

Preliminary assessment of impacts on the sandlance population by consumption of minke whales off Sanriku region

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Abstract

We develop a Bayesian assessment model to investigate the effects of consumption by minke whales on sandlances off the Sanriku region. The model allows for various uncertainties making use of time series data historically collected by fisheries and researchers. The impact of predation was examined in terms of MSY. When we used the linear functional response curve, the resultant impact was so great that the median value of MSY was increased by 154%. Whereas using the constant functional response, the impact was much smaller, where we saw only 17% increase of the median value of MSY. The estimation of functional response forms should therefore be important.

1. Introduction

The role of top predators on ecosystem is one of central interests in ecology and fisheries science. Tamura and Ohsumi (1999) claimed that whales consumed at least three times as many preys as fisheries in the world. However, Yodzis (2001) stressed that culling top predators does not always lead to an increase of their preys and can even provide a detrimental effect on the fishery. The objective of this paper is to quantify the impacts of the predators on the prey species and their fisheries and contribute the information to the fisheries management of the prey species.

The sandlance off Sarinku region, which is the northwestern Pacific coastal region of Japan, is an important fishery resource and is preyed by many predators including marine mammals such as minke whales and northern fur seals. We focus on interaction between sandlances and minke whales in this paper. Minke whales are transients in spring off Sanriku region, however, sandlances are regarded as a closed population (Although Sanriku sandlances include two stocks, one is much smaller than the other). So, as the first step, we develop a sandlance's population dynamics model. After the basic model development, we take account of predation by minke

whales in the fishing season. The developed model is considered as a kind of “Minimum Realistic Models (MRM)” (Punt and Butterworth 1995).

2. Materials and Methods

Brief History of Sandlance Fishery

Sandlances consist of juveniles and adults, which are categorized by their body length (Juveniles: $\leq 10\text{cm}$, Adults: $\geq 10\text{cm}$). Juveniles and adults are caught by different fishing gear, so fishermen are basically different for juveniles and adults. Although the amount of catch was about 14,000 ton on average between 1950s and early 1980s, the offshore trawl-net fishermen participated in fishery for adults in 1984 so the population size decreased dramatically (Hashimoto 1991; Nagashima 2004). Consequently, there occurred a serious conflict between coastal and offshore fisheries. After discussion, the trawl-net fishery has stopped voluntarily, lift net with light fishery cut fishing period, and the upper limit of total allowable catches was set to 10,000 tons by private fishing regulation (Nagashima 2004).

Data

Basic datasets are as follows:

- CPUE series of juvenile sandlances by lift net with light fishery from 1994 to 2006 (Top plots of Fig. 1)
- CPUE series of adult sandlances by dip nets from 1995 to 2006 (Middle plots of Fig. 1)
- Abundance estimates of adult sandlances by the DeLury method from 1984 to 1989 based on the offshore trawl-net fishery data, which are dealt with as relative abundance indices (Bottom plots of Fig. 1)
- Ages (Fig. 2), lengths, and weights time series data from 1999 to 2005 (Sandlances estivate in autumn after fishing seasons in spring. Sandlances estivating in sand are sampled and aged. Their lengths and weights are measured at the same time.)
- Catch series by lift net with light fishery, dip nets, and trawl-net fishery from 1901 to 2006 (Fig. 3). Data during the war are missed and data before the war do not have distinction between juveniles and adults. Data before the war was classified into juveniles and adults using the ratio after the war. We used a simple linear interpolation for the missing data during the war.
- Consumption of sandlances by minke whales in 2003 (Tamura et al. 2004).

Population Dynamics Model

We use a hierarchical Bayesian delay-difference model (Hilborn and Walters 1992; Meyer and Miller 1999a). The process model is given by:

- Juveniles (Number) :

$$N_{t+1,J} \sim \text{LN}[fN_{t+1,A}\{1 + r(1 - N_{t+1,A}/K_A)\}, \sigma_{A,1}^2]$$

- Adults (Number) :

$$N_{t+1,A} \sim \text{LN}[(1 - F_{A,p})S_A N_{t,A} + (1 - F_{J,p})\theta S_A^{0.5} N_{t,J}, \sigma_{A,2}^2]$$

- Juveniles (Biomass):

$$B_{t+1,J} = w_0 N_{t+1,J}$$

- Adults (Biomass) :

$$B_{t+1,A} = (\alpha N_{t,A} + \rho B_{t,A})S_A(1 - F_{A,p}) + w_1 N_{t,J}\theta S_A^{0.5}(1 - F_{J,p})$$

where :

$N_{A,t}$: Adult abundance in year t

$B_{A,t}$: Adult biomass in year t

$N_{J,t}$: Juvenile abundance in year t

$B_{J,t}$: Juvenile biomass in year t

S_A : Adult survival rate

θ : Juvenile survival rate (early half)

w_0 : body weight in age 0

w_1 : body weight in age 1

f : fecundity in equilibrium

r : density-dependence effect of recruitment

K_A : carrying capacity of adult abundance

α, ρ : Ford-Brody growth model parameters

$\sigma_{A,i}$: process errors

$F_{A,p}$: fishing rate for adult fish in period p

$F_{J,p}$: fishing rate for juvenile fish in period p

Fishing rate is estimated with five periods according to transition of fisheries:

Period 1: 1901–1936 (before the World War II)

Period 2: 1937–1964 (among and after the war)

Period 3: 1965–1983 (addition of fisheries by Fukushima prefecture)

Period 4: 1984–1989 (expansion of fishing by trawl-net fishery)

Period 5: 1990–2006 (modern fishing operation)

In equilibrium,

$$N_{J,0} = K_J = fK_A$$

and

$$K_A(1 - S_A) = K_J\theta S_A^{0.5}.$$

Therefore,

$$f = (1 - S_A)/(\theta S_A^{0.5}).$$

We assumed the population was in equilibrium without any fishing before 1901.

With relation to MSY, given $Y_A = F_A B_A$ (Catch of adult sandlances) and $Y_J = F_J B_J$ (Catch of juvenile sandlances), $\tilde{F} = F_{\text{MSY}}$ is given by solving the equations,

$$\left. \frac{dY_A}{dF_A} \right|_{F_A=\tilde{F}_A} = 0,$$

$$\left. \frac{dY_J}{dF_J} \right|_{F_J=\tilde{F}_J} = 0.$$

Equilibrium under constant fishing mortality F is given by

$$[1 - (1 - F_A)S_A]N_A(F_A, F_J) = (1 - F_J)N_J(F_A, F_J)\theta S_A^{0.5},$$

$$N_J(F_A, F_J) = fN_A(F_A, F_J)[1 + r\{1 - N_A(F_A, F_J)/K_A\}].$$

Since the above equations cannot be solved analytically, we calculate F_{MSY} and MSY using a numerical optimization and the posterior samples of basic parameters f, r, θ , etc.

The observation models (likelihood function) are composed of three parts on CPUE, catch, and age composition. The CPUE models are given by:

Adult:

$$\sum \frac{1}{2\text{CV}_0^2} \{\log(I_{A,t}) - \log(q_{A,k}B_{A,t})\}^2$$

where $I_{A,t}$ is adult abundance index (CPUE or abundance estimate from a DeLury method). The fishing efficiencies $q_{A,k}$ are different parameters between CPUEs and DeLury abundance estimates.

Juvenile:

$$\sum \frac{1}{2\text{CV}_O^2} \{\log(I_{J,t}) - \log(q_J B_{J,t})\}^2$$

where $I_{J,t}$ is juvenile abundance index (CPUE).

The catch models are given by:

Adult:

$$\sum \frac{1}{2\text{CV}_Y^2} \{\log(Y_{A,t}) - \log(\hat{Y}_{A,t})\}^2$$

where $Y_{A,t}$ is the observed catch of adult fish and $\hat{Y}_{A,t} = F_{A,t} B_{A,t}$.

Juvenile:

$$\sum \frac{1}{2\text{CV}_Y^2} \{\log(Y_{J,t}) - \log(\hat{Y}_{J,t})\}^2$$

where $Y_{J,t}$ is the observed catch of juvenile fish and $\hat{Y}_{J,t} = F_{J,t} B_{J,t}$.

The age composition models are given by:

$$n_{t,a} \sim \text{Multinom}(n_t, p_{t,0}, \dots, p_{t,2+})$$

where

$$\begin{aligned} p_{t,0} &\propto (1 - F_{J,t}) N_{J,t} \theta \\ p_{t,1} &\propto (1 - F_{A,t-1})(1 - F_{A,t}) N_{J,t-1} S_A \theta \\ p_{t,2+} &\propto (1 - F_{A,t-1})(1 - F_{A,t}) N_{A,t-1} S_A^{1.5} \end{aligned}$$

and $\sum_{a=0}^{2+} p_{t,a} = 1$ and $n_t = \sum_{a=0}^{2+} n_{t,a}$.

The prior distributions on the parameters are given by:

$$\begin{aligned} S_A &\sim \text{U}[0, 1] \\ \theta &\sim \text{U}[0, 1] \\ r &\sim \text{U}[0.1, 5.0] \\ K_A &\sim \text{U}[10^3, 10^5] \\ -\log(q_{\cdot,k}) &\sim \text{U}[0, 9] \\ F_{A,p} &\sim \text{U}[0, 1] \\ F_{J,p} &\sim \text{U}[0, 1] \\ 1/\sigma_{A,\cdot}^2 &\sim \text{Ga}[0.01, 0.01] \\ 1/\sigma_O^2 &\sim \text{Ga}[0.01, 0.01] \\ 1/\sigma_Y^2 &\sim \text{Ga}[0.01, 0.01] \end{aligned}$$

w_0, w_1, α, ρ were first estimated outside the Bayesian analysis and incorporated into the Bayesian analysis using the estimated values and their precisions.

The parameters and state variables in the models were inferred with their posterior distributions. However, the posterior distributions do not have explicit formulae for our state-space model. Thus, a numerical algorithm such as Markov chain Monte Carlo and Sequential Monte Carlo is necessary to assess the posterior distributions (Meyer and Miller 1999b; Newman et al. 2006). We used the software program WinBUGS (Bayesian Analysis Using Gibbs Sampler Windows version: Spiegelhalter et al. 2003) to generate the posterior samples. We generated two independent MCMC sequences of 30,000 iterations with different initial parameter values. We discard the first 15,000 iterations from each sequence as the burn-in samples, and thinned each sequence by keeping every 6th simulation draw. All inferences were derived using the remaining 5,000 samples obtained from concatenating the two chains.

Long-term Prediction

We examined the impacts of predation (i.e., reduction of natural mortality) on MSY to examine the long-term effect of culling predators. For simplicity, we assumed $F_A = F_J$ and maximized $Y_A + Y_J$ in this exercise. The following 3 scenarios were examined:

Scenario 1 (No predation effect): No change from 2006.

Scenario 2 (linear functional response): the ratio that corresponds to the amount of predation by minke whales is added to S_A . The modified survival rate is then $S'_A = S_A + R$ where $R = 3,885/\tilde{B}_{A,2003}$. The value 3,885 is the annual consumption of sandlances by minke whales estimated in 2004 in Tamura et al. (2004) and $\tilde{B}_{A,2003}$ is the median value of estimated adult biomass in 2003.

Scenario 3 (constant functional response): The adult dynamics equation was replaced by
$$N_{t+1,A} = (1-F_A)\{S_A(N_{t,A} - RN_{2003,A}) + RN_{2003,A}\} + (1-F_J)\theta S_A^{0.5} N_{t,J}$$
 where R is the same as that defined in Scenario 2 and the biomass equation is accordingly modified. Thus, the abundance in equilibrium is obtained by solving the quadratic equation. Because the constant amount, $RN_{2003,A}$, is always excluded from the natural mortality and independent from the prey abundance, $N_{A,t}$, the functional response for predators becomes constant to changes in prey abundance.

Scenario 2 corresponds to a so-called Type I functional response (Krebs 2001; Gotelli 2001). Since Type 2 and Type 3 functional response curves reach saturation as the prey density increases, Scenario 3 is considered as the most extreme functional form. The realistic functional form may be between Scenarios 2 and 3.

3. Results and Discussion

The goodness-of-fit plots for the model were shown in Figs. 1–3. The fitting was good in general, however, some of recently observed abundance indices were outside 95% credible intervals of the predicted values. The density plots of posterior samples for the parameters were shown in Figs. 4–5. Some parameters show a bimodal distribution, so the convergence was incomplete. In fact, \hat{R} (Spiegelhalter et al. 2003) for some parameters was much larger than 2. When we conducted more MCMC iterations, the result had not been improved. Since the parameter α had highest \hat{R} and we estimated the α outside the Bayesian analysis, the cause of unconvergence may be in the handling of growth parameters in our analysis. In addition, the bimodality of α was likely to be propagated to other parameters. We will modify the way to handle the growth equation in the future analysis.

The summary statistics (median, and the 2.5th and 97.5th percentiles which define the 95% Bayesian posterior credible interval) of the marginal posterior distributions for each parameter were given in Table 1. Median adult survival rate was 74%. This value is similar to previous estimate, 80% (Nagashima et al. 1995). Fishing rates were somewhat larger than estimates in Nagashima et al. (1995).

The predicted values of state variables, biomass and fishing rate, were given in Fig. 6. Biomass fluctuated greatly over time. The predicted biomass trajectories reproduced the rapid decline by participation of trawl-net fishery between 1984 and 1989. Although the patterns of changes in fishing rates was similar between adults and juveniles, the rise at period 4 for adults was keener than juveniles. This should be due to the direct impacts of participation to adult fishery by the offshore trawl-net fishermen.

The F_{MSYS} estimated by long-term predictions were 0.068 for Scenario 1, 0.112 for Scenario 2, and 0.080 for Scenario 3 in median. The corresponding MSYs were 7483 ton for Scenario 1, 19585 ton for Scenario 2, and 8889 ton for Scenario 3 (Table 2). Since the current observed yield for sandlances was 11533, the population could be overexploited under the current fishing rate. F_{MSY} was low than we expected. When we preliminarily fitted the model without process errors to the data, the resultant F_{MSY} was much higher. When there are measurement errors of stock and recruitment, optimum harvest rate will be overestimated (Hilborn and Walters 1992). In addition, Cooke (2007) showed using a simulation model that environmental variability can have a great impact on estimation of MSYR and MSYL. As

another example, Meyer and Miller (1999b) fitted three models, observation-error model, process-error model, state-space model, to the tuna data. From their results, the state-space model estimated the lowest intrinsic rate of increase among three models. The difference was not large compared to our result. However, the estimated process error in Meyer and Miller (1999b) was much smaller compared to our process error estimates. Possibly, our result might be the implication for fisheries management same as or similar to Cooke (2007), that is, when we ignore process errors, the MSYR would be overestimated so that the management implication might become too optimistic and dangerous, although MSY might be more stable since MSY is a function of product of increasing rate and carrying capacity, which is negatively correlated with increasing rate.

Comparing the results for Scenarios 2 and 3, Scenario 2 showed more explicit impacts of predation on the sandlance population dynamics. This result can be predicted from the deterministic models. Using the models used in Scenarios 2 and 3 with fixed parameter values, the predicted carrying capacities were shown in Fig. 8. The direct change of survival rate has a greater impact on equilibrium population size. The more realistic functional curve is between Scenarios 2 and 3 and should be Type 2 or Type 3 responses (Krebs 2001). When we have time-series data in abundance and consumption for predators, we would be able to estimate the functional response curve including Type 2 and 3 responses. JARPNII data can contribute toward providing necessary information to such trials in the near future (Tamura et al. 2009).

The results presented here are not meant to be a definitive assessment. Some of the assumptions used in the model were not ideal. In addition, there remains much to be done. In particular, the functional response we used is being oversimplified in terms of contemporary modeling such as Ecosim (Walters and Martell 2004; Mori et al. 2009). The model and the results in this paper should be considered as the first step in development. In the future, the more refined model will be used for sandlance fishery management taking the predator effect into consideration.

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Table 1. Summary statistics of the estimated posterior distributions for each parameter.

Parameter	Notation	Median	95% CI
w_0	weight at age 0	3.264	[1.619, 9.504]
w_1	Bycatch rate of adults	10.330	[6.833, 14.430]
α	Ford-Brody intercept	9.519	[6.539, 12.180]
ρ	Ford-Brody coefficient	0.234	[-0.218, 0.806]
θ	Juvenile survival rate	0.245	[0.120, 0.534]
S_A	Adult survival rate	0.741	[0.636, 0.851]
f	fecundity	1.263	[0.575, 1.794]
$q_{A,1}$	fishing efficiency of adult index 1	0.016	[0.004, 0.052]
$q_{A,2}$	fishing efficiency of adult index 2	0.255	[0.086, 0.599]
q_J	fishing efficiency of juvenile index	0.067	[0.028, 0.139]
r	density-depend. effect	0.601	[0.174, 1.616]
K_A	carrying capacity of adult abund. ($\times 10^6$)	12470	[5434, 25391]
K_J	carrying capacity of juvenile abund. ($\times 10^6$)	14925	[3681, 35441]
σ_{A1}	process error on fecundity	0.575	[0.432, 0.744]
σ_{A2}	process error on adult dynamics	0.280	[0.161, 0.412]
σ_O	observation error of abund. index	0.511	[0.382, 0.708]
σ_Y	observation error of catch	0.640	[0.562, 0.729]
$F_{A,1}$	Adult fishing rate in period 1	0.0016	[0.0008, 0.0034]
$F_{J,1}$	Juvenile fishing rate in period 1	0.0027	[0.0012, 0.0054]
$F_{A,2}$	Adult fishing rate in period 2	0.0211	[0.009, 0.0483]
$F_{J,2}$	Juvenile fishing rate in period 2	0.0339	[0.0146, 0.0702]
$F_{A,3}$	Adult fishing rate in period 3	0.0401	[0.0163, 0.0951]
$F_{J,3}$	Juvenile fishing rate in period 3	0.1885	[0.0877, 0.3512]
$F_{A,4}$	Adult fishing rate in period 4	0.3263	[0.1270, 0.5862]
$F_{J,4}$	Juvenile fishing rate in period 4	0.3800	[0.1694, 0.7468]
$F_{A,5}$	Adult fishing rate in period 5	0.1153	[0.0238, 0.2983]
$F_{J,5}$	Juvenile fishing rate in period 5	0.2324	[0.1095, 0.3966]

Table 2. Summary statistics of the estimated posterior distributions for F_{MSY} and MSY.

Parameter	Notation	Median	95% CI
$F_{\text{MSY},\text{SC1}}$	F_{MSY} at Scenario 1	0.0679	[0.0200, 0.1248]
MSY_{SC1}	MSY at Scenario 1	7483	[1080, 18474]
$F_{\text{MSY},\text{SC2}}$	F_{MSY} at Scenario 2	0.1119	[0.0645, 0.1658]
MSY_{SC2}	MSY at Scenario 2	19585	[10444, 36837]
$F_{\text{MSY},\text{SC3}}$	F_{MSY} at Scenario 3	0.0798	[0.0310, 0.1329]
MSY_{SC3}	MSY at Scenario 3	8889	[1721, 20236]

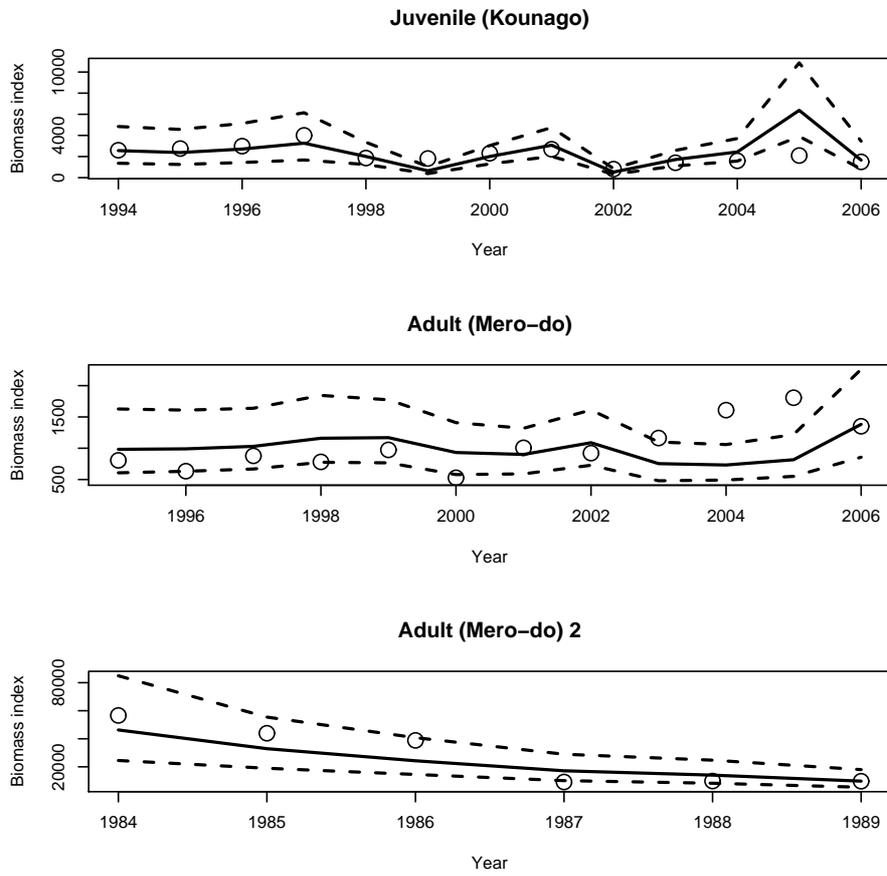


Fig. 1. Goodness of fit for abundance index data. The solid lines denote the median posterior predicted values and the broken lines denote 95% credible intervals. Open circles denote the observed values.

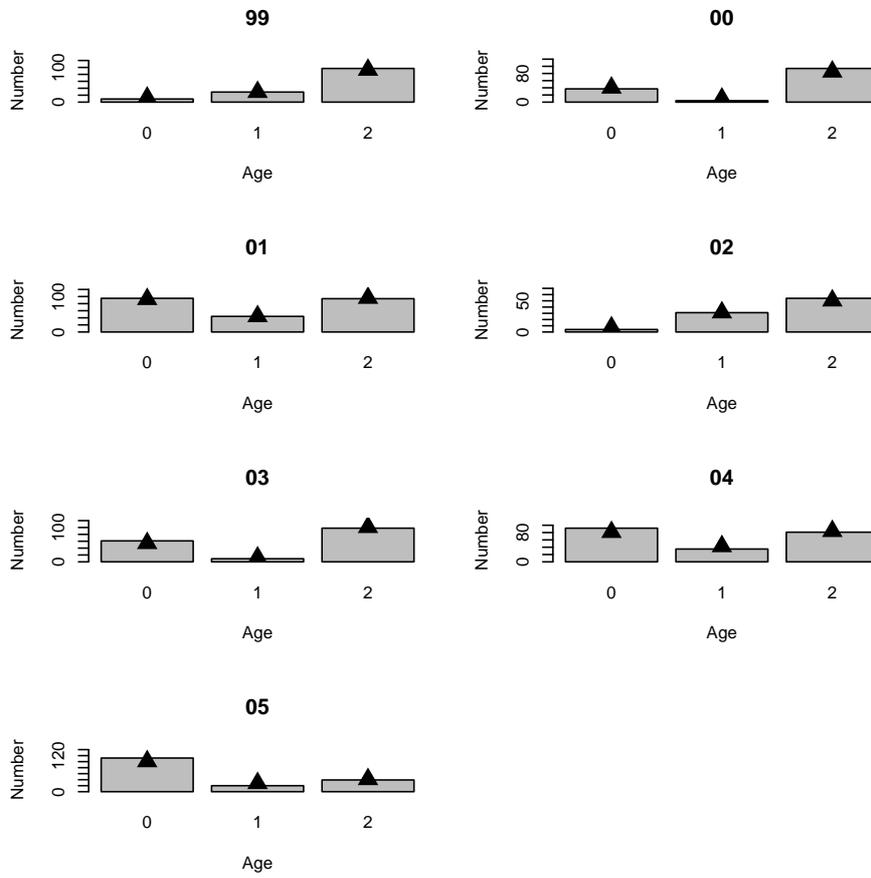


Fig. 2. Goodness of fit for age composition data. The histograms denote the observed values and the triangle marks denote the median predicted values.

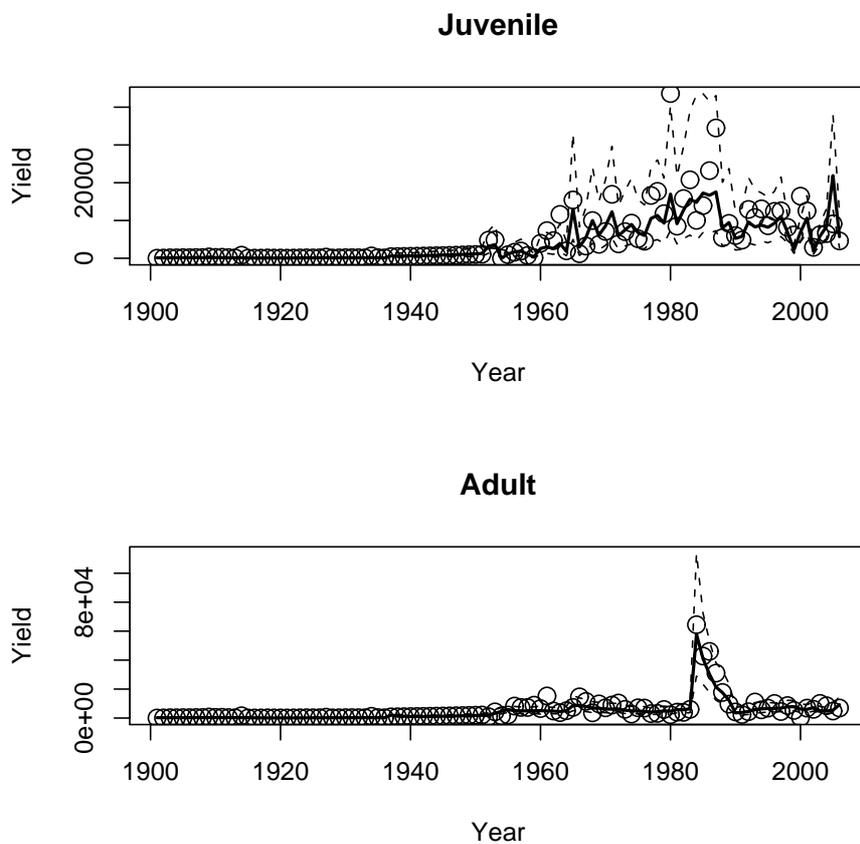


Fig. 3. Goodness of fit for catch statistics. The solid lines denote the median posterior predicted values and the broken lines denote 95% credible intervals. Open circles denote the observed values.

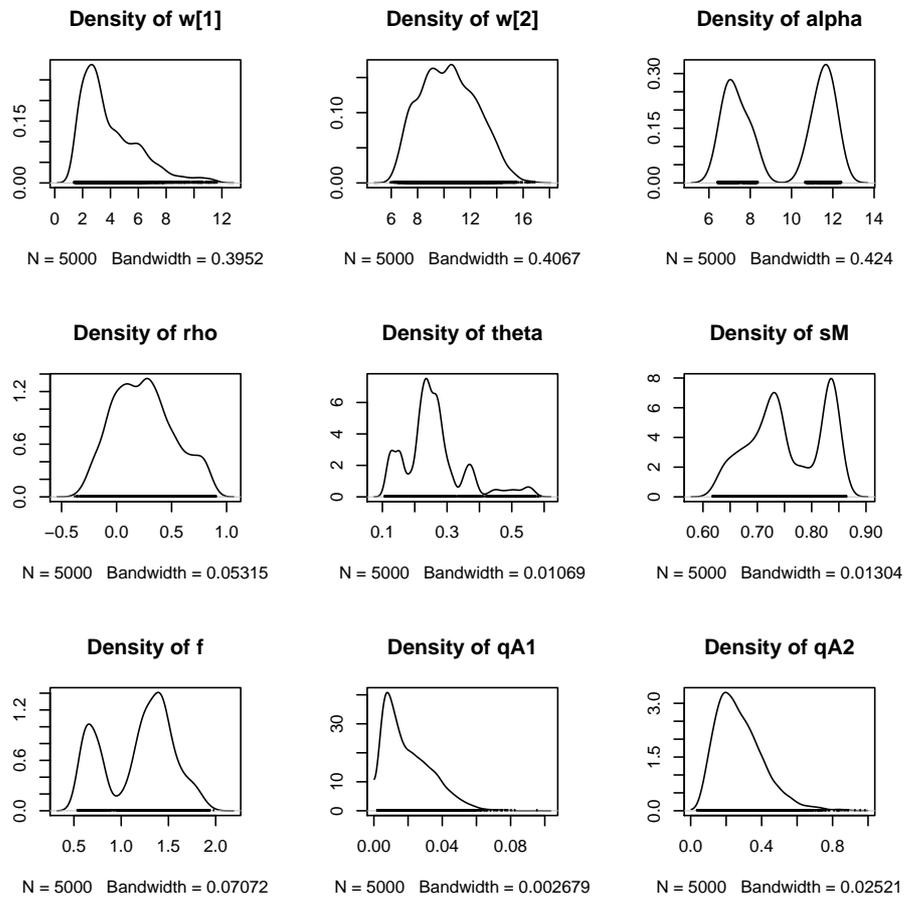


Fig. 4. Posterior probability densities of hyper parameters.

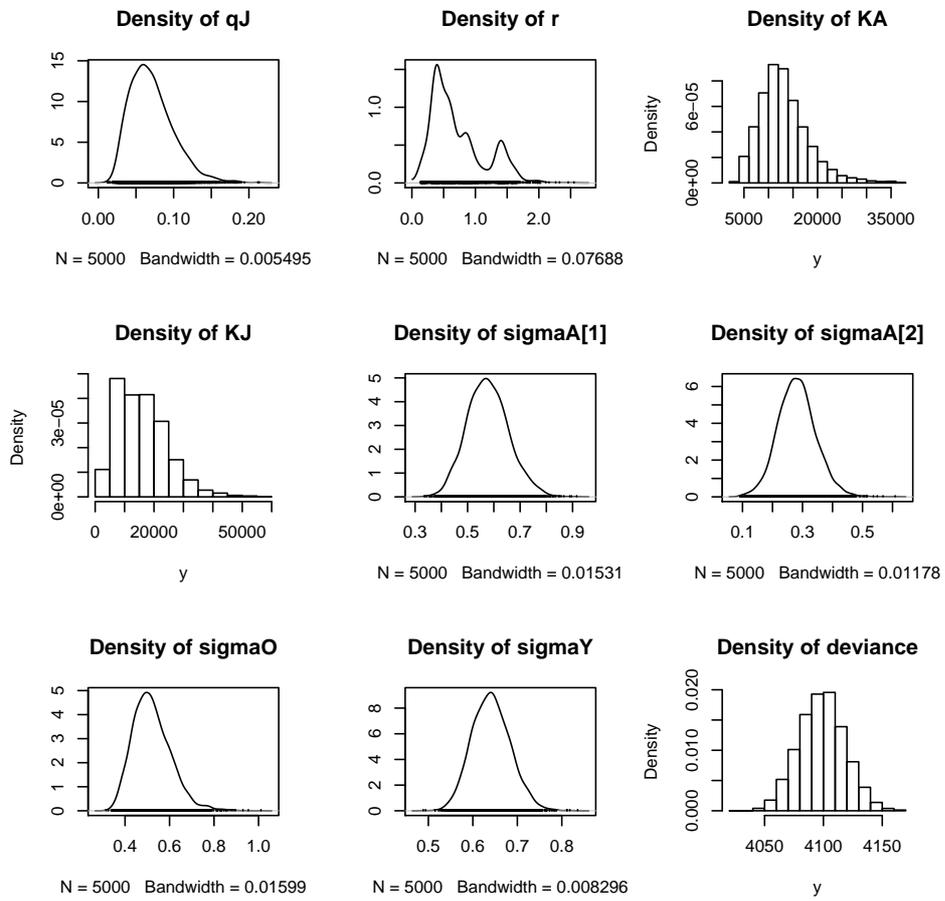


Fig. 5. Posterior probability densities of hyper parameters.

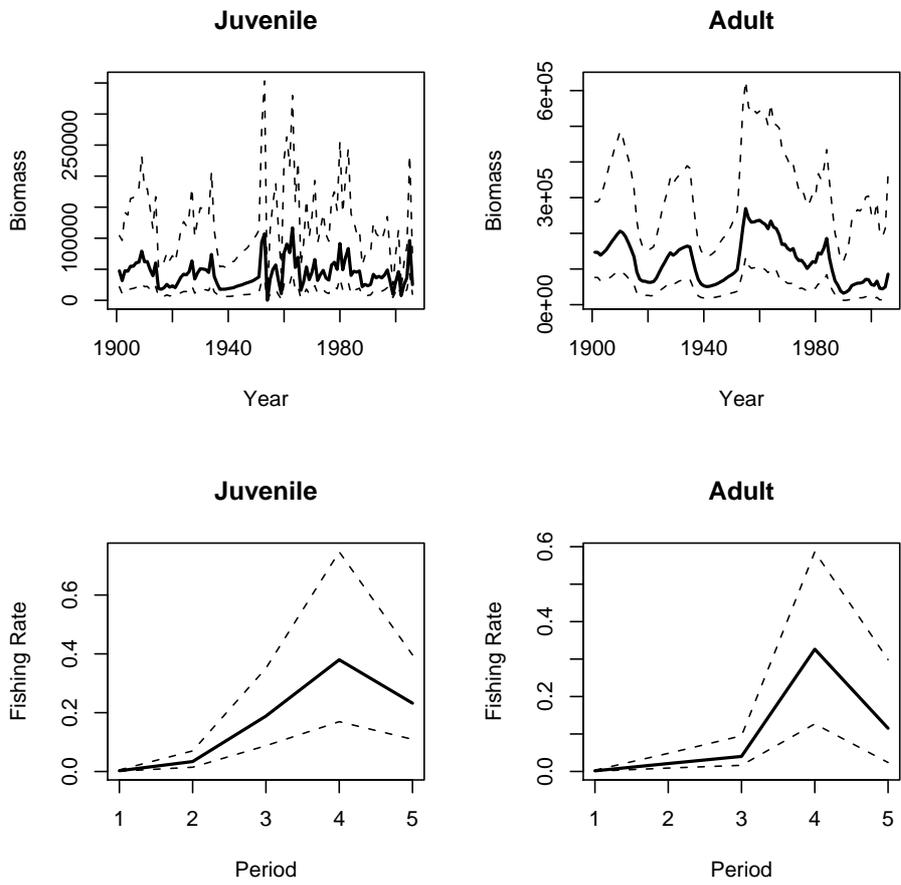


Fig. 6. Posterior probability densities of state variables. The solid lines denote the median posterior predicted values and the broken lines denote 95% credible intervals.

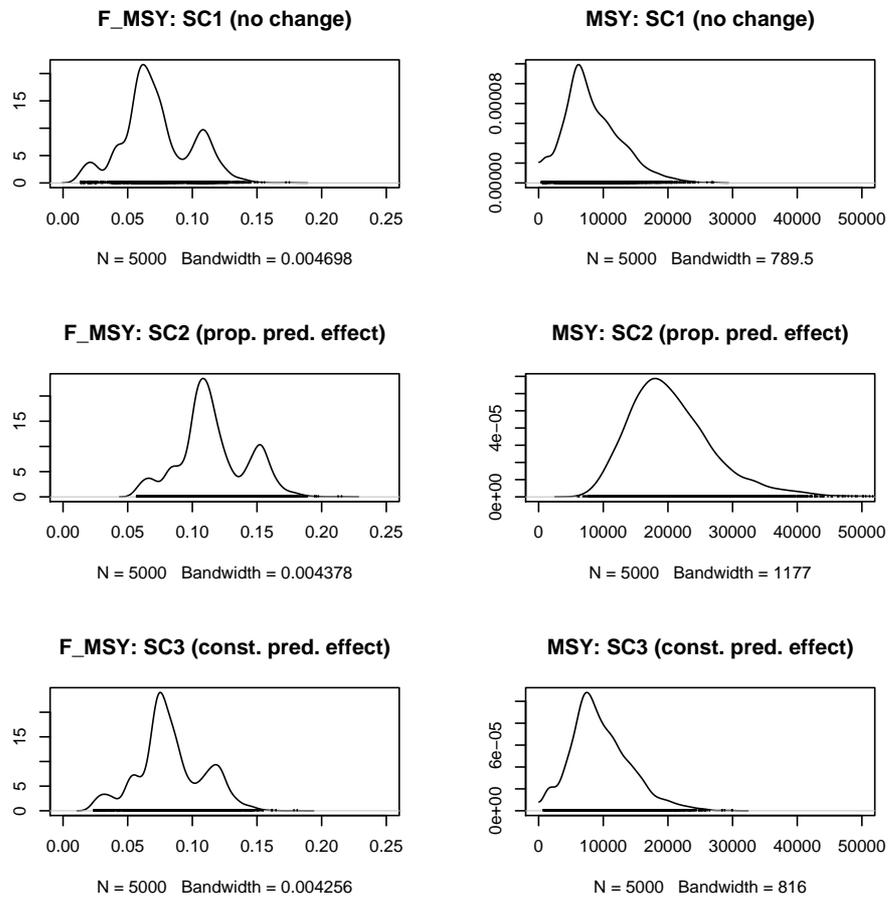


Fig. 7. Long-term predictions (F_{MSY} and MSY).

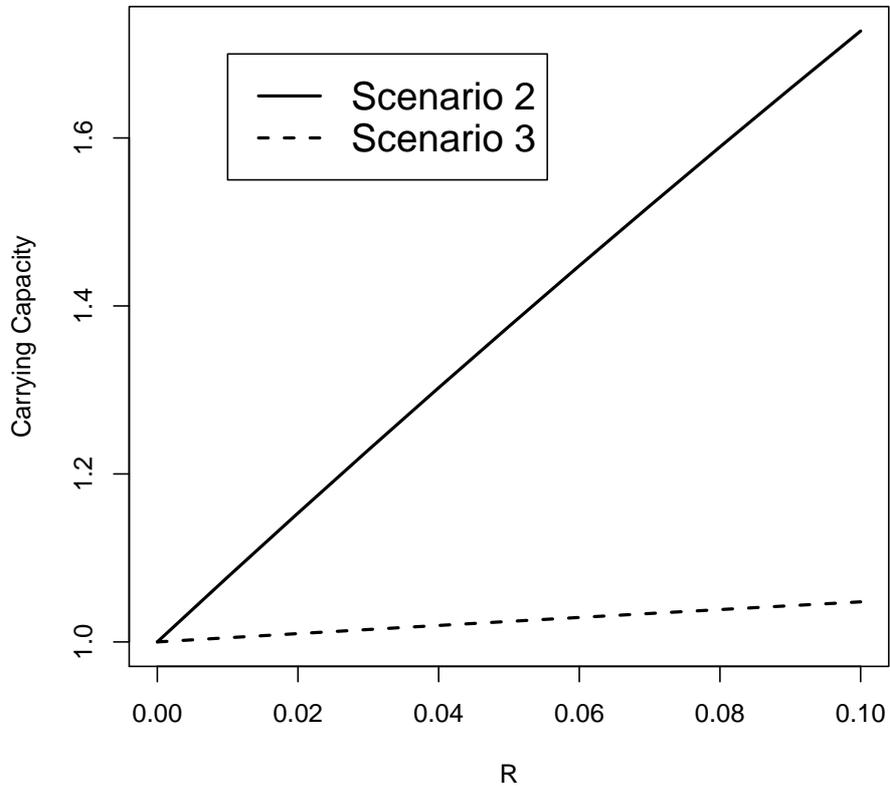


Fig. 8. Predicted carrying capacity to changes in R using the mathematical equations in Scenarios 2 and 3. We set $S_A = 0.75$, $\theta = 0.2$, $f = (1 - S_A)/(\theta S_A^{0.5})$, $r = 0.6$, and $N_{2003,A}/K_A = 0.3$.