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Bayesian State-Space Model**

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Estimation of Fisheries Bycatch and Risk Assessment for Short-Tailed Albatross Using a Bayesian State-Space Model

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Abstract

The short-tailed albatross (*Phoebastria albatrus*) in Torishima of Japan is now getting over the danger of extinction and increasing steadily under habitat management projects and strict protection with Dr. Hasegawa's devoted efforts. However, since the population still now remains reduced to small numbers, it is an important subject to estimate the impact that fishing-related mortalities put on the population. We developed a Bayesian state-space model to appropriately estimate the bycatch rates and the other important parameters along with inherent uncertainties. When the model was applied to the short-tailed albatross time-series data collected in Torishima, the bycatch rate for juvenile birds was estimated to be 1.5% per year in the posterior median (95%CI [0.2%, 6.5%]) and the bycatch rate for adult birds was 0.2% per year in the posterior median (95%CI [0.01%, 1.1%]). Using the same model, we made the future prediction of the impacts of bycatch on the recovering rate and the relative comparison between the bycatch mitigation effects and the breeding-area improvement effects. The future projections by the model showed that the impacts of future bycatch on the population were relatively small and sustainable, and the breeding-area improvement effects would be much greater than the bycatch mitigation effects.

1. Introduction

The short-tailed albatross (*Phoebastria albatrus*) in Torishima island of Japan had shown marked declines in abundance to near extinction, primarily because of excessive hunts for feathers conducted at the breeding colonies since 1880s. By 1949, there were no observation of short-tailed albatrosses breeding at any of the breeding sites and the species was thought to be extinct (U.S. Fish and Wildlife Service 2005). However, in 1951, about 10 short-tailed albatrosses were observed on Torishima and, since then, the population has steadily increased and recovered under habitat management projects and strict protection with Dr. Hasegawa's devoted efforts (Hasegawa 1997, 1998, 1999a, b, 2003).

Longline-related mortality is known as a potentially major threat to albatross populations, and a worldwide effort is under way to mitigate this problem (Boggs 2001; Government

of Japan 2001; U.S. Fish and Wildlife Service 2005). Since short-tailed albatrosses still seem to remain reduced to small numbers at present, even relatively mild threat to the population could put a large impact, in particular, when it is linked to the possibility of occasional catastrophic events such as volcanic eruption at Torishima. In spite of potential impact of seabird bycatch, quantifying the effects of fisheries on albatrosses is a challenging task. Fortunately, Dr. Hasegawa and his colleagues have collected very invaluable time-series data for short-tailed albatrosses on Torishima. Since Dr. Hasegawa provided us with his data generously, we can quantify the plausible range of incidental takes for short-tailed albatrosses combining with other available information.

Bayesian state-space modeling allows us to deal with natural variability underlying the annual population dynamics transitions (process error) and uncertainty in the observed abundance indices due to measurement and sampling error (observation error) distinguishably and incorporate various types of data, such as expert's opinions and information from similar populations or species into the analysis (McAllister and Kirkwood 1998; Meyer and Millar 1999; Wade 2000; Rivot, Prévost, Parent, and Baglinière 2004; Kaplan 2005). We develop a Bayesian state-space model to appropriately estimate the bycatch rate and the other important parameters along with inherent uncertainties. The model is applied to the short-tailed albatross time-series data collected by Dr. Hasegawa in Torishima. The calculation requires freely available online software, WinBUGS (Bayesian Analysis Using Gibbs Sampler Windows version: Spiegelhalter et al. 1999).

2. Materials and Methods

2.1 The data

Basic datasets consist of abundance and reported bycatch time-series data. Three time-series data sets of counts for eggs, fledglings, and all birds except fledglings on Torishima were collected from 1947 to 2005 (Fig. 1). Since we treat all birds except fledglings counted on Torishima as an index of breeding adults, we call that count data "adult counts" simply hereafter. These three time-series data sets were used as independent abundance indices. We set 1954 as the starting value since 1954 was the first year in which all three data were collected together. The reports of short-tailed albatross bycatch have been very few up to now (Table 1: Hasegawa 1998, 1999b; U.S. Fish and Wildlife Service 2005). This seems to reflect the fact that the bycatches are actually very few due to the small population size and/or there might be considerably unreported incidental takes.

2.2 State-space model

Process equation

The population dynamic model (process or transition equation) is semi-age-structured

with three main stages, eggs, juveniles (immature birds with ages less than six), and adults (mature birds with ages equal to and more than six). The model for each stage is given by

Adult-stage model (November)

$$N_{a+,t+1} = \{(1 - F_A)N_{a+,t} + (1 - F_J)N_{a-1,t}\}s_t \quad (1)$$

Juvenile-stage model (age: $1 \sim (a - 1)$) (November)

(1) age $i = 2 \sim (a - 1)$:

$$N_{i,t+1} = (1 - F_J)N_{i,t}s_t \quad (2)$$

(2) age 1:

$$N_{1,t+1} = \theta N_{0,t} \{(1 - F_J)s_t\}^{0.5} \quad (3)$$

Egg-stage model (November)

$$N_{0,t+1} = 0.5fN_{a+,t+1} \quad (4)$$

where a is the age of first breeding set at six years (Cochrane and Starfield 1999), t is the year, F_J is the juvenile bycatch rate, F_A is the adult bycatch rate, s_t is the survival rate common to juveniles and adults (This assumption is based on Dr. Hasegawa's personal communication), θ is the survival rate during the first six months from egg to fledgling, and f is the fecundity per adult female. Equation (1) means that the abundance in $t + 1$ is the survivors of adults in t plus the survivors of $a - 1$ aged juveniles in t . We use exactly age-structured models for juveniles like Equations (2) and (3). As in Equation (3), we assume that the survival rate of the first 6 months of juvenile life is the same as the baseline juvenile and adult survivorship (Cochrane and Starfield 1999). The first term in the right-hand side of Equation (5), 0.5, is based on the assumption that the sex ratio for adult albatrosses is 1:1 since they are monogamous.

We assume that the survival rate and the fecundity are stochastically variable annually. For the survival rate for juveniles and adults, $s_t = \exp(-M_t)$, the distribution of the natural mortality M_t is

$$M_t \sim \text{LN}(\bar{M}, \tau_M) \quad (5)$$

where LN denotes a log-normal distribution. For the survival rate from eggs to fledglings $\theta_t = \exp(-\eta_t)$, the natural mortality η_t is

$$\eta_t \sim \text{LN}(\bar{\eta}, \tau_\eta), \quad (6)$$

where $\bar{\eta}$ and τ_η are estimated separately for two periods of "before 1983" and "after 1984" to quantify the effects of habitat improvement, since there was the first observation of conspicuous improvement in breeding sites in 1984 (Dr. Hasegawa's personal communication). Furthermore, to make the fecundity stochastic, we use the following equation:

$$N_{E,t} \sim \text{LN}(\bar{N}_{E,t}, \tau_E), \quad (7)$$

where $\bar{N}_{E,t}$ is the number of eggs calculated by the above deterministic equation (3).

The measures to reduce incidental takes of sea birds were introduced actively in the North Pacific after 2001 (Dr. Hasegawa's personal communication. In addition, see U.S. Fish and Wildlife Service 2005, and Government of Japan 2001). To estimate this effects, we introduce the additional parameter d multiplied by the bycatch rates F_J and F_A in the years after 2001. d is the bycatch mitigation effect, which is the reduction rate of the incidental takes after 2001 compared to those before 2000.

Observation equation

The observation equations link the available data to the underlying population dynamics models. The available data we use are the time-series data of abundance. For the adult counts collected in April, X_t , the probability distribution is given by:

$$X_t \sim N(bN_{A,t}, \sigma_A N_{A,t}), \quad (8)$$

where N denotes a normal distribution with mean $bN_{A,t}$ and standard deviation $\sigma_A N_{A,t}$. b is the bias factor, which means that all animals do not always return to the breeding grounds and part of adults take part in breeding. In other words, $100(1-b)\%$ adults are not observed at Torishima annually. The adult count data actually include some juveniles. However, since most of individuals that do not return to the breeding grounds are juveniles and the most part of counts is mature birds, we can reasonably assume that the X_t is proportional to the adult abundance. The standard deviation is assumed to be proportional to the abundance. For the counts of fledglings collected in April, Y_t , the similar probability distribution is used as:

$$Y_t \sim N(\theta N_{E,t}, \sigma_F N_{F,t}), \quad (9)$$

where θ is the survival rate during the first six months from egg to fledgling. For the egg counts in November, Z_t , the probability distribution is given by:

$$Z_t \sim N(N_{E,t}, \sigma_E N_{E,t}). \quad (10)$$

Note that the counts of fledglings and eggs are treated as absolute abundances while the counts of adult are treated as relative abundance indices.

The bycatch data can be linked to the age-class or stage-class (Table 1). The probability distribution of the bycatch of juveniles, $C_{J,t}$, is given by:

$$C_{J,t} \sim \text{Po}(qF_J N_{J,t}), \quad (11)$$

where Po is the Poisson distribution with mean $qF_J N_{J,t}$. q is the bias factor, which means that all the birds incidentally taken are not necessarily reported. For the bycatch of adults, $C_{A,t}$, the probability distribution is:

$$C_{A,t} \sim \text{Po}(qF_A N_{A,t}). \quad (12)$$

The likelihood function used in the analysis is the sum of the logarithm of the above probability distributions.

Prior distribution

We assume that each of parameters is independent in the joint prior distribution. We put informative priors on some parameters related to mortality and recruitment based on Dr. Hasegawa's suggestion and the existing information (Cochrane and Starfield 1999; US Fish and Wildlife Service 2005). The range of informative prior distributions is set to be sufficiently broad so that the even least reality can be picked up by the analysis. We use noninformative priors for the process and observation errors since there is no existing information available for them. Consequently, as prior distributions of each parameter, we use the following ones:

$$F_J: U[0, 0.3]$$

$$F_A: U[0, 0.3]$$

\bar{M} : N[-3.2, 2.44] (This corresponds to the average of survival rate $s=96\%$ with CV = 20%)

$$\bar{\eta}_{83}: U[-2.26, 0.83] \text{ (The prior mean of } \theta_{83} \text{ is about } 0.1 \sim 0.9)$$

$$\bar{\eta}_{84}: U[-2.26, 0.83] \text{ (The prior mean of } \theta_{84} \text{ is about } 0.1 \sim 0.9)$$

b : U[0.6, 0.9] (About 80% of the breeding-age birds nest annually (US Fish and Wildlife Service 2005))

$$f: U[0.6, 0.9]$$

$$q: U[0, 1]$$

$$\tau_M: \text{IG}[0.001, 0.001]$$

$$\tau_{\eta_{83}}: \text{IG}[0.001, 0.001]$$

$$\tau_{\eta_{84}}: \text{IG}[0.001, 0.001]$$

$$\tau_E: \text{IG}[0.001, 0.001]$$

$$\sigma.: \text{IG}[0.001, 0.001]$$

As initial values, the adult counts from 1954 to 1954+ a are assumed to have a log-normal distribution with median X_t/b and CV = 20%. Therefore, the starting year of estimation is virtually 1960.

2.3 Bayesian estimation and future projection

All unobservable quantities (abundance, bycatch rate, and other model parameters) are estimated using a Bayesian approach. The inference is carried out using WinBUGS (Spiegelhalter et al., 2003), which produces the posterior samples using the Gibbs sampler (Gelfand and Smith, 1990). We use the 3 MCMC sequences with different initial parameter values to diagnose the convergence and the MCMC simulation for each sequence is repeated 13,000

times. We remove the first 3,000 iterations as the burn-in samples and thin each sequence by keeping every 10th simulation draw. All inferences are derived using the 3,000 sample obtained from concatenating the three chains.

As a future projection, we compare the population trajectories during 30 years from 2011 to 2040 based on four scenarios. The four scenarios are:

Scenario 0: Bycatch = 0 from 2011 to 2040,

Scenario 1: Bycatch rate from 2011 to 2040 is equal to the present rate including bycatch mitigation effects and no other changes,

Scenario 2: Bycatch rate from 2011 to 2040 is set back to that before 2000 without bycatch mitigation effects and no other changes,

Scenario 3: Survival rate of eggs to fledglings from 2011 to 2040 is set back to that before 1983 without habitat improvement and no other changes.

We see the impacts of future bycatches on the population through comparing Scenarios 0 and 1. Comparison between Scenarios 1 and 2 shows the magnitude of positive impacts of recent bycatch mitigation efforts on the population. Furthermore, Scenarios 2 and 3 give relative comparison between the bycatch mitigation effects and the improvement/enhancement effects of breeding colonies.

3. Results and Discussion

Trace plots and kernel estimates for the marginal posterior densities of main parameters were listed in Figures 2 and 3. The trace plots of each parameter indicated the convergence and the \hat{R} statistics of all the parameters was less than 1.3. When \hat{R} is near 1, we can generally think that the analysis is acceptable in terms of convergence of MCMC simulations (Gelman et al., 2004). We repeated the analyses with different initial values several times so that we got almost identical results from every run. We therefore judged that we had the converged posterior samples.

The marginal posterior distributions are less diffuse than the priors (Figure 3). In particular, the posterior distributions of parameters related to natural mortality and recruitment were greatly updated due probably to the data-rich situation (Figure 1) and the posteriors of them seem to be robust to the priors. By contrast, the marginal posterior distributions of the parameters related to fisheries tend to have great variances and remain to be relatively uncertain (e.g., see the result of d in Figure 3). This may be due to the data-poor situation of bycatch information (Table 1). Nevertheless, the parameters such as the bycatch rates were greatly updated. The reason is probably that the biological parameters such as natural mortality and population growth rate provided information to the plausible range of bycatch and confined the posterior distributions of fisheries-related parameters. This is one

advantage of analysis with integrated information.

The goodness-of-fit plots between observed and predicted values were given in Figure 4. The fit was visually good, especially for eggs and adults. Fitting of the model for fledglings was not as good as those for eggs and adults. This is reflected by the biggest sighting errors in fledgling counts (Table 2). In general, all the sighting errors are reasonably small, which reflects the thorough investigations annually conducted on Torishima.

The summary statistics of the marginal posterior distributions for each parameter were given in Table 2. The median value of the posterior samples for bycatch rate of juvenile birds, F_J , was about 1.5% (95% CI = [0.2%, 6.5%]), while the median value of the posterior samples for bycatch rate of adult birds, F_A , was about 0.2% (95% CI = [0.01%, 1.1%]). Considering the growth rate of albatross population to be near 10% (Cochrane and Starfield 1999; Niel and Lebreton 2005), the estimated bycatch rate seems to be relatively low. The median values of bycatches predicted in 2006 based on these posterior samples were 0.61 birds (95%CI [0.02, 6.53]) for adults ($BC_{A,2006}$ in Table 2) and 4.32 birds (95%CI [0.25, 33.27]) for juveniles ($BC_{J,2006}$ in Table 2). Since the estimated reported rate, q , was 7.5% (median), the reported bycatches predicted in 2006 became much lower. The median reported bycatches predicted in 2006 were 0.051 birds (95%CI [0.005, 0.238]) for adults ($OBC_{A,2006}$ in Table 2) and 0.368 birds (95%CI [0.058, 0.924]) for juveniles ($OBC_{J,2006}$ in Table 2).

The total abundance estimated in November of 2006, $N_{T,2006}$ was 1,656 birds in median (95%CI [1,372, 1,913]). Dr. Hasegawa's abundance estimate in 2006 (1,755; Dr. Hasegawa's personal communication) was within the 95% confidence interval of this total abundance estimate. Although the estimated value might be underestimated by a Bayesian nature (Nielsen and Lewy 2002), the confidence interval seems to make it fit for practical use.

The estimated bycatch mitigation effect, d , was 0.45 in median (95%CI [0.07, 0.95]). The confidence interval was wide reflecting the fact that there is only one report of bycatch after 2001 (Table 1). However, the median value (0.45) was similar to the effects by introduction of the streamer lines investigated by the experiments (Boggs 2001). As far as we know, this is the first trial to estimate the mitigation effects quantitatively from the field data.

The survival rate from eggs to fledglings was changed from 0.46 before 1983 (θ_{83} in Table 2) to 0.59 after 1984 (θ_{84} in Table 2) in median. In addition, the magnitude of fluctuation was greatly reduced after 1984 (Table 2 and Figure 3). These suggest the improvement of breeding ground put a large positive impact on albatross rehabilitation up to present.

Figure 5 provides the correlation matrix among posterior samples of representative parameters. The bycatch rates and the reporting rates are highly negative-correlated. This indicates that we cannot estimate these two parameters distinguishably based on the information we used at present. If we have some information on the reporting rate, the estimation will be improved. When the natural mortality is low, the bycatch rate is also low. The reason is that the high bycatch rate cannot explain the high growth rate shown in Figure 1 for the

low natural mortality. Therefore, if we have the independent evidence that the survival rate is lower (e.g., ring recovery data), the bycatch rates will be estimated to be lower than our present result.

Future projections show that the impacts by the improvement of breeding ground would be much bigger than those by the bycatch mitigation effects (Figure 6). The influence of bycatch to this species looks relatively small when the present bycatch mitigation efforts continue in the future. The final median abundances in 2040 for each scenario were 33,005 for Scenario 0, 28,660 for Scenario 1, 25,030 for Scenario 2, and 15,760 for Scenario 3, respectively. The relative abundances to Scenario 0 for other scenarios (the median abundance of Scenario 0 = 1) were 0.868 for Scenario 1, 0.758 for Scenario 2, and 0.478 for Scenario 3.

We used the model with the exponential growth. The short-tailed albatrosses are still at the first stage of recovery. Consequently, it seems difficult at present to estimate any density-dependent effects. Since the initial pristine abundance was guesstimated to be more than 1,000,000 (Hasegawa 2001), the exponential growth model can probably perform well for the present data with very small compensatory effects if any (The median abundance predicted in 2040 for Scenario 1 is less than 30,000, which is less than 3% of the initial abundance).

Our future projections showed that the protection of breeding grounds would be the most important. However, since the population size is still very small compared with the initial abundance and there is a possibility of occasional catastrophic events such as volcanic eruption at Torishima, we must make the best efforts to restore the short-tailed albatrosses. We should therefore continue to search the most effective recovery plan balancing out the costs and benefits appropriately.

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Table 1. The reported bycatch data. The data were extracted and compiled from Hasegawa (1998, 1999b) and U.S. Fish and Wildlife Service (2005).

Year	Location	Age
1982	near Torishima	5
1983	near Alaska	0.6
1985	near Torishima	4
1987	near Alaska	0.8
1995	near Alaska	1.7
1995	near Alaska	3.7
1996	near Alaska	5.8
1998	near Alaska	8.8
1998	near Alaska	juvenile
2003	near Alaska	3

Table 2. Summary statistics of the estimated posterior distributions for each parameter. A, J, F, and E denote adults, juveniles, fledglings, and eggs, respectively. PE and OE denote process error and observation error, respectively.

Parameter	Notation	Median	95% CI
F_J	Bycatch rate of juveniles	0.015	[0.002, 0.065]
F_A	Bycatch rate of adults	0.002	[0.0001, 0.011]
q	Reporting rate	0.075	[0.016, 0.684]
s	Mean survival rate	0.977	[0.961, 0.990]
θ_{83}	Mean recruitment rate from E to F before 1983	0.457	[0.362, 0.547]
θ_{84}	Mean recruitment rate from E to F after 1984	0.592	[0.548, 0.639]
f	Breeding success rate	0.835	[0.687, 0.893]
b	Breeding participating rate	0.858	[0.714, 0.898]
d	Reduction rate of bycatch after 2001	0.453	[0.072, 0.951]
τ_M	PE of natural mortality	0.921	[0.080, 1.814]
$\tau_{\eta_{83}}$	PE of recruitment from E to F before 1983	0.542	[0.304, 0.885]
$\tau_{\eta_{84}}$	PE of recruitment from E to F after 1984	0.105	[0.066, 0.148]
τ_E	PE of E production	0.139	[0.027, 0.372]
σ_A	OE of A counts	0.100	[0.073, 0.137]
σ_F	OE of F counts	0.137	[0.035, 0.217]
σ_E	OE of E counts	0.051	[0.022, 0.124]
$N_{T,2006}$	Total population size (A+J) in 2006	1656.0	[1372.0, 1913.0]
$N_{A,2006}$	Adult population size in 2006	899.0	[722.7, 1104.0]
$N_{J,2006}$	Juvenile population size in 2006	754.7	[640.7, 837.5]
$N_{F,2006}$	Fledgling population size in 2006	217.6	[150.6, 302.9]
$N_{E,2006}$	Egg population size in 2006	370.5	[276.5, 476.5]
$BC_{A,2006}$	Actual bycatch number of adults in 2006	0.61	[0.02, 6.53]
$BC_{J,2006}$	Actual bycatch number of juveniles in 2006	4.32	[0.25, 33.27]
$OBC_{A,2006}$	Reported bycatch number of adults in 2006	0.051	[0.005, 0.238]
$OBC_{J,2006}$	Reported bycatch number of juveniles in 2006	0.368	[0.058, 0.924]

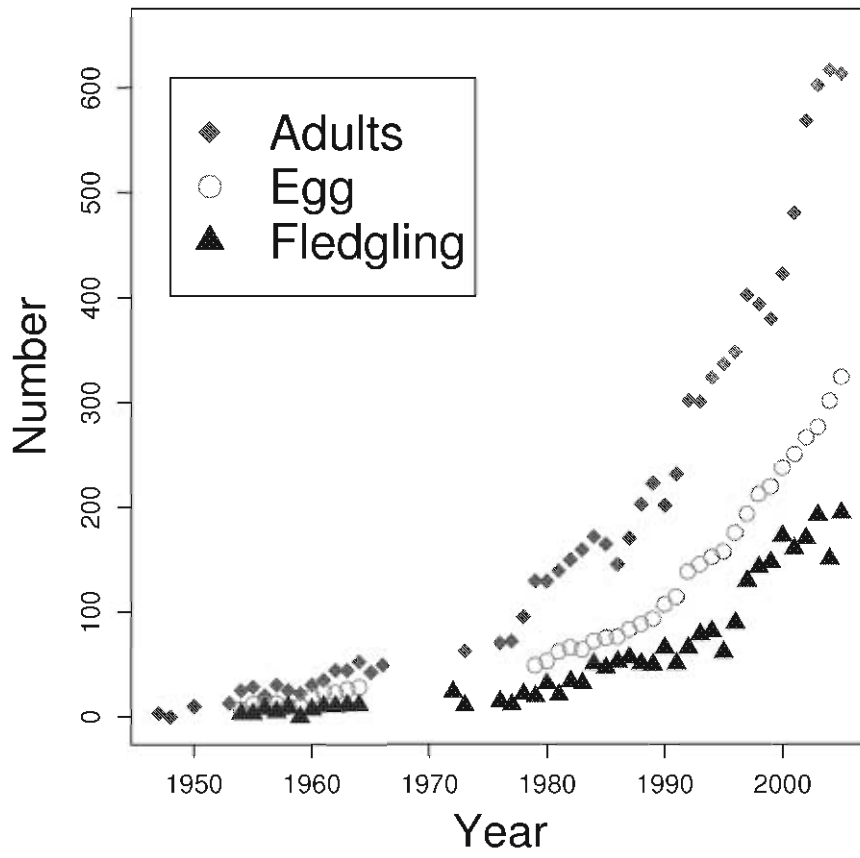


Figure 1. Time-series abundance data observed on Torishima.

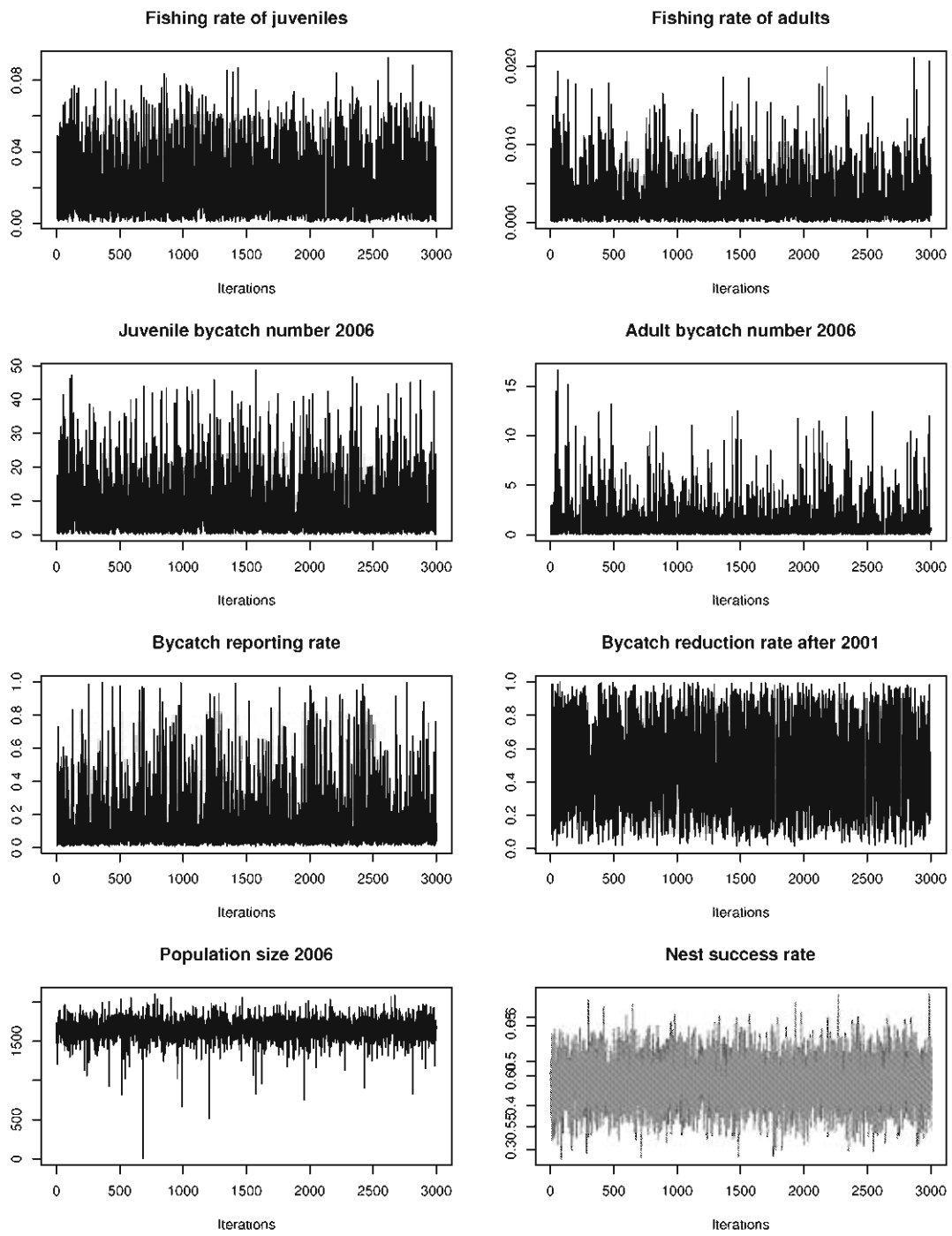


Figure 2. Trace plots for some important parameters.

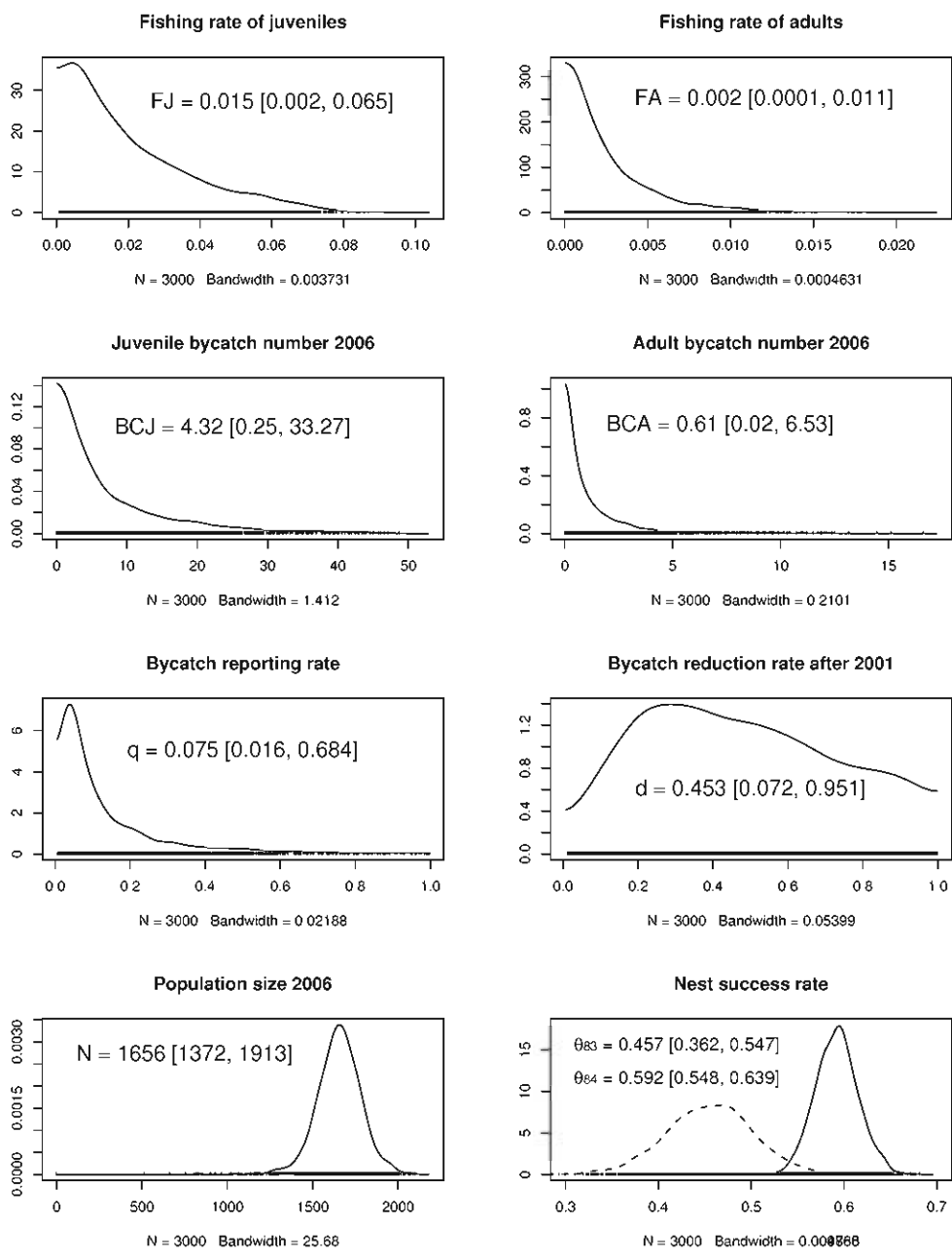


Figure 3. Kernel density plots for some important parameters. The values on the panels denote the posterior median and the 95% confidence interval.

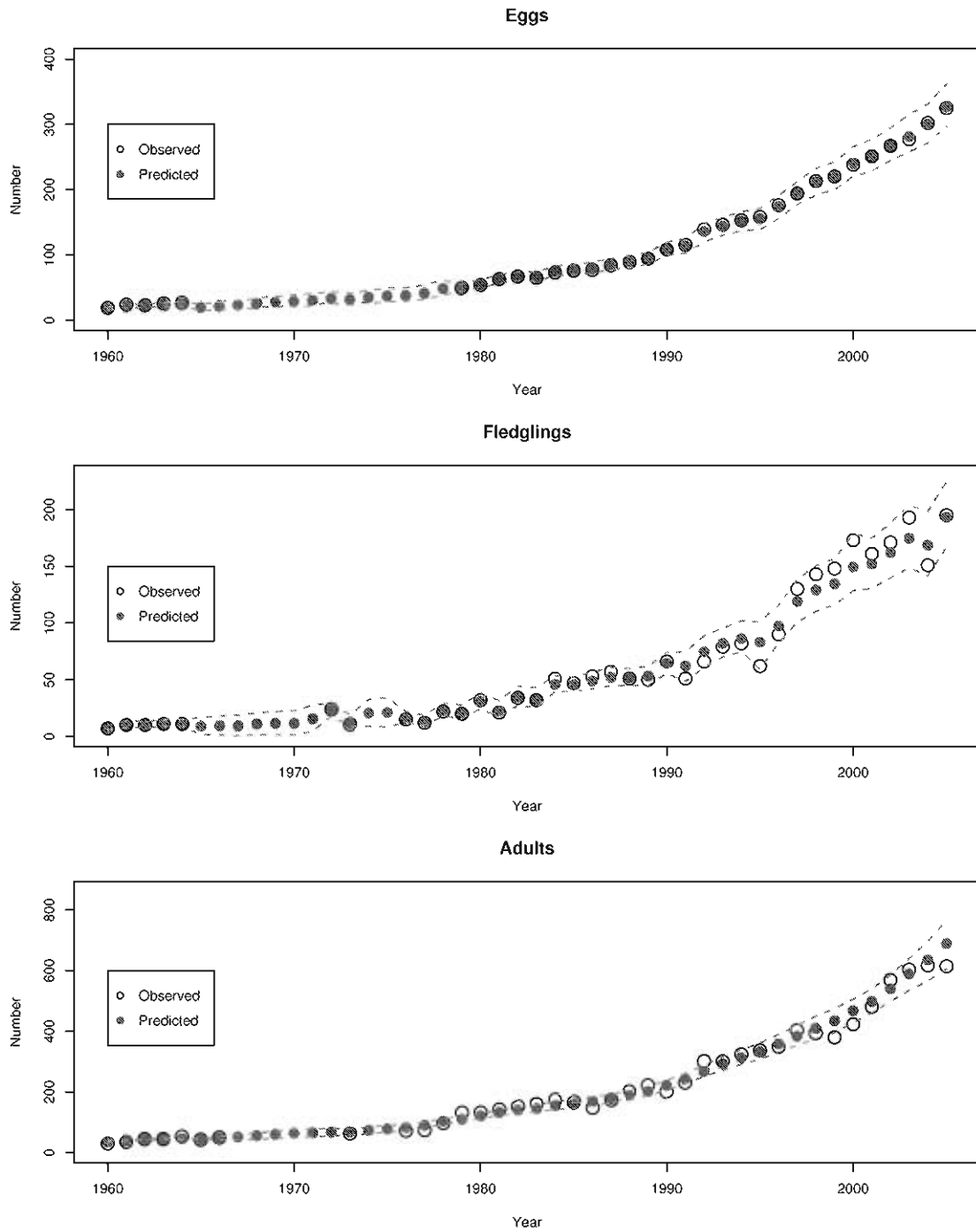


Figure 4. Comparison between observed and predicted counts. The open circles denote the observed values and the closed circles denote the predicted values. The broken lines show the 95% confidence intervals.

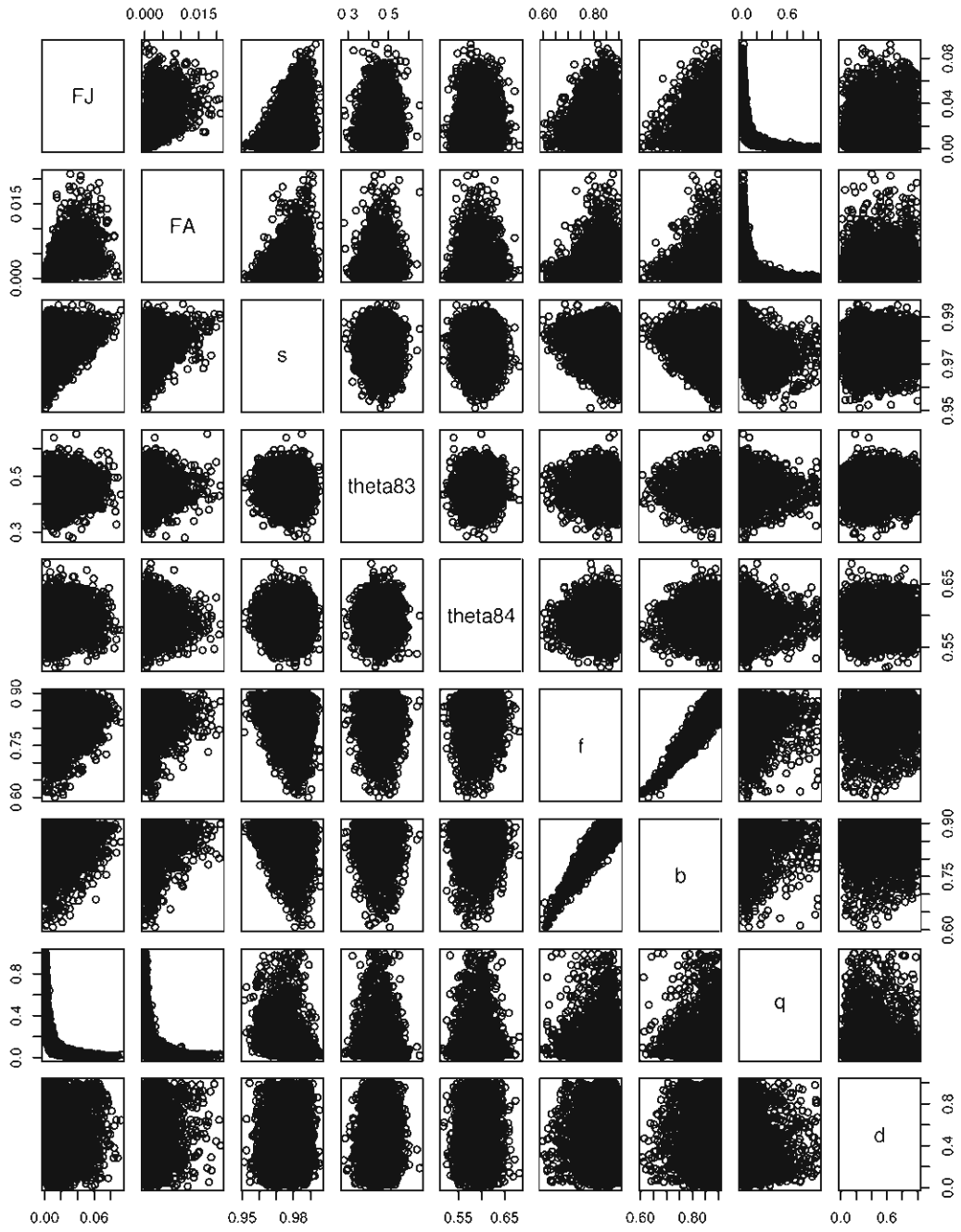


Figure 5. Pairs plot for representative posterior samples.

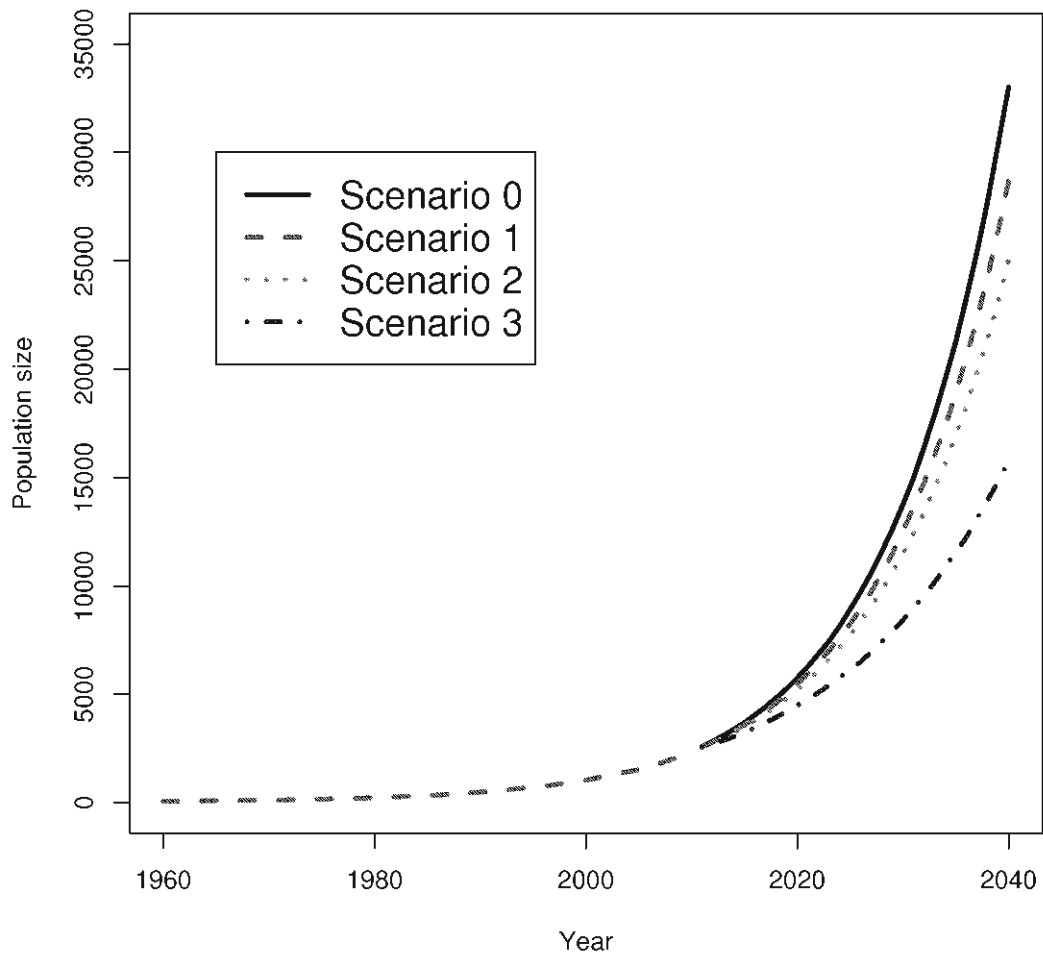


Figure 6. Comparison among median 30-year time trajectories of abundance under each scenario.