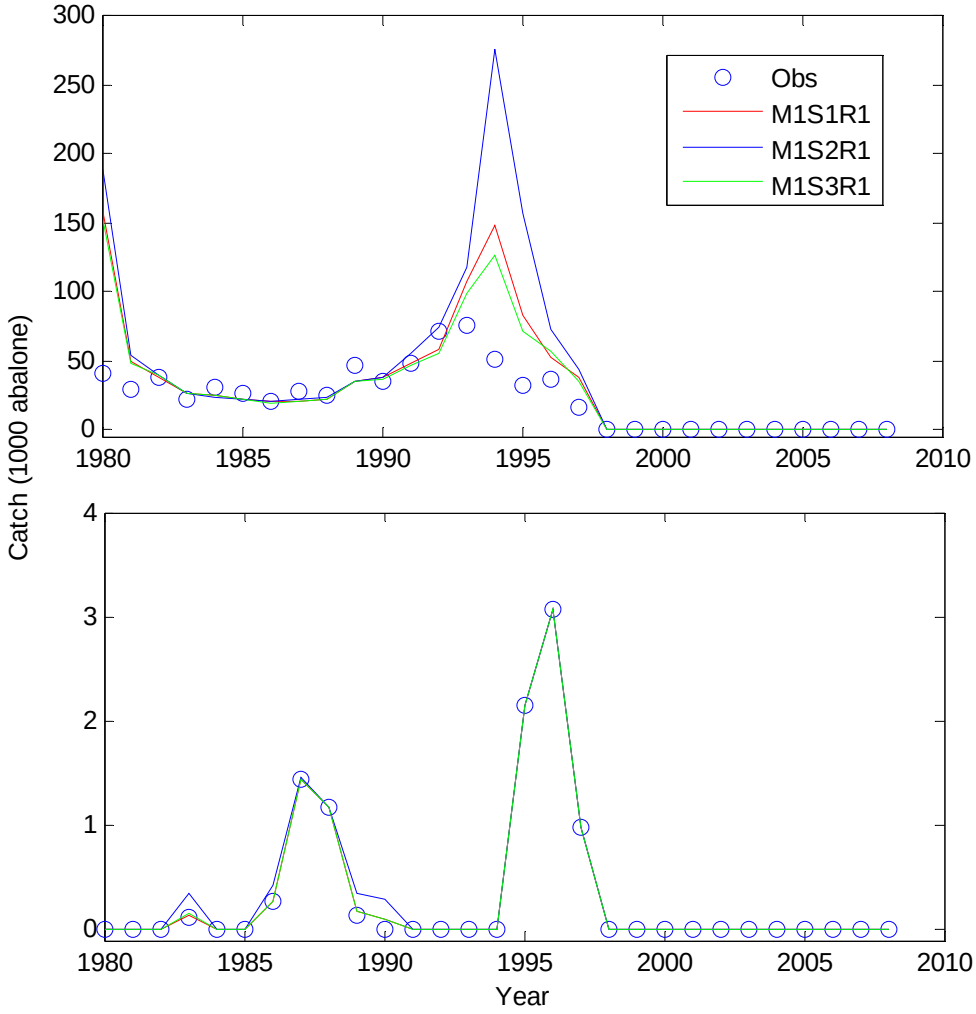

Figure 4: Estimated selectivity curve from the 3 model scenarios. Red line: fit by MS1R1; blue line: fit by MS2R1; green line: fit by MS3R1. Continuous lines over years denote the mean; dotted lines denote 95% credible intervals.

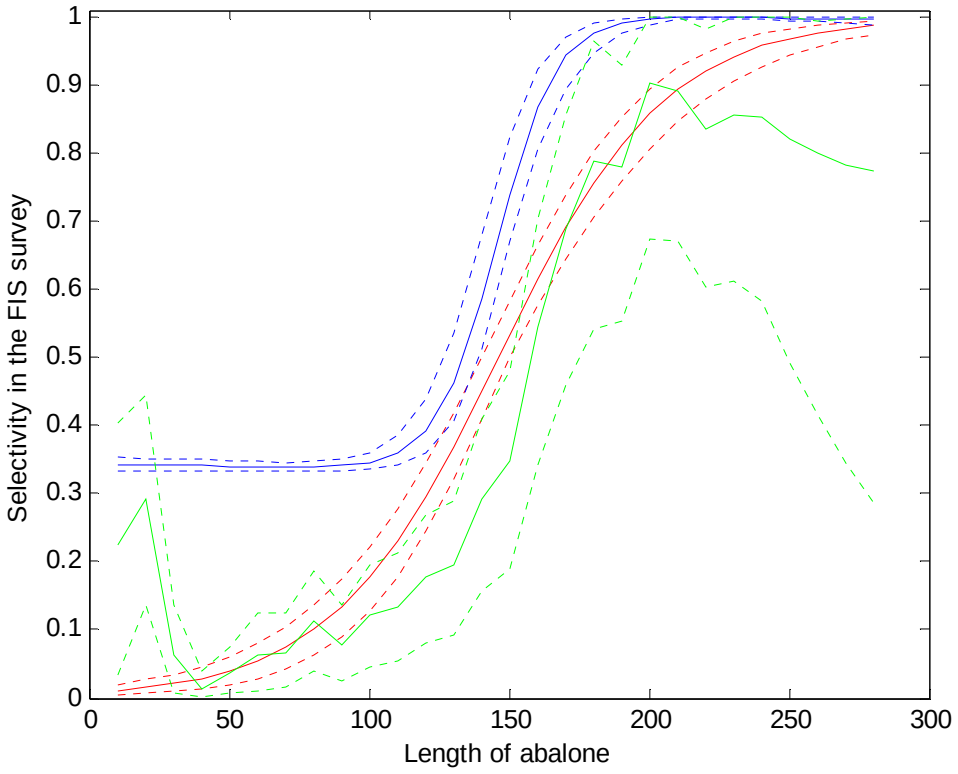

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Figure 5: Estimated posterior distribution of natural mortality M.

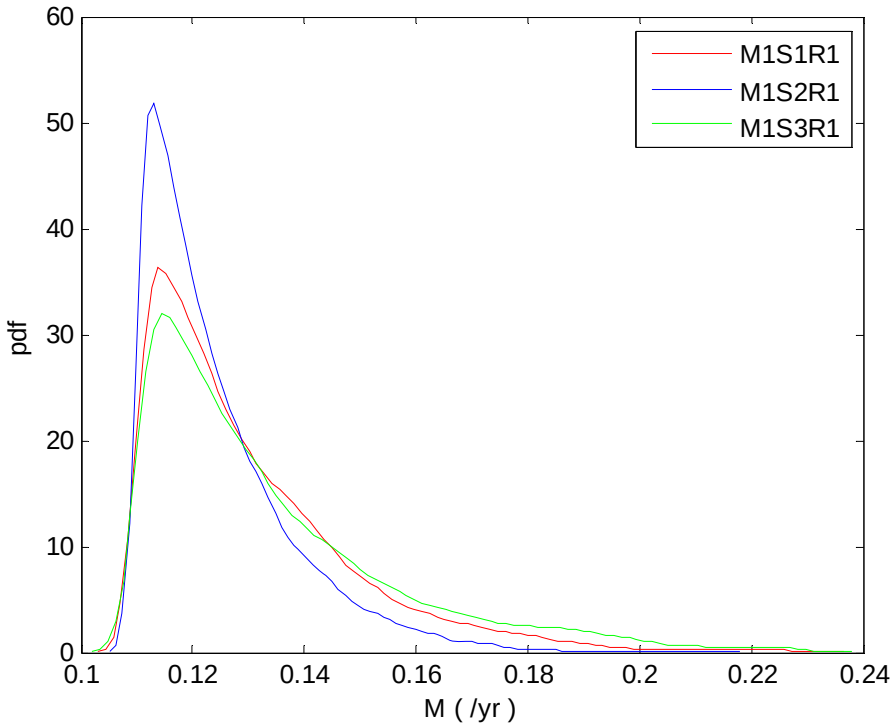

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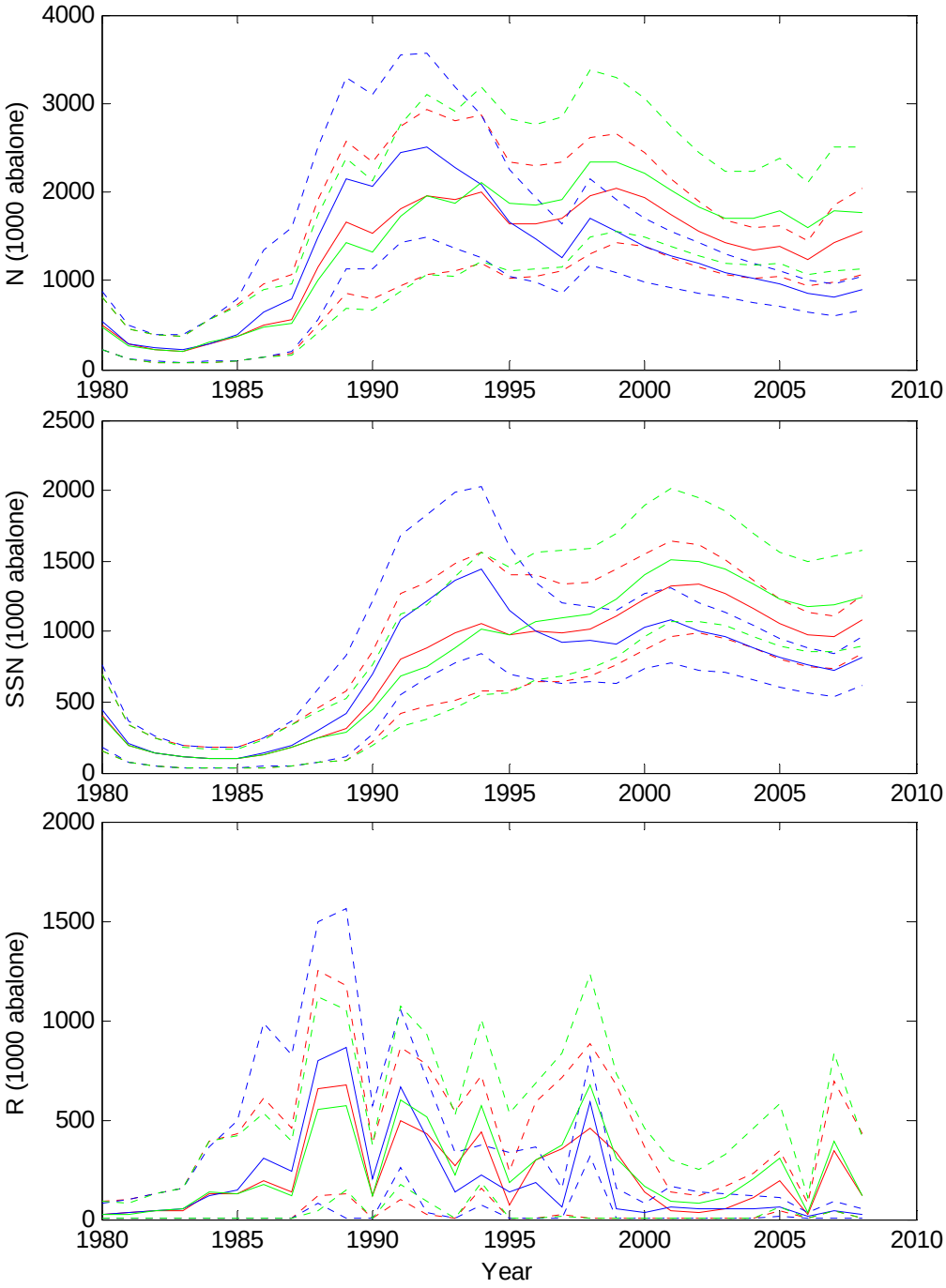
Figure 6: Estimates of population abundance and fishing mortality when data from 1980-2008 were used. Red line: fit by MS1R1; blue line: fit by MS2R1; green line: fit by MS3R1. Continuous lines over years denote the mean; dotted lines denote 95% credible intervals.

6a: Credible interval of population abundance (N), Spawning stock size (SSN) and recruitment (R) estimates.



6b: Credible interval of fishing mortality estimates. From top to bottom, the corresponding panels are for commercial and recreational Fs.

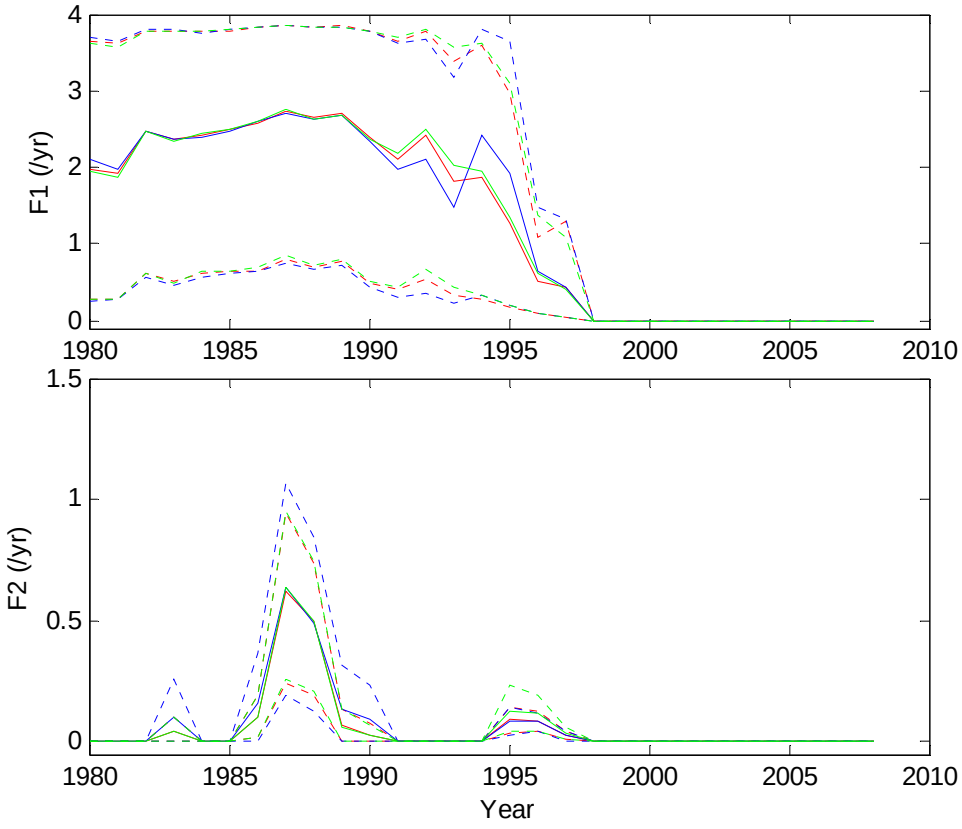


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Figure 7: Posterior mean of S and R in 1000 abalones. Figures on the left column show the S and R relationship; Figures on the right column show the recruitment under different SOI (South Oscillation Index). Figures on the first to third rows are from the MS1R1, MS2R1, and MS3R1 separately.

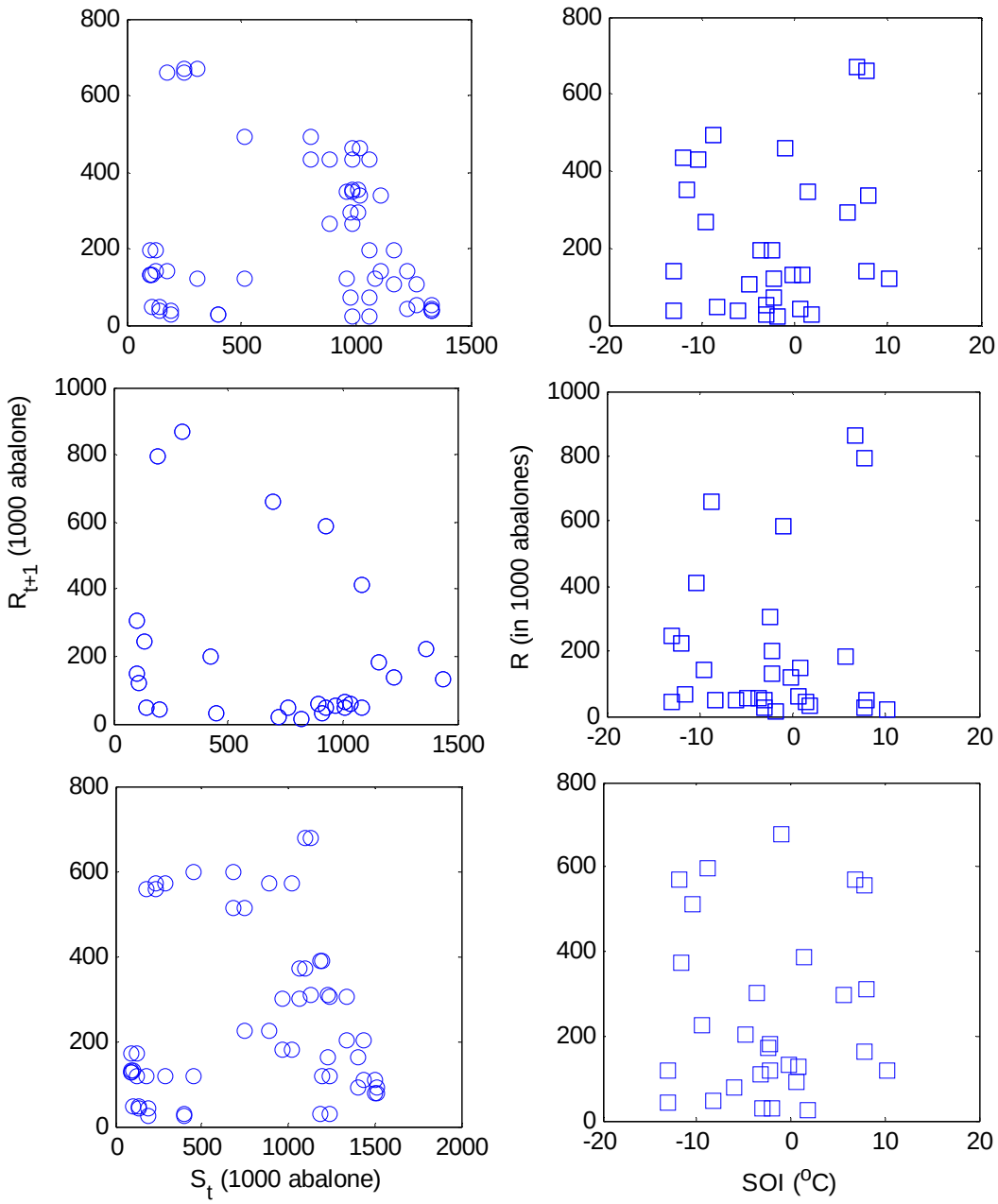
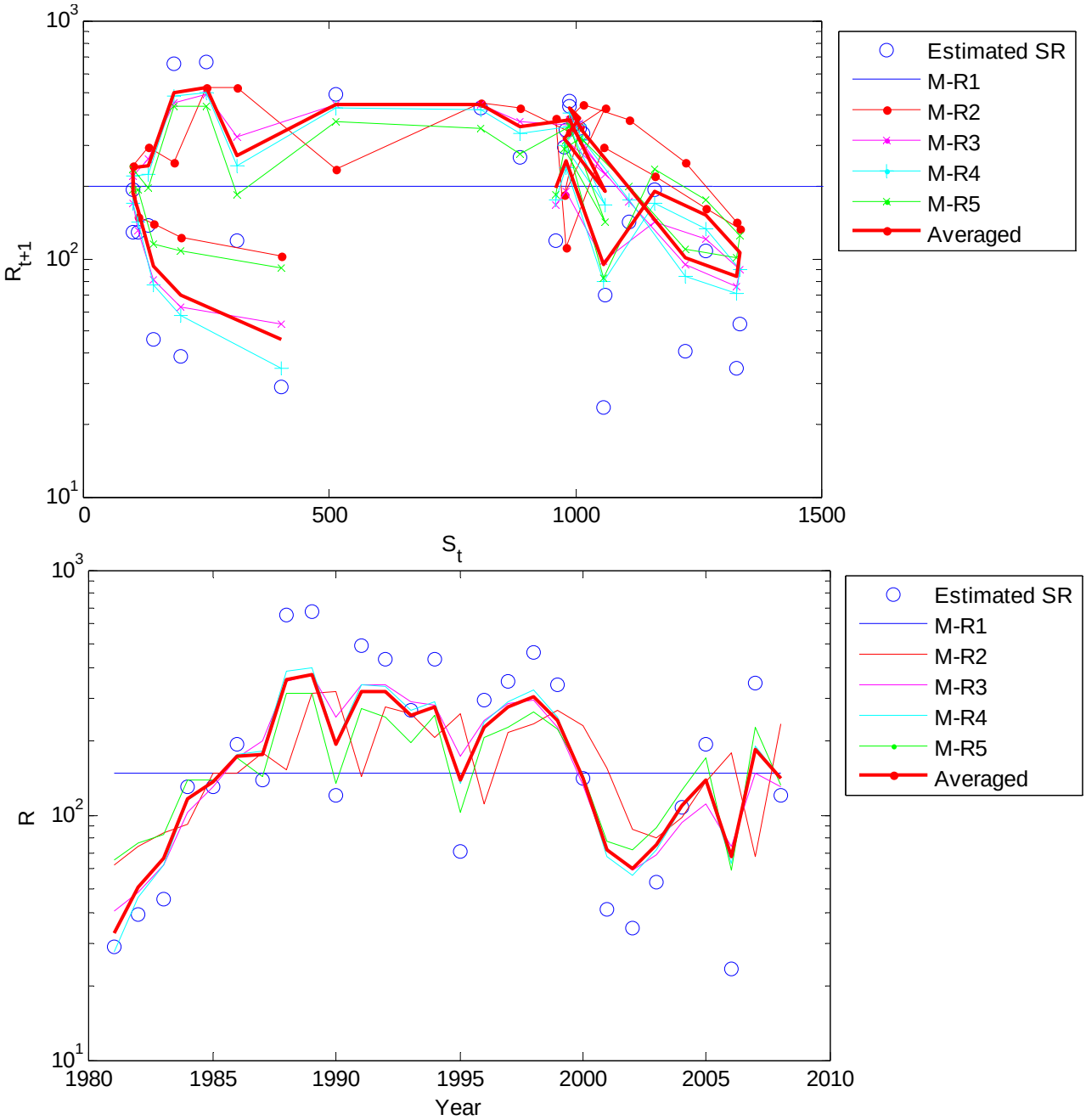


Figure 8: Posterior mean of S and R in 1000 abalones from MS1R1, and the fits to them when different SR models in table 2 were used.
8a: Beverton-Holt model and its alternations



8b: Ricker models with its alternations

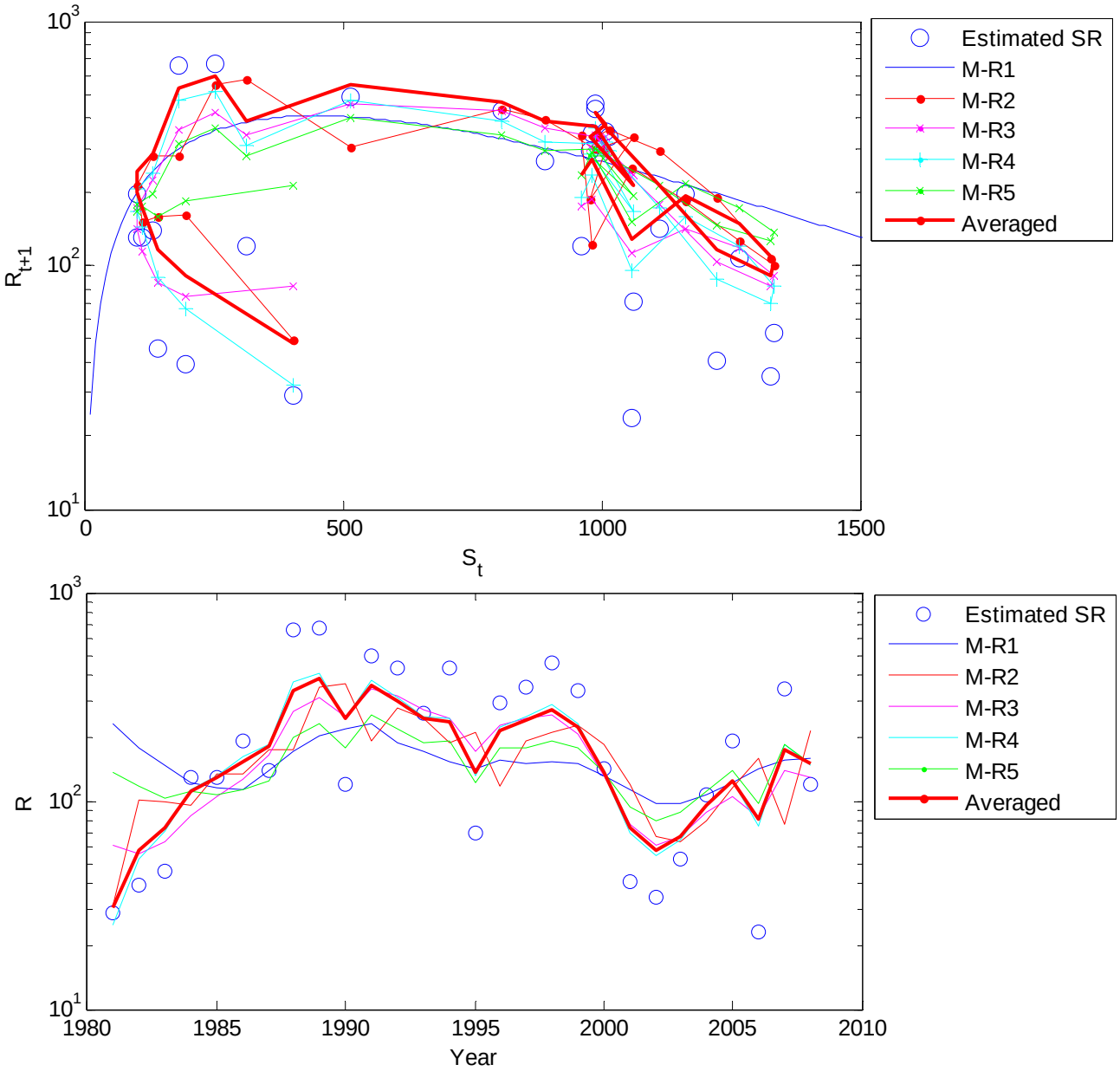
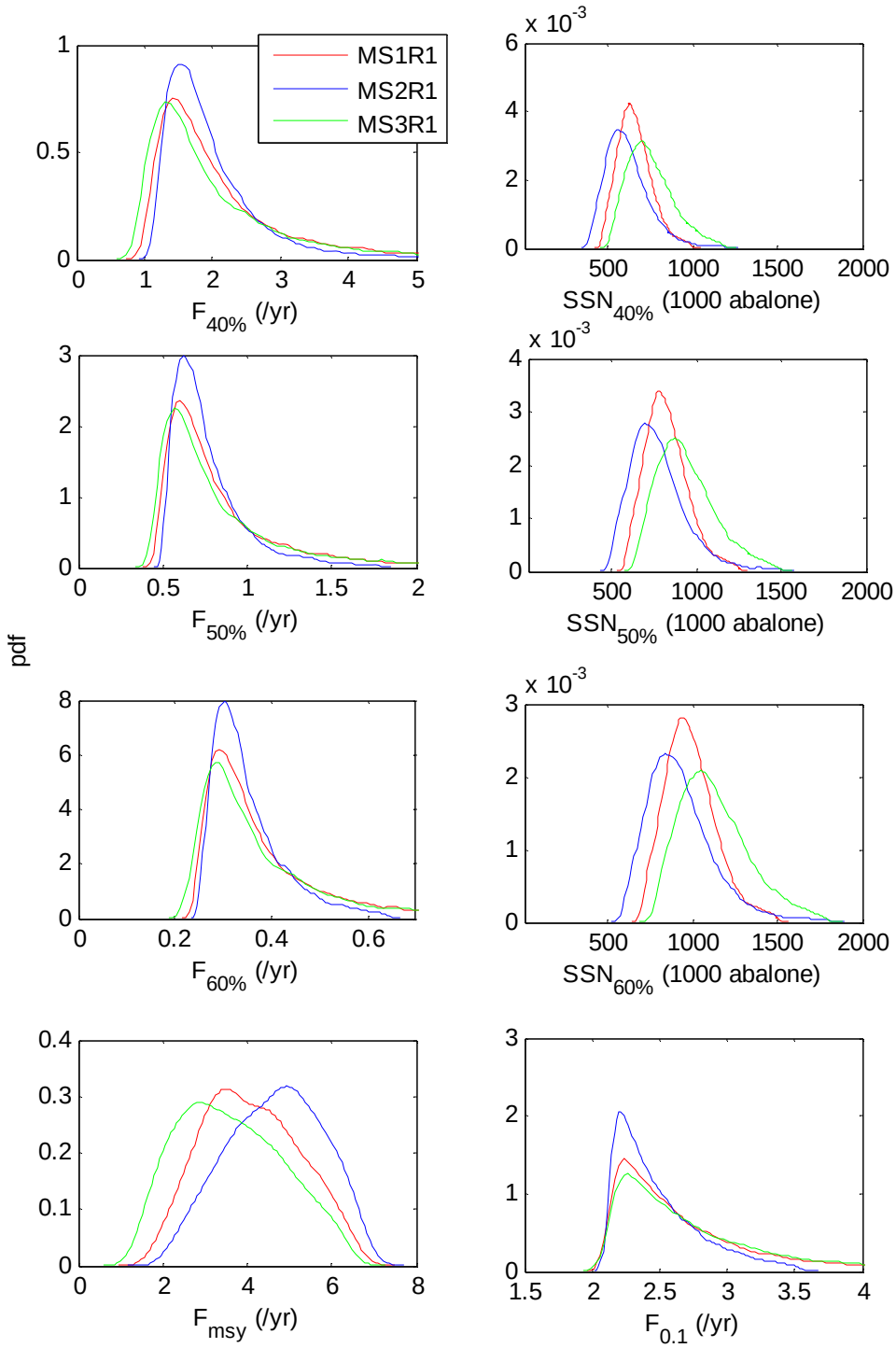


Figure 9: Estimated *BRPs* when Beverton-Holt (Fig 9a) and Ricker (Fig 9b) models were used as the recruitment models.
9a:



9b:

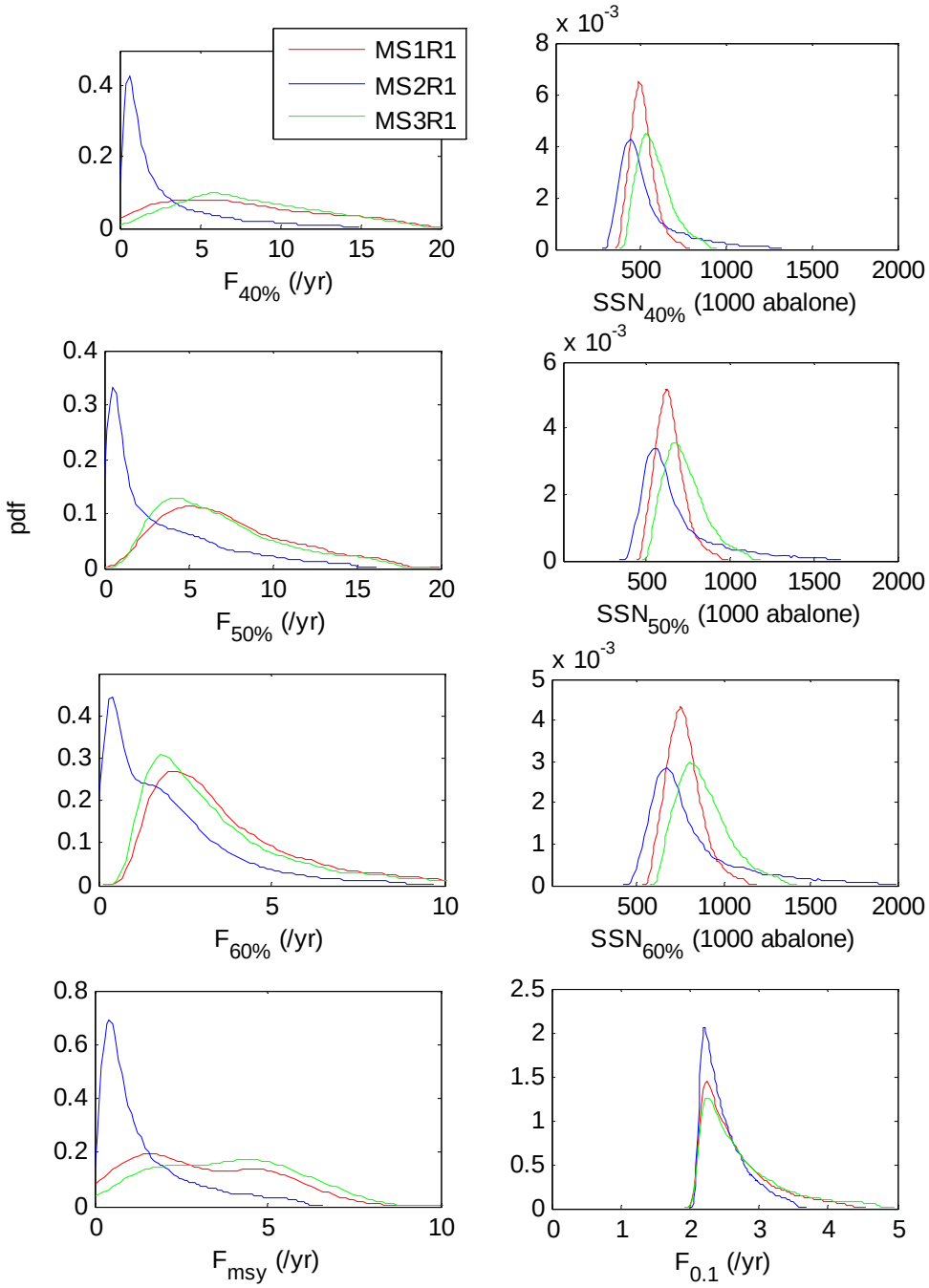

MS1R1
MS2R1
MS3R1
pdf
F40% (/yr)
SSN40% (1000 abalone)
x 10-3
F50% (/yr)
SSN50% (1000 abalone)
x 10-3
F60% (/yr)
SSN60% (1000 abalone)
x 10-3
Fmsy (/yr)
F0.1 (/yr)

Figure 10: cdf (cumulative distribution function) or the $P(F>F_{BRP})$ when MS1R1 and BRPs from Beverton-Holt Recruitment model was used.

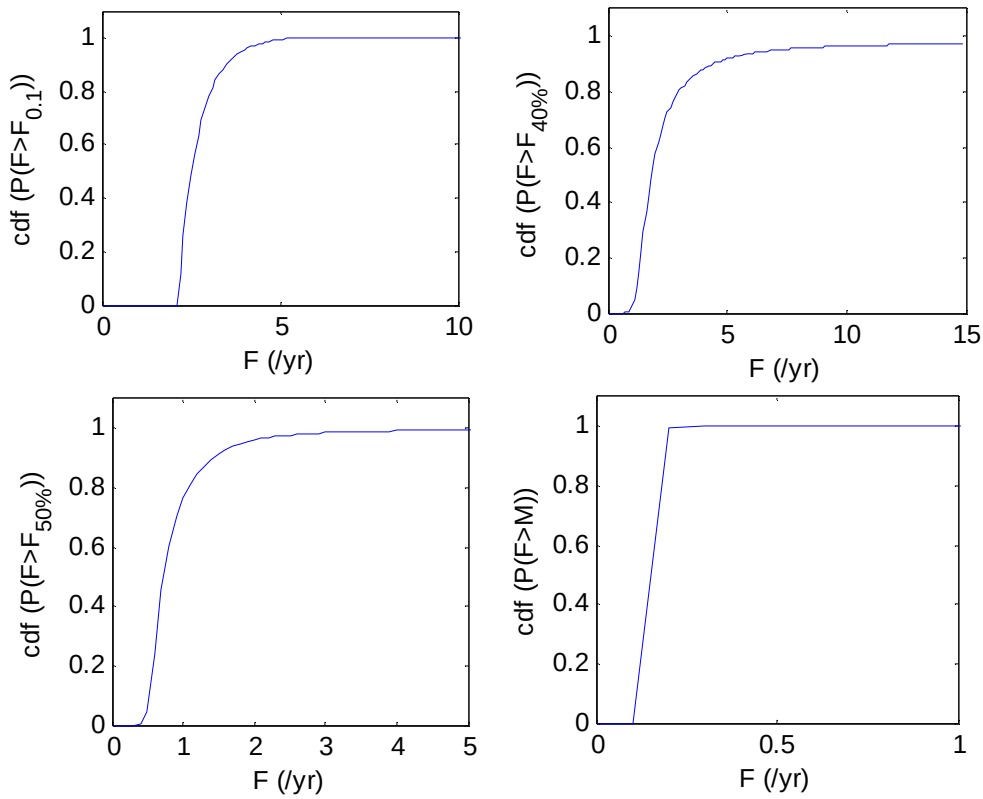
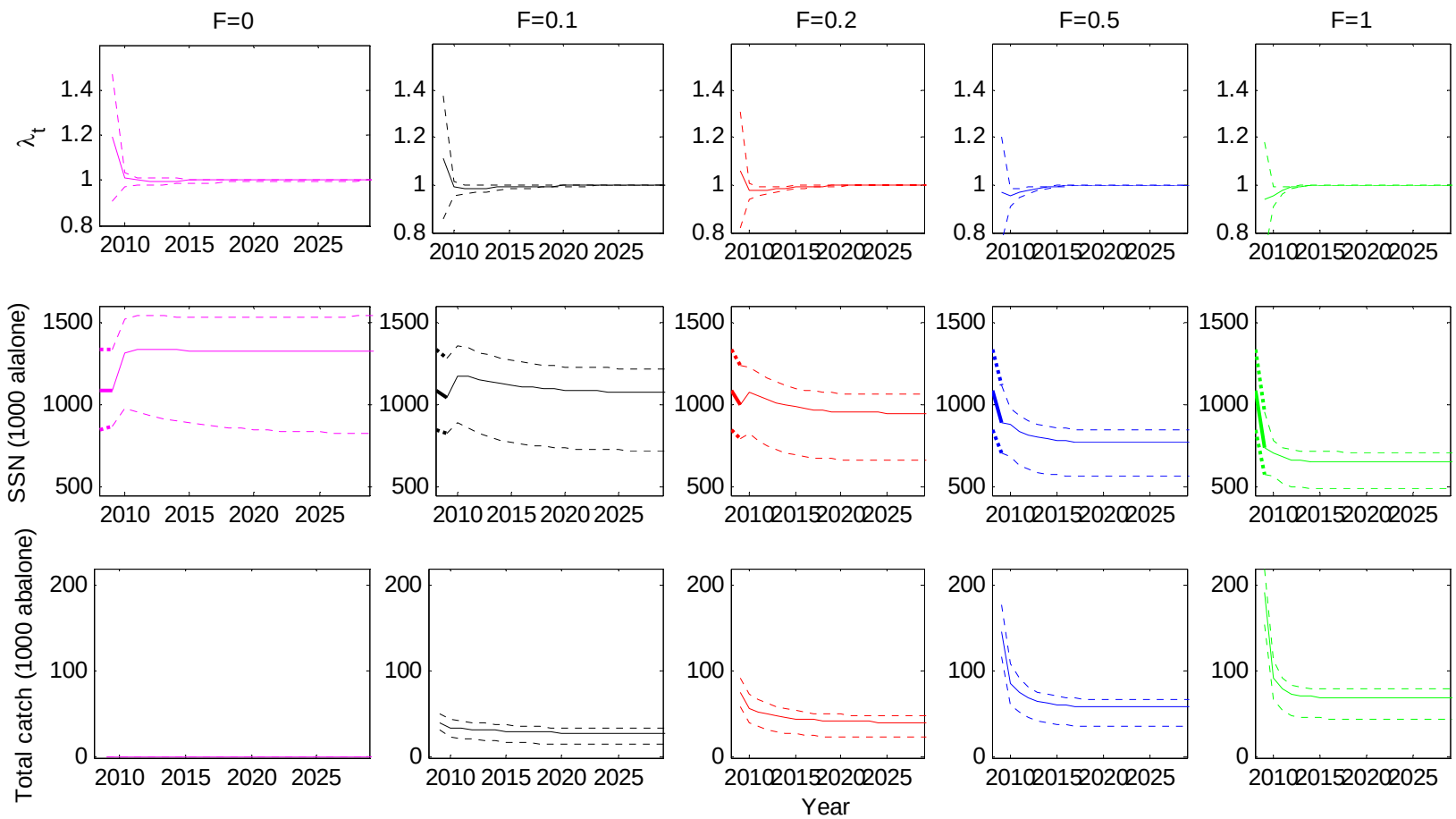
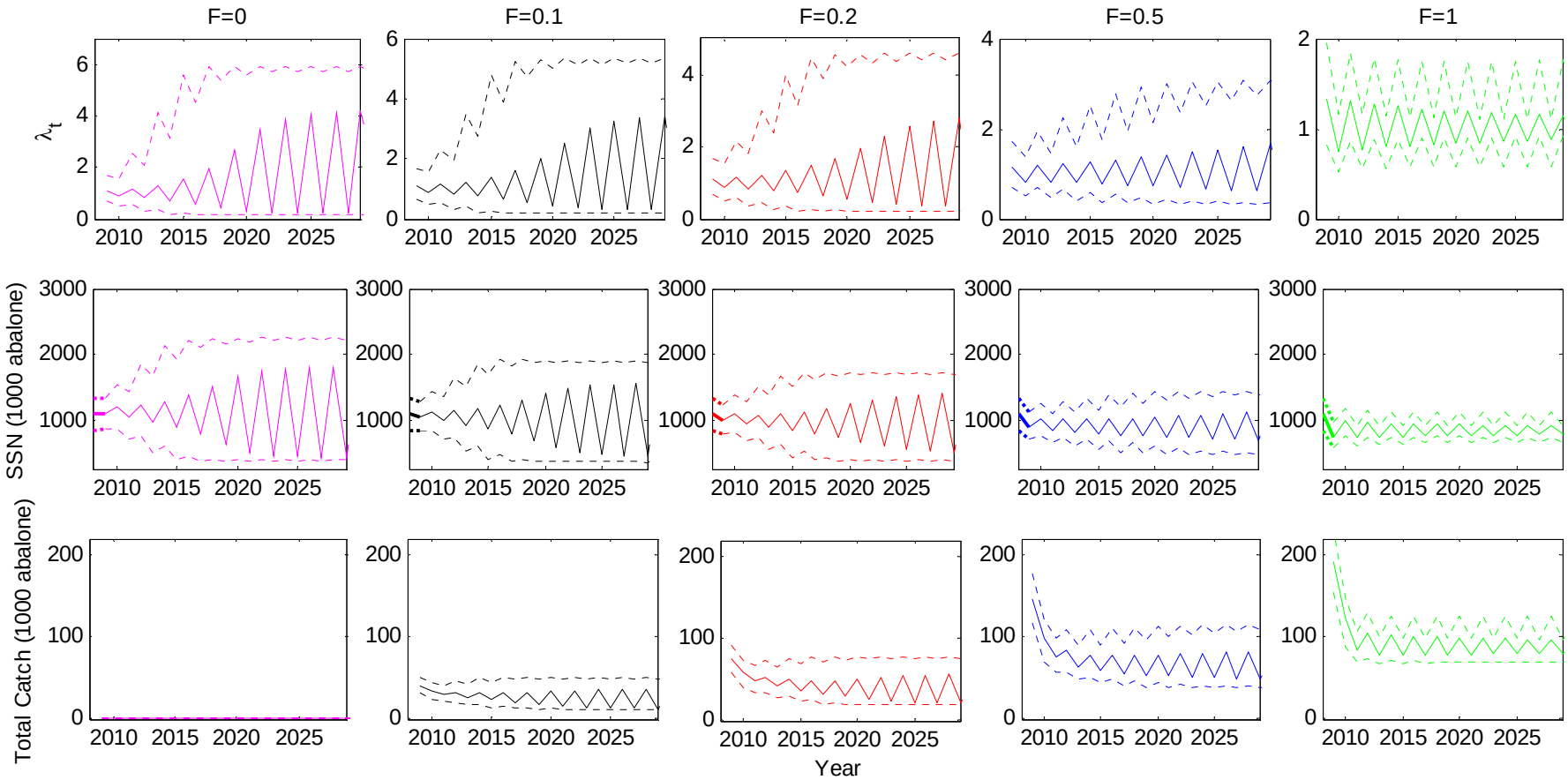


Figure 11: Changes of population growth rate (λ , N_{t+1}/N_t), SSN (abaone>100mm), Total catch (1000 abalone) over time given 5 fishing mortality levels (0, 0.1, 0.2, 0.5 and 1) based on model MS1R1 and different R models in the population projection.
11a: the joint posterior distribution of $N_{a,2008}$, and a Beverton-Holt Recruitment model from each posterior runs of Na,y., is used in the projection of the risk assessment;



11b: the joint posterior distribution of $N_{a,2008}$, and a Ricker Recruitment model from each posterior runs of Na,y., is used in the projection of the risk assessment;



11c: recruitment in the projection is assumed to follow $\ln N(Ln(\bar{R}),\sigma_R^2)$ based on estimated historical R from MS1R2. Other parameters such as $N_{a,2008}$ and selectivity are still based on the joint posterior distributions.

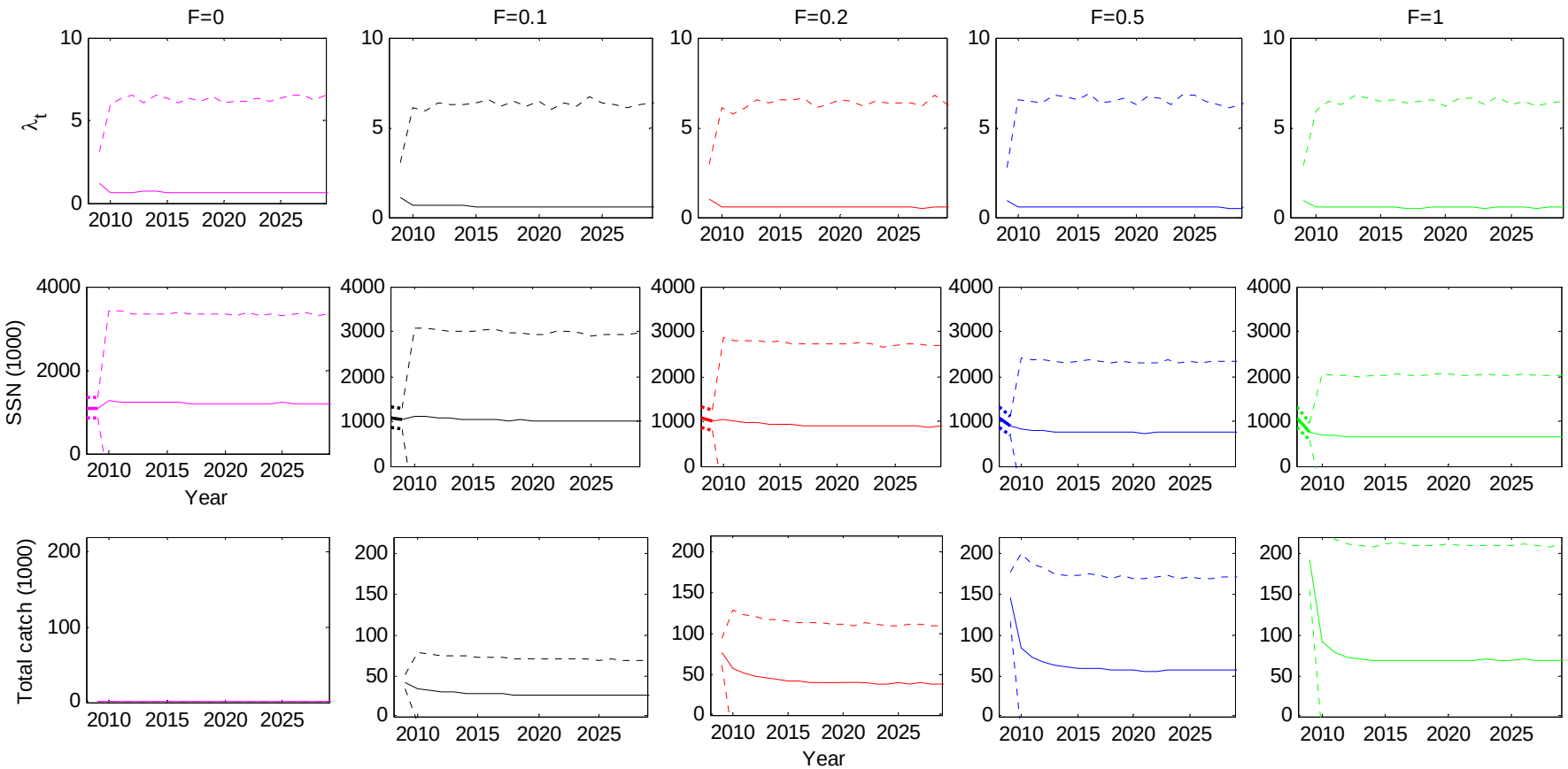
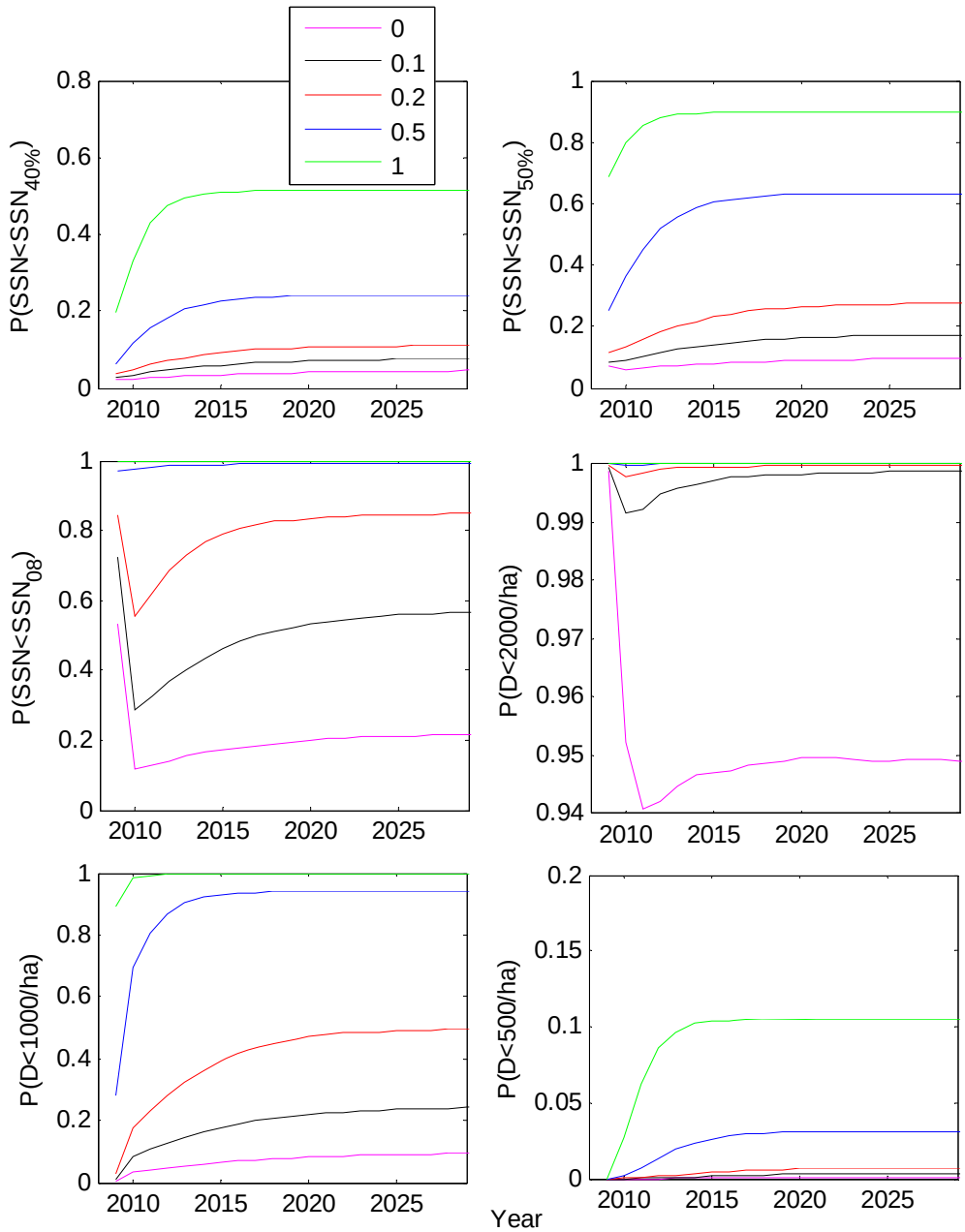
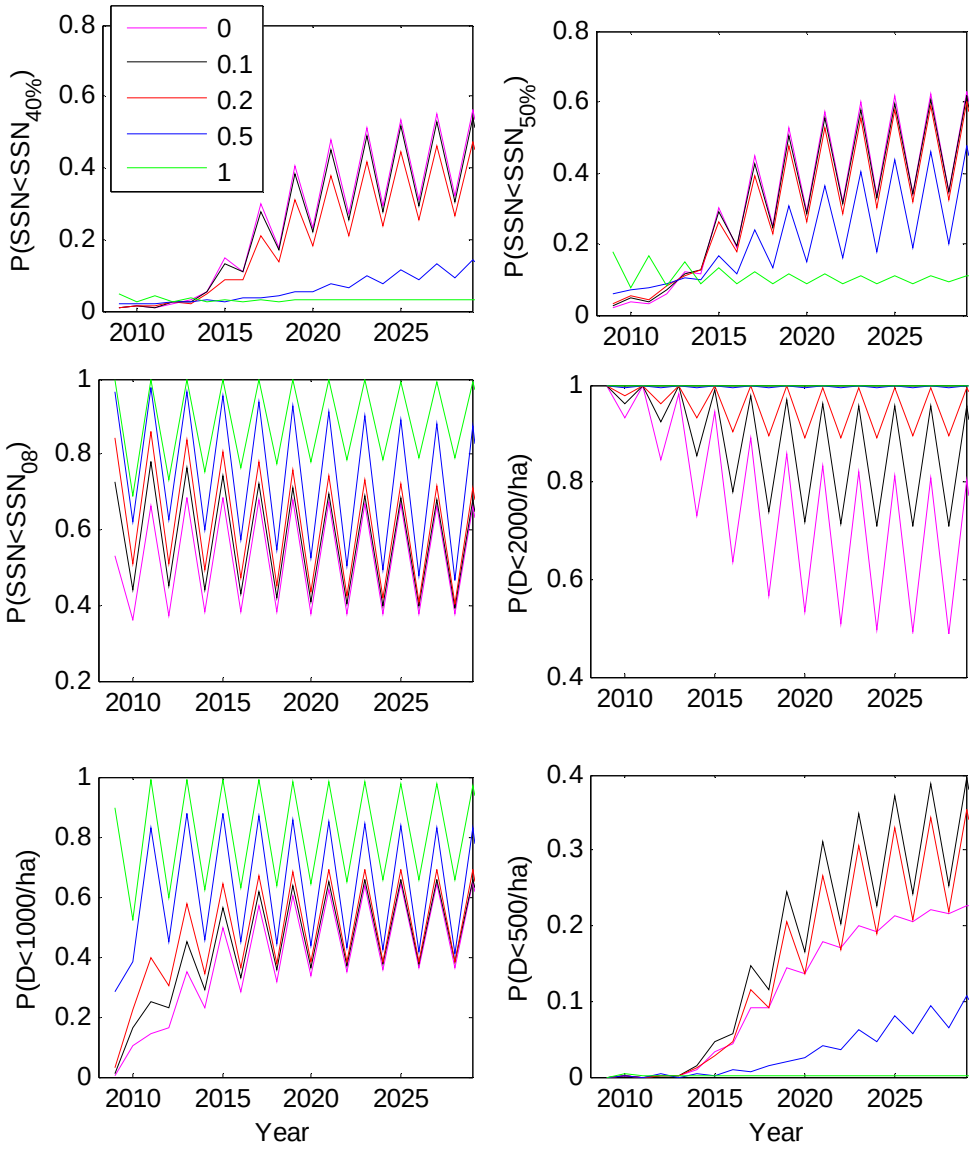
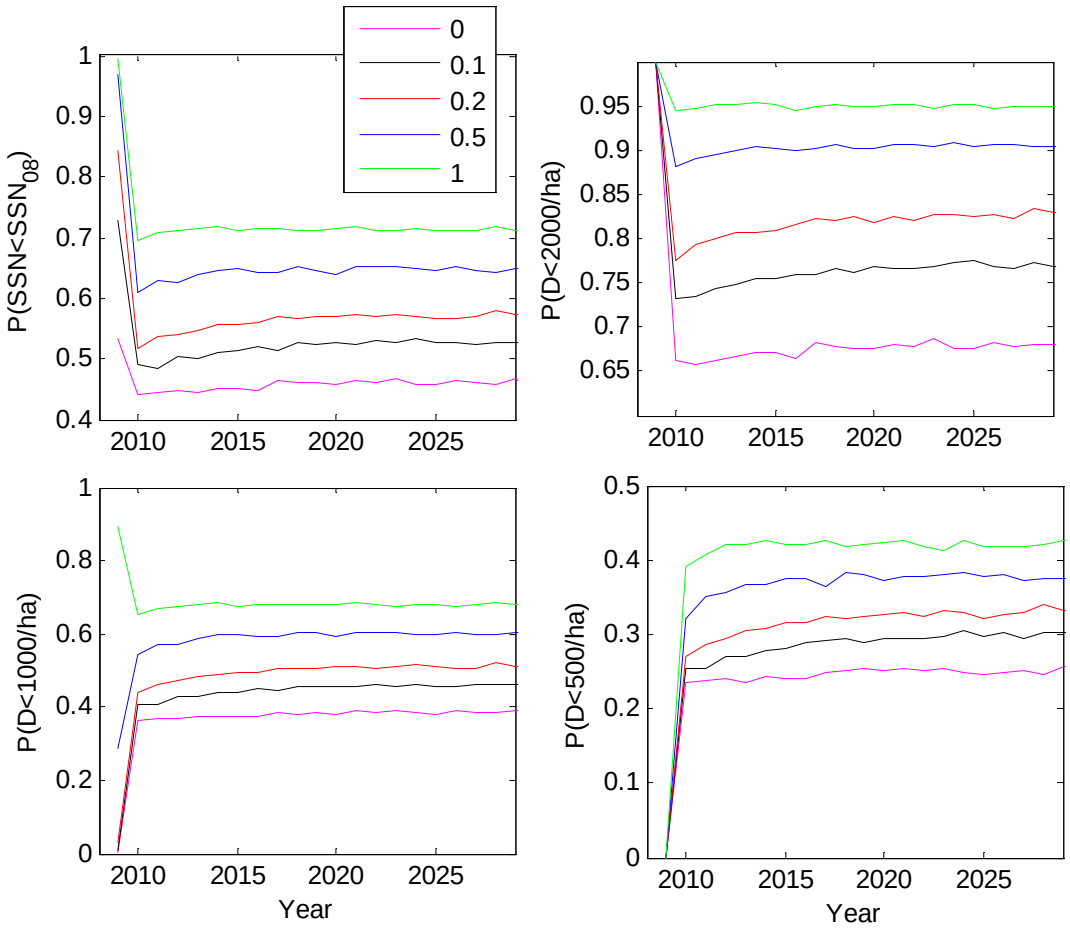


Figure 12: Risks based on different reference points.
12a: the joint posterior distribution of $N_{a,2008}$, and a Beverton-Holt Recruitment model from each posterior runs of $N_{a,y}$, is used in the projection of the risk assessment;



12b: the joint posterior distribution of $N_{a,2008}$, and a Ricker Recruitment model from each posterior runs of Na,y., is used in the projection of the risk assessment;



12c: recruitment in the projection is assumed to follow $\ln N(Ln(\bar{R}),\sigma_R^2)$ based on estimated historical R from MS1R2. Other parameters such as $N_{a,2008}$ and selectivity are still based on the joint posterior distributions.