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A risk assessment framework for Pacific herring stocks in British Columbia

Un cadre d'évaluation du risque pour les stocks de hareng du Pacifique en Colombie-Britannique

J.F. Schweigert, C. Fu, C.C. Wood, and T.W. Therriault

Fisheries and Oceans Canada
Pacific Biological Station
Nanaimo, B.C. V9T 6N7

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Abstract

A risk assessment framework was developed with the goal of determining conservation limit reference points for harvested species as part of the Department of Fisheries and Oceans initiative on Objectives Based Fisheries Management (OBFM). In Pacific Region, Pacific herring (*Clupea pallasi*) was one of two pilot species chosen based on the availability of extensive biological and fisheries data. A critical component of the risk assessment was the development of a population dynamics model of Pacific herring stocks reflecting the best current understanding of fishery and environmental impacts to assess current abundance and make stock projections. A series of performance indicators (measures) were developed to evaluate the impacts of various harvest policy options on the viability and sustainability of Pacific herring stocks in British Columbia. The performance indicators were developed through consultations with stakeholders throughout Pacific Region. Performance indicators utilized in the risk assessment were measured over a 15 year projection period (three generations) and included: the average spawning stock biomass (SSB), the average annual catch, the number of years of fishery closure, the proportion of the population consisting of individuals age 4 and older, the probability of SSB declining below a fixed threshold (the current cutoff level), the probability of the SSB declining below a floating cutoff level, the probability of a 50% decline in abundance within three generations, and the probability of the SSB increasing to the biomass generating the maximum sustainable yield (B_{MSY}) in three generations. The performance indicators were compared for a suite of proportional threshold harvest policies of which the current policy is one possible example. Five scenarios were designed for projection simulations to investigate the sensitivity of performance indicators to structural assumptions in the model (stock recruitment function and variable versus constant natural mortality), length of closure when biomass falls below a cutoff threshold, and average marine survival. Performance indicators were broadly similar across all five herring stocks in each scenario. The existing herring harvest policy remains precautionary for all stocks, particularly in the current environment of reduced survival. The risk assessment framework appears to be robust and should be applicable across a broad range of species in support of other OBFM initiatives.

Résumé

Un cadre d'évaluation du risque a été établi afin de déterminer les points de référence limite de la conservation des espèces exploitées, dans le contexte de l'initiative de gestion des pêches par objectif (GPO) du ministère des Pêches et des Océans. Dans la Région du Pacifique, le hareng du Pacifique (*Clupea pallasi*) était l'une des deux espèces pilotes choisies, compte tenu de l'existence de données exhaustives sur leur pêche et leur biologie. Un des éléments cruciaux de l'évaluation du risque était la mise au point d'un modèle de la dynamique des populations de hareng du Pacifique prenant en compte les meilleures connaissances actuelles de la pêche et des effets environnementaux en vue d'évaluer l'abondance actuelle et de faire des prévisions des stocks. Une série d'indicateurs (mesures) du rendement ont été définis pour déterminer les effets de divers choix de politique de pêche sur la viabilité et la durabilité des stocks de hareng du Pacifique en Colombie-Britannique. Les indicateurs de rendement ont été choisis au cours de consultations avec des intervenants de la Région du Pacifique. Les indicateurs utilisés pour l'évaluation du risque ont été mesurés au cours d'une période prévisionnelle de 15 ans (trois générations); ils comprenaient : la biomasse moyenne du stock géniteur (BSG), la moyenne des prises annuelles, le nombre d'années de fermeture de la pêche, la proportion de la population composée d'individus d'âge 4 et plus, la probabilité de baisse de la BSG sous un seuil fixe (le seuil actuel), la probabilité de diminution de la BSG sous un seuil flottant, la probabilité d'une réduction de 50 % de l'abondance en trois générations et la probabilité d'augmentation de la BSG jusqu'à la biomasse assurant le rendement maximal soutenu (B_{RMS}) en trois générations. Les indicateurs de rendement ont été comparés pour une série de politiques de pêche à seuil proportionnel dont la politique actuelle est un exemple possible. Cinq scénarios ont été conçus pour la simulation de projections, afin d'examiner la sensibilité des indicateurs de rendement aux hypothèses structurales du modèle (fonction de recrutement du stock et mortalité naturelle variable comparée à constante), la durée de fermeture quand la biomasse descend sous un seuil donné et le taux de survie moyen en mer. Les indicateurs de rendement étaient généralement semblables pour les cinq stocks de hareng de chaque scénario. La politique de pêche du hareng existante demeure un choix prudent pour tous les stocks, surtout dans le contexte actuel de survie réduite. Le cadre d'évaluation du risque semble robuste et devrait être applicable à un large éventail d'espèces pour appuyer d'autres initiatives de gestion des pêches par objectif.

Introduction

Pacific herring (*Clupea pallasi*) has been one of the most important components of the British Columbia commercial fishery with catch records dating from 1877 (Schweigert 2004). A reduction fishery began in the 1930s and collapsed in the late 1960s. After a four-year fishery closure, a roe fishery began in 1972 and has continued to the present time. Since 1983, the herring resource has been managed to achieve a constant harvest rate with the quota recommendation for each stock set at 20% of the spawning biomass forecast. In 1986, a threshold spawning stock biomass or "Cutoff" level was introduced for each stock to restrict harvest at low stock abundance (Haist et al. 1986, Schweigert 2004). The harvest policy adopted at that time was supported by an extensive series of studies conducted in British Columbia, Washington, and Alaska (Trumble 1983, Fried and Wespestad 1985, Doubleday 1985, Ware 1985, Haist 1988, Hall et al. 1988, Zheng et al. 1993, Haist et al. 1993), at a time when fisheries harvest controls and reference points were relatively unknown.

For the past two decades, the herring stocks in British Columbia have sustained a relatively stable harvest under this policy. However, recent declines in two of the five major British Columbia herring stocks have raised concerns about the status and management of Pacific herring by some stakeholders, including First Nations. As a result, Fisheries and Oceans Canada (DFO) committed to a science-based review of the stock assessment and fishery management framework for Pacific herring to address these concerns. In early 2002, DFO also embarked on the Objectives Based Fisheries Management initiative (OBFM) as a basis for developing Integrated Fisheries Management Plans that are required under the Ocean's Act. The OBFM initiative identified two pilot species for the Region, Pacific herring and sablefish. For this OBFM initiative, DFO's Science Branch was tasked with determining conservation limit reference points for each of the five major herring stocks. To address this requirement and the science-based review, a risk assessment framework was developed for potential application to a variety of species (Fu et al. 2004a). In conjunction with this, DFO also committed to review the existing harvest policy for Pacific herring. To implement the risk assessment a population model of Pacific herring that reflected current understanding of herring biology and data uncertainty was required. Accordingly, a series of assessment models were developed to address concerns about aspects of data representativeness over the period 1951 to 2005, to incorporate flexibility in model structure that account for temporal variations in survival rate; model and environmental uncertainties; and to provide a framework for evaluating conservation limit reference points for harvest levels relative to the existing management policy (Fu et al. 2004b). An evaluation of these alternative models has been completed, and the stage is now set for the next step – risk assessment.

The conventional interpretation of risk consists of two components, the probability of an event occurring and the magnitude of the impact of the event. In the context of this paper, we provide a tool (the framework) for stakeholders to evaluate the magnitude of the impact of a change in harvest policy. The framework illustrates the average outcome over a number of simulation projections and so provides the most probable expectation for the harvest policy. As such, the framework is not a classical risk assessment but provides stakeholders with a tool to evaluate one aspect of risk assuming that the observed outcome is the most probable. The objective of this paper is to apply the risk assessment framework to Pacific herring using the best available knowledge of stock status and herring population dynamics, as recently reviewed and documented by PSARC (**http://www.dfo-mpo.gc.ca/csas/Csas/publications/ResDocs-DocRech/2004/2004_011_e.htm**). A stock projection model was developed to compare the probable outcomes of alternative proportional threshold harvesting policies under a series of different scenarios. Outcomes are summarized in eight "performance indicators" developed in consultations with stakeholders and designed to reflect various aspects of biological, social, and economic well-being.

Methods

Pacific herring in British Columbia have been characterized as a metapopulation (Ware and Schweigert 2001, 2002) with five relatively distinct sub-units or stocks: Queen Charlotte Islands (QCI), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SOG), and west coast of Vancouver Island (WCVI) (Figure 1). Since the rates of immigration and emigration among stocks are not well known and cannot be accurately modeled at this time, each stock was treated as a distinct unit. Thus, performance of various harvesting options is evaluated for each stock independently although future modeling efforts might be able to incorporate migration among stocks and could improve overall understanding of Pacific herring dynamics in British Columbia.

Evaluation of the performance indicators under various harvesting options was conducted using an assessment and projection model that is a variant of the NASM-3 model described in Fu et al (2004b) and is described in greater detail below. The model differs from that currently employed in the annual assessment and is a forward projection age-structured model developed in a Bayesian context. Its performance was evaluated relative to the current model by conducting simulation-estimation experiments and by reconstructing the dynamics of the five major herring stocks (Fu et al. 2004a). The simulation-estimation experiments indicated that explicitly estimating annual variations in natural mortality resulted in significantly lower mean absolute deviations for important parameter estimates including recruitment and spawning stock biomass when the simulated natural mortality changed randomly around a constant level, and even more so when the simulated mean value of natural mortality changed from one period of time to another (i.e., regime shift) (Fu et al. 2004a).

Model structure

The model begins the population dynamics from an unfished state with virgin recruitment (R_0) assumed constant up to 1951 when age-structure data first become available. Numbers at age in each successive year are calculated by accounting first for instantaneous natural loss and then removing catch during the short fishing season at the end of the modelled year before incrementing the age of each cohort. Data input to the stock reconstruction included the total catch in weight for fishing gear *g* ($C_{g,t}$), catch at age ($P_{g,t,a}$), the spawning biomass index (S_t), the proportion mature at age (m_a), and the average weight at age ($w_{t,a}$). The model notation and equations are presented in Appendix 1 (equations A 1.1 to A 2.6).

Two stock-recruitment (S-R) models are available in the framework for calculating deterministic recruitment R_t in equation (A2.1) including the Beverton-Holt (B-H) ($R_t = \dfrac{S_{t-r}}{\alpha + \beta S_{t-r}}$) and the Ricker ($R_t = aS_{t-r}e^{-bS_{t-r}}$) formulations. For the B-H model, parameters α and β are re-parameterized according to Francis (1992): $\alpha = S_0 \dfrac{1-h}{4hR_0}$ and $\beta = \dfrac{5h-1}{4hR_0}$, where *h* is the steepness of the S-R relationship, which is the fraction of R_0 to be expected in the absence of recruitment variability when spawning biomass is reduced to 20% of the unfished spawning biomass S_0. With the same rationale, the parameters a and b in the Ricker model are expressed as: $a = \frac{R_0 e^{bS_0}}{S_0}$ and $b = \frac{5\ln(5h)}{4S_0}$. The inclusion of a S-R model permits the calculation of the biomass to produce maximum sustainable yield (MSY), S_{MSY} and other related quantities. A numerical method implementing the Newton-Raphson technique is used to solve for MSY and determine S_{MSY} using average natural loss $\overline{M}$ and average fecundity at age $\bar{f}_a$.

The recruitment residual term (ε) in equations (A1.5 and A1.9) is adjusted by a lognormal bias correction factor ($-0.5\sigma_R^2$),

(1) $$\varepsilon_t = \xi_t - 0.5\sigma_R^2 ,$$

where σ_R is the standard deviation of the logarithm of the annual recruitment residuals. Assuming the recruitment residuals are correlated with a correlation coefficient of ρ following Ianelli et al. (2001), then

(2) $$\xi_t = \rho\xi_{t-1} + \sqrt{1-\rho^2}\varpi_t ,\ \varpi_t \sim N(0,\sigma_R^2).$$

The annual natural loss in the dynamics equation A1.10 is modelled as the product of the average natural loss and a lognormal random error,

(3) $$M_t = \overline{M} \cdot \exp(\nu_t),\ \nu_t \sim N(0,\sigma_M^2).$$

The gear-, year- and age-specific selectivity term ($s_{g,t,a}$) in equation A1.15 is defined using a logistic curve for each gear type

(4) $$s_{g,t,a} = (1 + e^{-\gamma_g (a - \varphi_g \exp(\varsigma_{g,t}))})^{-1},$$

and it varies over time through the lognormal gear-specific time-varying parameter $\varsigma_{g,t}$, $\varsigma_{g,t} \sim N(0,\sigma_{g,s}^2)$. The expression $\varphi_g \exp(\varsigma_{g,t})$ in equation (4) denotes the age at which 50% of fish are vulnerable to specific fishing gear g. Parameter γ_g is the gear-specific shape parameter.

The framework incorporates a spawning index conversion factor q_t to scale the spawn survey index to the actual spawning biomass level. Prior to 1988, the spawn survey index was only based on surface observations, but subsequently dive surveys have been conducted in all areas. The current assessment utilizes two separate *q* parameters for the surface and dive spawn survey eras (Schweigert 2001). However, there is no clear rationale for choosing among models that estimate one *q*, two *q*'s or fix both *q*'s for the two eras (Schweigert 2001). In this study, we only estimated one constant q_c for the period before 1988 and fixed the other at 1. Therefore, in equation A1.16, $q_t = q_c$ for $1951 \le t \le 1987$ and $q_t = 1$ for $1988 \le t \le 2003$.

Overall, the model estimates 234 parameters including R_0, $\overline{R}$, σ_R, h, ρ, q_c, 63 recruitment residuals ϖ_t, 55 random variations in natural mortality ν_t, and 110 variations in the selectivity parameter $\varsigma_{g,t}$. Alternatively, another assessment was conducted by ignoring the random variations in natural mortality and estimating only one constant value resulting in only 180 parameters to be estimated. The estimation of the various parameters is carried out in a number of phases, which averts problems where highly non-linear models enter biologically unreasonable regions (Ianelli et al. 1998). Bayesian priors are assumed for a number of variables using one of four available density functions: uniform, normal, lognormal or beta distribution. Appendix 2 presents the specific priors used in this study and are used as fixed values for other parameters in the model.

Likelihood functions were used to fit the model to the available data (Appendix 2). Although different types of error structure can be assumed, in this particular study we assumed lognormal error for catch in weight and the spawning biomass index. Coefficients of variation (CVs, assumed equal to the standard deviations of the lognormal distributions) for total catch and the spawning biomass index are inputs to the model. The CVs for both data sets are modelled in such a way that they can vary over time. In this study, CVs for total catch are assumed to be 0.30 throughout the time series. Previously, the spawning biomass index was treated as one time series assuming a fixed CV of $\sqrt{0.025}$ (Schweigert 2001). However, it is believed that the spawning biomass index measurement was more accurate after 1988 with the aid of SCUBA surveys. Therefore, CVs are set at two different levels for these two periods: 0.30 before 1988 and 0.25 afterwards, levels higher than those used in Schweigert (2001) in order to be more conservative. The robust likelihood formulation slightly modified from that in Fournier et al. (1990) is used for the catch-at-age data. The robust normal model was designed to minimize the impact of outliers relative to its counterpart, the more traditional multinomial error model (Fournier et al. 1990).

Parameter estimates were obtained by minimizing an overall objective function (Appendix 2), which was the sum of three components: (a) the negative log-likelihoods for all data sets, (b) the negative logarithm of penalties corresponding with prior assumptions made about the stochastic processes including recruitment (Equation 2), annual natural mortality (Equation 3), and selectivity (Equation 4), and (c) the negative logarithm of the prior density functions. The Markov Chain Monte Carlo (MCMC) method supplied with AD Model Builder software (Otter Research Ltd 2001) was used to sample from the posterior distribution. The MCMC algorithm starts at the mode of the joint posterior distribution with jumping rules based on the estimated variance-covariance matrix. In the analyses the MCMC was conducted with 1 million replications sampling every 1000th parameter vector from the original chain.

Alternative management policies were evaluated by simulating future stock trajectories for a given number of years into the future. Two sources of uncertainty were incorporated into the projections: (1) uncertainty in current population size and (2) process uncertainty. Uncertainty in the current population size that is projected forward is determined during the MCMC simulation and is a function of all the uncertainty in the model. The process uncertainty includes variability in recruitment and implementation error due to errors in future assessments. Two options are available in the framework to use either the estimated σ_R and ρ or some given levels of σ_R^{proj} and ρ^{proj} for determining the level of recruitment variability (using the same error structure given in Equations 1 and 2). The assessment errors are modelled by assuming that future estimates of exploitable biomass $\hat{B}_t$ are log-normally distributed around the true value B_t so that $\hat{B}_t = B_t \exp(\varepsilon_t^{assess})$, where $\varepsilon_{t+1}^{assess} = \rho^{assess}\varepsilon_t^{assess} + \xi_{t+1}$, and $\xi_{t+1} \sim N(0,(\sigma^{assess})^2(1-(\rho^{assess})^2)$. In this study, the level of assessment error σ^{assess} was set at 0.60 and the autocorrelation ρ^{assess} at 0.30.

Age-specific annual survival rate for the projection period can be calculated as the average over a chosen period of time or entered manually as required. Selectivity for future projections is calculated as the combined selectivity for all gears weighted according to some pre-determined values or from the gear-specific exploitation rates in the terminal year of the assessment $s_a^{proj} = \frac{\sum_g s_{g,t,a}\mu_{g,t}}{\sum_g \mu_{g,t}}$.

Performance Indicators

Conservation and sustainable resource management requires a good understanding of current stock status relative to some evaluation criteria. A common goal of fisheries management is to institute a harvest policy that will maintain the population at the level that produces the maximum sustainable yield, MSY (Maunder and Starr 2001) or endeavours to rebuild the stock to this level. Another consideration for many fishers is the probability that the population will decline to a reduced level that will permit little or no harvest. Other non-consumptive considerations such as the level of biomass of the population that is required to sustain ecosystem function also are important. The risk assessment framework was designed to provide guidance for evaluating the relative probabilities of these outcomes given alternative harvesting policies and assumptions about population dynamics. The performance indicators provide a measure of the magnitude of the impact associated with attaining various management goals for the resource given alternative harvesting policies. Performance indicators were chosen to cover a broad range of both socio-economic factors important to the fishing industry and First Nations and biological measures that would reflect population viability and long-term sustainability of the resource. A total of 8 performance indicators were identified during consultation with stakeholders and are included in the risk assessment framework:

1) Average spawning stock biomass (SSB) of the population. SSB reflects the biological status of the herring population and its contribution to ecosystem function. A high spawning biomass is desirable for long-term population viability during periods of unfavourable environmental conditions, to support long-term yield to the fishery, and to maintain ecological functions such as providing forage for ecologically-dependent species.

2) Average annual catch from the stock. This is primarily an economic indicator that depends on fishing effort and stock size.

3) The number of years that the stock is projected to be less than the cutoff level and consequently the fishery would be closed to facilitate stock rebuilding. Increased

numbers of years of closure would indicate negative impacts to the fishing industry and possibly impact market share.

4) Proportion of the stock that is composed of fish age 4 and older. A number of stakeholders expressed concern about the apparent reduction in size of herring and the lack of older fish in the population. Other things being equal, a stock with a higher proportion of older (and larger) fish should produce more eggs providing a higher probability of recruitment success. It would also result in a better product to the fishing industry and allow for better gillnet fisheries that target the largest fish in the population.

5) Probability that the spawning stock biomass declines below the current ("fixed") cutoff level (25% of the previous S_0). Reduction of population abundance below this level has for many years been considered undesirable because it would delay population rebuilding and may compromise ecosystem function. In fact, this level was chosen (in combination with a 20% harvest rate) to reduce the probability of fishery closures to less than 10 percent over the long term.

6) Probability that the spawning stock biomass declines below a new trial (or "floating") cutoff level expressed as a percentage of the estimated unfished stock level (0 to 60% of S_0). Reduction of population abundance below this level is considered undesirable because it would delay population rebuilding and may compromise ecosystem function.

7) Probability of a 50% decline in spawning stock biomass from the current level in three generations. This indicator is comparable to that used by a number of organizations to assess conservation risk. To evaluate risk of extinction, the IUCN uses a timescale of 10 years or three generations, whichever is longer (Baillie and Groombridge 1996). For Pacific herring, average age of maturity is about three years and generation time is about 5 years (4.98 in Fu et al. 2004a following the approach of Restrepo et al. 1998). Therefore, in our simulations, a time-scale of 15 years (i.e., three generations) was used to be consistent with the IUCN species listing criteria.

8) Probability that the spawning stock biomass will rebuild from the current level to exceed the biomass level required to produce maximum sustainable yield (B_{MSY}) within three generations (15 years). This indicator was intended to measure the ability of a depressed stock to recover over a longer period to target levels of abundance at which the population is most productive.

These performance indicators were used to measure the effectiveness of alternative reference points and harvest strategies for achieving the conservation objective of maintaining populations and species within bounds of natural variability. To evaluate the effects of harvest rate μ and cutoff coefficient π on population dynamics, the program looped over values of these two variables with a step size of 0.05, from 0.01 to 0.96 for μ, and from 0% to 60% for π.

Population Projections

To assess the harvest policy alternatives using the various performance indicators a series of population projections were compared for each of the five major herring stocks. The performance indicators were assessed for the following five projection scenarios:

1) Stock projections assuming a Ricker S-R function, spawning stock biomass beginning at the current level, all harvest with seine gear only, annual variation in M during parameter estimation, and survival fixed at the average during the last 10 years. Recent analyses by Ware and Schweigert (2001, 2002) indicated that the Ricker function was appropriate under cold environmental conditions for most stocks.
2) Stock projections assuming a Beverton-Holt S-R function, spawning stock biomass beginning at the current level, all harvest with seine gear only, annual variation in M during parameter estimation, and survival fixed at the average during the last 10 years. Ware and Schweigert (2001, 2002) noted that the Hockey Stick model was most appropriate under warm environmental conditions. However, attempts to use the Hockey Stick model were not successful for some stocks (model failed to converge). The B-H function should provide comparable results to the H-S function under most conditions.
3) Stock projections assuming a Ricker S-R function with a constant M (assumed during parameter estimation), spawning stock biomass beginning at the current level, all harvest with seine gear only, and survival fixed at the average during the last 10 years. Although functionally not identical to the current model, the constant M assumption is comparable to models used previously to investigate harvest rules for Pacific herring stocks (Trumble 1983, Fried and Wespestad 1985, Doubleday 1985, Haist 1988, Hall et al. 1988, Haist et al. 1993, Zheng et al. 1993).
4) Stock projections assuming a Ricker S-R function, spawning stock biomass beginning at the current level, all harvest with seine gear only, annual variation in M during parameter estimation, and survival fixed at the average during the last 10 years. An extended fishery closure is simulated deferring the resumption of harvest by one year after the stock rebuilds above cutoff to ensure recovery is continuing.
5) Stock projections assuming a Ricker S-R function, spawning stock biomass beginning at the current level, all harvest with seine gear only, annual variation in M during parameter estimation, and survival fixed at 75% of the average during the last 10 years to investigate the impact of poor environmental conditions such as during a regime shift on stock resilience and productivity.

Results

The assumptions about population dynamics underlying the stock reconstruction model chosen for conducting the stock projections and evaluating performance criteria is critical to the risk assessment framework presented in this study. Fu et al. (2004a) noted that a number of population assessment models with slightly different assumptions about herring population dynamics provided similar performance in reconstructing simulated population data and there was no clear basis for choosing one model over another. To proceed with the risk assessment framework, it was necessary to select a single robust Bayesian model rather than attempt to conduct the risk assessment with multiple models, some of which do not yet include a Bayesian framework. Fu et al. (2004b) suggested that a model incorporating annual variation in natural mortality (NASM-3) performed best under the specific simulations examined in their study. Consequently the NASM-3 model was chosen for this study recognizing that selection of a different population model might have resulted in a somewhat different outcome but the risk assessment framework would have been the same.

The basic biological data supporting the stock reconstruction and projections are presented in Figures 2 and 3. The results of the population projections for the five scenarios for the eight performance measures in each of the five major assessment regions are presented in Figures 4 to 43. A summary of the performance indicators under the current harvest policy is provided for each of the stocks in Tables 1 to 5. Each set of projections and output figures provides the basis for evaluating the current harvest policy as well as alternatives under the various scenarios. Examining the magnitude of the change in the performance indicator in response to changes in either the harvest rate or cutoff level provides a measure of the risk or desirability of the outcome associated with the harvest policy choice.

Queen Charlotte Islands

Stock reconstruction and parameter estimates

The results for the stock reconstruction on the Queen Charlotte Islands are presented in Tables 1 and 2 and Figures 2 and 3. Stock reconstruction assuming a Beverton-Holt (B-H) stock-recruitment (S-R) function and annually varying M yielded an estimate of unfished biomass (S_0), similar to the current value of 42800 tonnes (Table 1). Assuming a Ricker S-R function with constant or annually varying M produced estimates of S_0 substantially lower than the currently assumed value (31648 and 20645 tonnes, respectively). The estimates of B_{MSY} ranged from 16273 - 22518 tonnes while the estimates of the fishing mortality rate to achieve this yield ranged from 0.29 - 0.36. All reconstructions indicated a depleted abundance level ranging from 3977 to 5991 tonnes. The MCMC trace plots from the posterior distributions for the estimated steepness at the origin (*h*), the unfished spawning stock biomass or S_0, the estimate of current biomass, and the fishing mortality to achieve MSY, are presented in Figures 4, 6, and 8 for Ricker and B-H models with annually varying M, and the Ricker model with constant M, respectively. The trace plots for the B-H model are stable with no trends evident over the period of the simulation whereas the Ricker analysis with varying M indicates an increasing trend in S_0 and a decreasing trend in the estimate of μ_{MSY} while the Ricker analysis assuming constant M indicates initial trends in *h*, S_0 and μ_{MSY} that subsequently stabilize. The results suggest that the MCMC may not have reached the global minimum for the Ricker analyses and the resulting estimate of S_0 may be conservative. The results also suggest only moderate uncertainty in the estimate of unfished biomass S_0, and at a level comparable to that derived in previous analyses. The estimated steepness for the two Ricker model analyses was unexpectedly high in comparison to estimates for other pelagic species whereas the result for the B-H model falls within the expected range of 0.5 to 1.0.

Stock projections

The results for the five projection scenarios and eight performance indicators are presented in Table 2 and Figures 5, 7, and 9 - 11. Results were very similar for all scenarios except when assuming a reduced level of survival which resulted in a reduced average level of SSB and high probability of being below either a fixed (0.55) or floating (0.50) cutoff level and low probability (0.07) of stock rebuilding to the B_{MSY} level in three generations under the existing harvest policy (Table 2). The other scenarios all indicated healthy SSB levels ranging from 13-16000 tonnes, a lower probability of declining below cutoff (0.20 - 0.25) and rapid stock rebuilding with fishery closures occurring in 1 - 4 years. The contour surfaces for the performance indicators for the Ricker and B-H projections assuming an annually varying M were very similar with subtle differences under the current harvest policy. The projections with the Ricker function assuming a constant M suggested a slightly more productive stock with higher average SSB and annual catch. Compared to the B-H model, the Ricker model with annually varying M had higher probability of rebuilding the SSB to the MSY level within 15 years. Introducing a one year lag in re-opening the fishery after a closure had little impact on the results.

Prince Rupert District

Stock reconstruction and parameter estimates

The results for the stock reconstruction in the Prince Rupert area are presented in Tables 1 and 3 and Figures 2 and 3. Stock reconstructions assuming either a B-H stock-recruitment function with annually varying M or Ricker S-R function with constant M yielded estimates of unfished biomass (S_0), at least double the current estimate of 48400 tonnes. The estimate of S_0 from the Ricker S-R model with annually variable M was 64108 tonnes and most closely approximates the current estimate. Estimates of B_{MSY} ranged from 37550 to 63682 tonnes for the three models with the fishing mortality to achieve this level ranging from 0.24 - 0.31 (Table 1). The estimates of current biomass were very similar for the three models ranging from 24496 - 26471 tonnes. The MCMC trace plots from the posterior distributions for the estimated steepness at the origin (h), the unfished spawning stock biomass or S_0, the estimate of current biomass, and the fishing mortality to achieve MSY, are presented in Figures 12, 14, and 16 for Ricker and B-H models with annually varying M, and the Ricker model with constant M, respectively. The trace plots for the MCMC simulations for the three models were quite variable and indicated slightly increasing trends for the B-H model and the Ricker model with constant M while the Ricker model with variable M appeared stable. The results suggest that the MCMC may not have reached the global minimum for the B-H model and Ricker model with constant M so the resulting estimates of S_0 may be inflated. The estimated posteriors for steepness for all three models are within the expected range, roughly between 0.60 - 0.90.

Stock projections

The results for the five projection scenarios and eight performance indicators are presented in Table 3 and Figures 13, 15, and 17 - 19. Results were very similar for all scenarios except when assuming a reduced level of survival which resulted in a roughly 50% reduction in the average level of SSB and annual catch. It also resulted in an increase in the number of years of fishery closure (4) and a marked reduction in the probability of the SSB exceeding the MSY level within 15 years (0.08). The other scenarios all indicated healthy SSB levels ranging from 45000 - 60000 tonnes, a very low probability of declining below cutoff (<0.1) and rapid stock rebuilding with fishery closures occurring in only one year. The contour surfaces for the performance indicators for the three model projections were very similar with subtle differences under the current harvest policy. The projections with the Ricker function assuming a constant M suggested a slightly more productive stock with higher average SSB and annual catch (Figures 13, 15, 17). The Ricker model with annually varying M had the highest probability of rebuilding the SSB to the MSY level within 15 years. Introducing a one year lag in re-opening the fishery after a closure had virtually no impact on the results (Table 3, Figures 13 and 18).

Central Coast

Stock reconstruction and parameter estimates

The results for the stock reconstruction for the Central Coast are presented in Tables 1 and 4 and Figures 2 and 3. Stock reconstructions assuming either a B-H stock-recruitment function with annually varying M or Ricker S-R function with constant M yielded estimates of unfished biomass (S_0) ranging from 49149 – 72993 tonnes, within the range of the current estimate of 70400 tonnes. The estimate of S_0 from the B-H model with annually variable M most closely approximates the current estimate. Estimates of B_{MSY} ranged from 36035 to 42901 tonnes for the three models with the fishing mortality to achieve this level ranging from 0.27-0.35 (Table 1). The estimates of current biomass were very similar for the three models ranging from 23131 - 28670 tonnes. The MCMC trace plots from the posterior distributions for the estimated steepness at the origin (h), the unfished spawning stock biomass or S_0, the estimate of current biomass, and the fishing mortality to achieve MSY, are presented in Figures 20, 22, and 24 for Ricker and B-H models with annually varying M, and the Ricker model with constant M, respectively. The trace plots for the MCMC simulations for the three models were quite variable and indicated some slight trends in all cases. The Ricker model with annually variable M had an increasing trend in h and μ_{MSY} and a slightly decreasing trend in S_0 (Figure 20). The B-H model showed a slightly decreasing trend in μ_{MSY} (Figure 22). The Ricker model with constant M had a slightly decreasing trend in h and μ_{MSY} and a slight increasing trend in S_0 (Figure 24). The results suggest that the MCMC may not have reached the global minimum in these simulations but the trends were so slight that they are unlikely to affect results markedly. The estimated steepness values for the two Ricker model analyses were unexpectedly high whereas the result for the B-H model was within the expected range (0.60 - 0.90).

Stock projections

The results for the five projection scenarios and eight performance indicators are presented in Table 4 and Figures 21, 23, and 25-27. Results were very similar for all scenarios except when assuming a reduced level of survival which resulted in a reduced level of SSB and annual catch although less than observed for either QCI or PRD. There was no impact on the number of years of fishery closure (1) but a marked reduction in the probability of the SSB exceeding the MSY level within 15 years (0.13). The other scenarios all indicated healthy SSB levels ranging from 37000 - 45000 tonnes, a very low probability of declining below cutoff (<0.05) and rapid stock rebuilding with fishery closures expected in only one year during the projection period. The probability of rebuilding to the B_{MSY} level within 15 years ranged from 0.40 – 0.45. The contour surfaces for the performance indicators for the three model projections were all similar with subtle differences under the current harvest policy.

Strait of Georgia

Stock reconstruction and parameter estimates

The results of the stock reconstruction for the Strait of Georgia are presented in Tables 1 and 5 and Figures 2 and 3. Stock reconstructions assuming either a B-H stock-recruitment function with annually varying M or Ricker S-R function with constant M yielded estimates of unfished biomass (S_0) ranging from 106156 – 170408 tonnes, all considerably higher than the current estimate of 84800 tonnes but in agreement with recent observations. The estimate of S_0 from the B-H model with annually variable M most closely approximates the current estimate. Estimates of B_{MSY} ranged from 76130 to 99185 tonnes for the three models with the fishing mortality to achieve this level ranging from 0.30 - 0.35 (Table 1). The estimates of current biomass were very similar for the three models ranging from 93484 - 104968 tonnes. The MCMC trace plots from the posterior distributions for the estimated steepness at the origin (*h*), the unfished spawning stock biomass or S_0, the estimate of current biomass, and the fishing mortality to achieve MSY, are presented in Figures 28, 30, and 32 for Ricker and B-H models with annually varying M, and the Ricker model with constant M, respectively. The trace plots for the MCMC simulations for the three models were quite variable but generally stable. The Ricker model with constant M had a slightly increasing trend in *h* and μ_{MSY} and a slightly decreasing trend in S_0 (Figure 32). However, the degree of variation in the four variables of interest was limited and should not impact the overall results. The estimated steepness for the three models ranged from about 0.75- 1.20 and was within the expected range for this species.

Stock projections

The results for the five projection scenarios and eight performance indicators are presented in Table 5 and Figures 29, 31, and 33-35. Results were very similar for all scenarios except when assuming a reduced level of survival which resulted in a roughly 35% reduction in average SSB and annual catch. It had no impact on the number of years of fishery closure but increased the probability of a 50% decline in SSB within 15 years (0.35) and a marked reduction in the probability of the SSB exceeding the MSY level within 15 years (0.22). The other scenarios all indicated healthy SSB levels ranging from 90000 - 110000 tonnes, a very low probability of declining below cutoff (<0.05) and rapid stock rebuilding with fishery closures occurring only once during the projection period. The contour surfaces for the performance indicators for the three model projections were all very similar with subtle differences under the current harvest policy. The projections with the B-H function with annually variable M suggested a slightly more productive stock with higher average SSB and annual catch (Table 5, Figures 28, 30, 32). The Ricker model with annually varying M and a one year lag in fishery opening had the highest probability of rebuilding the SSB to the MSY level within 15 years.

West Coast of Vancouver Island

Stock reconstruction and parameter estimates

The results of the stock reconstruction for the west coast of Vancouver Island are presented in Tables 1 and 6 and Figures 2 and 3. Stock reconstructions assuming either a B-H or Ricker stock-recruitment function with annually varying M or Ricker S-R function with constant M yielded estimates of unfished biomass (S_0) ranging from 52297 – 76800 tonnes, within the range of the current estimate of 75200 tonnes. The estimate of S_0 from the B-H model with annually variable M most closely approximates the currently assumed value. Estimates of B_{MSY} ranged from 37647 to 43974 tonnes for the three models with the fishing mortality to achieve this level ranging from 0.29 - 0.35 (Table 1). The estimates of current biomass were very similar for the three models ranging from 10215 - 14064 tonnes. The MCMC trace plots from the posterior distributions for the estimated steepness at the origin (*h*), the unfished spawning stock biomass or S_0, the estimate of current biomass, and the fishing mortality to achieve MSY, are presented in Figures 36, 38, and 40 for Ricker and B-H models with annually varying M, and the Ricker model with constant M, respectively. The trace plots for the MCMC simulations for the three models were quite variable with some minor trends over the course of the simulations. The Ricker model with annually varying M showed a slightly declining trend in *h* and an increasing trend in S_0 while μ_{MSY} is fluctuating (Figure 36). The Ricker model with constant M showed a slightly declining trend in S_0 while μ_{MSY} was increasing although both appear to stabilize at the end of the simulations (Figure 40). Although it appears that the MCMC may not have reached the global minimum in some of these simulations the degree of variation in the estimates of interest were quite limited and so should not affect the conclusions. The estimated steepness for the three models ranged from about 0.90 - 1.30 and were at the upper end of the expected range for this species.

Stock Projections

The results for the five projection scenarios and eight performance indicators are presented in Table 6 and Figures 37, 39, and 41-43. Results were very similar for all scenarios except when assuming a reduced level of survival which resulted in a roughly 35% reduction in the average level of SSB and almost 50% reduction in annual catch. The expected number of years of fishery closures also increased while the probability of the SSB exceeding the MSY level within 15 years (0.02) decreased significantly. The other scenarios all indicated healthy SSB levels ranging from 26000 - 32000 tonnes, a low probability of declining below cutoff (<0.20) and relatively slow stock rebuilding with fishery closures occurring 1-4 times during the projection period. The contour surfaces for the performance indicators for the three model projections were generally similar with subtle differences under the current harvest policy. The projections with the Ricker model with constant M suggested a slightly more productive stock with higher average SSB and annual catch (Table 6, Figures 37, 39, 41). Also, it had the highest probability of rebuilding the SSB to the MSY level within 15 years.

Discussion

The concept of risk assessment in fisheries science is relatively new and has been dealt with largely from the perspective of risk to the resource as a consequence of the fishery (Francis 1993). More recently, socio-economic factors and ecosystem viability also have become important considerations. The concept of risk is often difficult to quantify because the components, probability of an undesirable event, and the extent of loss associated with the event are complex. Additionally, subjective reactions to the assessment of probabilities and extent of loss differ among stakeholders who often have conflicting interests and objectives. The risk assessment framework developed here is intended to demonstrate probable outcomes based on population projections under various scenarios. Outcomes are captured by performance indicators of interest to the various stakeholders. Agreeing on the acceptable level of risk and an associated harvest policy will require consultation among all users of the resource. However, it is the mandate of DFO to promote the sustainable management of all marine species in the context of the precautionary approach and an associated conservation reference must be identified (Shelton and Rice 2002). A variety of possible reference points (RPs) have been proposed to achieve this objective but no consensus has been reached on the ideal RPs or approach to their determination (Richards and Maguire 1998, Shelton and Rice 2002). Reference points may be expressed in terms of fishing mortality rate or harvest rate and stock biomass (Caddy 1998). Two types of RPs have been identified, conservation or limit RPs intended to constrain harvesting within safe biological limits, and management or target RPs intended to meet management objectives (Caddy and Mahon 1995). For RPs to be effective managers require a good understanding of current stock status relative to evaluation criteria and the risk associated with various alternative management actions (Maunder and Starr 2001). Estimating uncertainty in the management parameters is also very important, and the incorporation of Bayesian procedures into stock assessments has become an accepted method to assess parameter uncertainty and to estimate the probability of performance indicators for evaluating RPs and risk (Punt and Hilborn 1997).

From the perspective of the OBFM initiative, fishery managers may want to know how low the abundance of a population can go without causing irreversible harm to the stock. Establishing a minimum viable population size is problematic, particularly for pelagic species like herring that exhibit high natural variation in productivity and abundance. However, it may be feasible to determine a limit reference point based on population size that would satisfy stated conservation criteria and determine the long-term risk to the population and fishery of being at this level. For example, managers might choose a population abundance level large enough to ensure an acceptably low probability of triggering an IUCN listing criteria (Mace and Stuart 1994) or of falling below a threshold or quasi-extinction level of abundance in the long term. A population reduced to this level should have an acceptably high probability of recovery to a sustainable target level within a short time period. The US Magnuson-Stevens Fishery Conservation and Management Act specifies a legal requirement for recovery within 10 years or as soon as possible (Restrepo et al. 1998) and Johnston et al. (2000) propose a limit to allow recovery within a single generation.

In practice, fishery managers are interested in harvest strategies that not only reduce conservation concerns but also achieve maximal benefits, perhaps by increasing total catch over the long term or reducing the probability of a low catch in a particular season. Optimal harvest strategies often involve “proportional threshold harvesting” (Lande et al. 2001) in which no harvest occurs when abundance is below a management threshold. When the management threshold is set to satisfy conservation objectives, it can be considered as the conservation limit reference point although it generally exceeds the latter. Harvest strategies with cutoff thresholds are more robust to adverse environmental regimes in which survival rate falls below the long-term average for extended periods (Fu et al. 2000), although they may entail a higher variance in annual catch (Lande et al. 1997). Cutoff thresholds are often set at 20% of unfished equilibrium abundance (Francis 1993, Thompson 1993). Risk analyses are necessary to evaluate the likely consequences and tradeoffs associated with alternative decisions about harvest rates and cutoff thresholds.

The current harvest policy for Pacific herring was established in the early to mid-1980s when the major emphasis was placed on maximizing the number of years of viable fishing opportunities while allowing for adequate spawning escapement to ensure future recruitment and stock viability (Haist 1988, Hall et al. 1988, Zheng et al. 1993, Haist et al. 1993). As noted above, the development of a harvest policy for any species now involves a variety of tradeoffs between economic, social, and biological factors. The difficulty lies in determining a relative weighting for each of the criteria being considered to ensure that each is given equitable consideration. The approach adopted here was to identify a series of performance criteria that encompass a range of biological and socio-economic considerations and to assess their impacts on each of the herring stocks under a variety of scenarios. The outcomes were then compared to the current harvest policy. In effect, we were asking whether there is an unacceptable risk to the stock under the existing harvest policy, and if so, how could the policy be modified to reduce the risk level? The framework presented here allows managers to compare the tradeoffs in the performance indicators associated with different harvest policies (i.e., increasing the harvest rate under a given scenario will decrease average spawning stock biomass and the proportion of the population consisting of older individuals, and it may increase the probability of spawning biomass falling below the fishery threshold). However, determining whether the increase in average catch warrants the increased risk to the population remains a difficult decision that cannot be readily quantified given the suite of other considerations. Nevertheless, some general themes emerged from the stock projections presented here.

Currently, cutoff levels for British Columbia herring stocks are set at 25% of the estimated unfished biomass, S_0 (Table 1). The Bayesian posterior distributions from the current analyses generally supported the existing choice of cutoff levels although the estimates differed substantially between the three models (i.e., B-H and Ricker function assuming annually variable M and a Ricker model with constant M). In general, the B-H function yielded the highest estimates of unfished abundance but there is no rationale for preferring it over the Ricker models. In fact, Ware and Schweigert (2001, 2002) found that the B-H stock recruitment function fit herring stock and recruitment data better during the recent warm period for most stocks whereas the Ricker function was more appropriate during the earlier cool period. The posterior distributions for S_0 are relatively narrow for some stocks but rather broad for others which complicates a decision on the appropriate level of unfished biomass to be used for setting cutoff levels. In addition, trends in the trace plots for S_0 for some stocks and for some recruitment functions suggest that the minimization in the MCMC simulations may not have converged to the global minimum. Methodologies for assessing convergence in these models are still being developed and these criteria should be investigated in future work to determine appropriate S_0 levels for these stocks. A related question was how to best incorporate the uncertainty in the estimated unfished abundance level in determination of an appropriate fishing threshold given the broad posterior distribution for S_0 knowing that the point estimate of S_0 would directly impact the outcome and interpretation of the performance indicators.

Stock projections and contour plots for the five assessment regions were generally consistent regardless of the model used in the projection suggesting that the framework proposed here is quite robust to the choice of model. One criticism of our approach is that we chose to conduct the risk assessment exclusively with the NASM-3 model which raises the question of how the results would differ if another model were chosen. We expect that other models would yield broadly similar results with minor differences in the performance indicators under these scenarios. The only scenario that yielded moderately different results was when the survival rate was reduced to simulate the possible impact of a regime shift or broader scale climatic variability (Tables 2-6). Even a modest reduction in survival (as modelled here) can have a marked impact on stock productivity and the uncertainty needs to be incorporated into the harvest policy in some fashion.

The performance indicators chosen for the framework were of mixed utility. The average spawning stock biomass and average annual catch were useful indicators of stock health and economic return. The proportion of age 4 and older fish in the stock was intended to reflect the reproductive potential of the population. A greater proportion of older and more fecund individuals was expected to increase the population productivity. A greater proportion of larger fish also represents better fishing opportunities for the gillnet gear sector targeting larger and more valuable roe. Unfortunately, this indicator was really a function of the average SSB since higher SSB was consistent with a higher proportion of age 4 and older fish in the population. The indicator for the number of years of fishery closures was useful but the results were intuitive with higher exploitation rates and higher cutoff levels resulting in more years of fishery closures. It was also inversely related to the average annual catch which one would expect. The indicators relating the probability of SSB falling below a fixed or floating cutoff level yielded similar results. The indicator for the probability of a 50% decline in 3 generations was not especially useful. It was chosen as one of the criteria used by the IUCN in making listing decisions. However, Pacific herring like other species with episodic large recruitments were resilient enough to sustain harvest over the 3 generation projection period with a negligible probability of this degree of decline unless the harvest rate exceeded 30% and the cutoff level was relatively low. Finally, the indicator of the probability that the SSB would recover to the B_{MSY} level within 3 generations was intended to reflect the degree of difficulty in rebuilding depleted stocks to a highly productive level. The indicator provided a very useful criterion for evaluating the tradeoffs between increasing yield versus increasing SSB for different harvesting options.

The framework illustrated here provides a useful tool for comparing the impacts of harvesting policy alternatives. For example, in Figure 5 we found that the current harvest policy with a 20% harvest rate and 25% fixed cutoff level should result in an average SSB of about 13000 tonnes and annual catch of about 2500 tonnes in the Queen Charlotte Islands. Reducing the harvest rate to 10% with a 25% Cutoff level would increase the SSB marginally to about 15000 tonnes while reducing the average catch to about 1250 tonnes. It would result in no fishery closures and a slight increase in the proportion of fish age 4 and older. It also would increase the probability of rebuilding to B_{MSY} (21,592 tonnes) from about 25% to about 35%. The issue then becomes one of deciding whether foregoing an average of 1250 tonnes of yield annually for 3 generations (15 years) is preferable to the increased yield of about 4400 tonnes annually that would be available at the B_{MSY} level. Another way to apply the framework is shown in Figure 11, the scenario with reduced survival possibly reflecting a regime shift, where SSB is reduced to an average of 9200 tonnes and catch is reduced to 1500 tonnes annually. A total of 3 fishery closures are anticipated in the next 15 years and the probability of SSB reaching the B_{MSY} level is about 7%. In this instance, reducing the harvest rate to 10% would reduce catch to about 800 tonnes but would almost double to almost 12% the probability of rebuilding to $B_{MSY.}$ In this case, the tradeoffs appear similar but the payoff in terms of longer term yield as a result of stock rebuilding may be higher depending how environmental conditions change over the projected 15 year horizon. The other more difficult and subjective consideration is how to weight the value of increased ecosystem function that would accrue at the higher biomass level as the stock rebuilds.

The conclusion from the risk assessment framework presented here is that Pacific herring are resilient to exploitation rates approaching 40% during average conditions and more than 20% under the reduced survival scenario examined here (see results for the probability of 50% population declines). The specific results of this study for herring do not differ markedly from the research conducted two decades ago that indicated a 20% harvest rate for herring was sustainable under most conditions (Haist 1988, Hall et al. 1988, Zheng et al. 1993). Perhaps the most surprising result was the apparent sensitivity of herring populations to vagaries of survival rate. Haist et al. (1993) previously noted that a model including density dependent (i.e., predation driven) rather than constant mortality suggested a more conservative harvesting approach to minimize the probability of fishery closures. Therefore, it appears that any factors that impose increased mortality on herring stocks reduce short term resilience and longer term population sustainability and productivity. Environmental impacts on herring productivity have been well documented (Ware 1996, Ware and Schweigert 2001, 2002) and indicate that survival rates are high during productive cold periods such that reference points will likely not be reached. However, the recent warm regime and associated mortality vectors have apparently significantly decreased survival rates of some stocks, especially the Queen Charlotte Islands stock more than simulated here.

The risk assessment framework provides a vehicle for assessing the possible value of alternative harvesting choices in terms of foregone yield and rehabilitation of depressed stocks. The existing harvest policy is robust to the challenges imposed by environmental perturbations and protects adequate spawning stock to rebuild the populations as conditions for herring survival improve. Further research to increase understanding of the factors that regulate herring survival and its prediction would provide the basis for developing a more precautionary harvesting strategy that directly incorporates those risk factors.

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Table 1. Estimates of current biomass, biomass at maximum sustainable yield,and unfished biomass for Ricker S-R functions assuming variable and constant natural mortality and Beverton-Holt S-R function with variable natural mortality for five herring stocks.

	Queen Charlotte Islands	Prince Rupert District	Central Coast	Strait of Georgia	W.C. Vancouver Island
Cutoff Level	10700	12100	17600	21200	18800
Current S_0	42800	48400	70400	84800	75200
Beverton-Holt – Variable M					
S_0	38187	91048	72993	170408	76800
$B_{Current}$	3977	24756	23131	104968	10437
B_{MSY}	21592	47387	39848	99185	43974
μ_{MSY}	0.29	0.24	0.27	0.30	0.29
Ricker – Variable M					
S_0	20645	64108	58822	106156	52297
$B_{Current}$	4083	24496	24053	99748	10215
B_{MSY}	16273	37550	42901	76130	37647
μ_{MSY}	0.36	0.31	0.35	0.35	0.35
Ricker – Constant M					
S_0	31648	123634	49149	133214	58047
$B_{Current}$	5991	26471	28670	93484	14064
B_{MSY}	22518	63682	36035	90468	40523
μ_{MSY}	0.34	0.28	0.35	0.34	0.35

Table 2. Queen Charlotte Islands performance indicators under the current harvest policy for 15 year stock projections.

	Ricker Var. M	B-H– Var. M	Ricker – Const. M	Fishery Lag	Reduced Survival
Average SSB	13000	13000	16000	13500	9200
Average Annual Catch	2500	2100	2900	2300	1500
Number of Years Fishery Closed	1	4	1	2	2
Proportion Greater than Age 4	0.18	0.19	0.21	0.19	0.16
Probability SSB < Fixed Cutoff	0.22	0.25	<0.20	0.22	0.55
Probability SSB < Floating Cutoff	0.19	0.2	0.15	0.19	0.5
Probability 50% Decline (15 Yrs)	<0.10	<0.10	<0.10	<0.10	<0.10
Probability SSB > B_{MSY} (15 Yrs)	0.25	0.07	0.14	0.27	0.07

Table 3. Prince Rupert District performance indicators under the current harvest policy for 15 year stock projections.

Indicators	Ricker Var. M	B-H– Var. M	Ricker – Const. M	Fishery Lag	Reduced Survival
Average SSB	45000	45000	60000	48000	25000
Average Annual Catch	9000	7800	11000	9000	4000
Number of Years Fishery Closed	<1	1	1	<1	4
Proportion Greater than Age 4	0.32	0.32	0.37	0.32	0.23
Probability SSB < Fixed Cutoff	<0.10	<0.05	<0.10	<0.10	<0.10
Probability SSB < Floating Cutoff	<0.05	<0.05	<0.05	<0.05	<0.05
Probability 50% Decline (15 Yrs)	<0.10	<0.10	<0.10	<0.10	<0.10
Probability SSB > B_{MSY} (15 Yrs)	0.65	0.35	0.35	0.65	0.08

Table 4. Central Coast performance indicators under the current harvest policy for 15 year stock projections

Indicators	Ricker Var. M	B-H– Var. M	Ricker – Const. M	Fishery Lag	Reduced Survival
Average SSB	43000	38000	37000	45000	32000
Average Annual Catch	8500	7300	7500	9000	6000
Number of Years Fishery Closed	<1	<1	<1	<1	<1
Proportion Greater than Age 4	0.32	0.30	0.34	0.32	0.19
Probability SSB < Fixed Cutoff	<0.05	<0.05	<0.05	<0.05	<0.1
Probability SSB < Floating Cutoff	<0.05	<0.05	<0.05	<0.05	<0.1
Probability 50% Decline (15 Yrs)	<0.10	<0.10	<0.10	<0.10	<0.10
Probability SSB > B_{MSY} (15 Yrs)	0.41	0.40	0.45	0.41	0.13

Table 5. Strait of Georgia performance indicators under the current harvest policy for 15 year stock projections.

Indicators	Ricker Var. M	B-H– Var. M	Ricker – Const. M	Fishery Lag	Reduced Survival
Average SSB	90000	110000	98000	90000	60000
Average Annual Catch	18000	21000	20000	18000	12000
Number of Years Fishery Closed	<1	<1	<1	<1	<1
Proportion Greater than Age 4	0.31	0.26	0.24	0.30	0.20
Probability SSB < Fixed Cutoff	<0.05	<0.05	<0.05	<0.05	<0.1
Probability SSB < Floating Cutoff	<0.05	<0.05	<0.05	<0.05	<0.05
Probability 50% Decline (15 Yrs)	<0.10	<0.10	<0.10	<0.10	0.35
Probability SSB > B_{MSY} (15 Yrs)	0.65	0.60	0.55	0.68	0.22

Table 6. West Coast Vancouver Island performance indicators under the current harvest policy for 15 year stock projections.

Indicators	Ricker Var. M	B-H– Var. M	Ricker – Const. M	Fishery Lag	Reduced Survival
Average SSB	27000	26000	32000	28000	17500
Average Annual Catch	5000	4000	6000	4800	2500
Number of Years Fishery Closed	2	4	1	3	5
Proportion Greater than Age 4	0.20	0.21	0.21	0.20	0.13
Probability SSB < Fixed Cutoff	<0.20	<0.2	0.09	<0.20	0.53
Probability SSB < Floating Cutoff	0.15	0.15	0.09	0.15	0.48
Probability 50% Decline (15 Yrs)	<0.10	<0.10	<0.10	<0.10	<0.10
Probability SSB > B_{MSY} (15 Yrs)	0.15	0.07	0.23	0.15	0.02

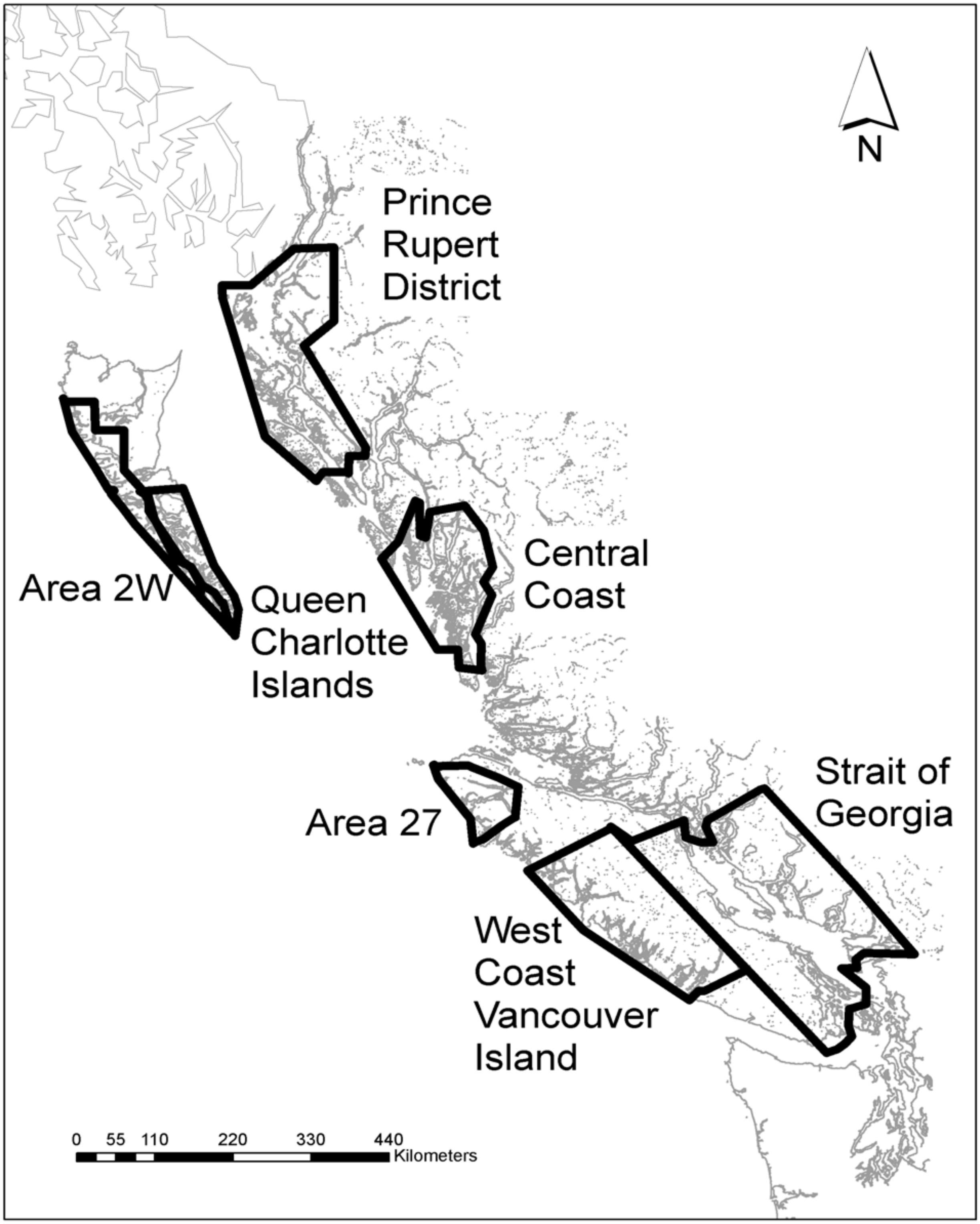

Figure 1. The five major British Columbian herring stock assessment regions: Prince Rupert District (PRD), Queen Charlotte Islands (QCI), Central Coast (CC), west coast Vancouver Island (WCVI) and the Strait of Georgia (SOG).

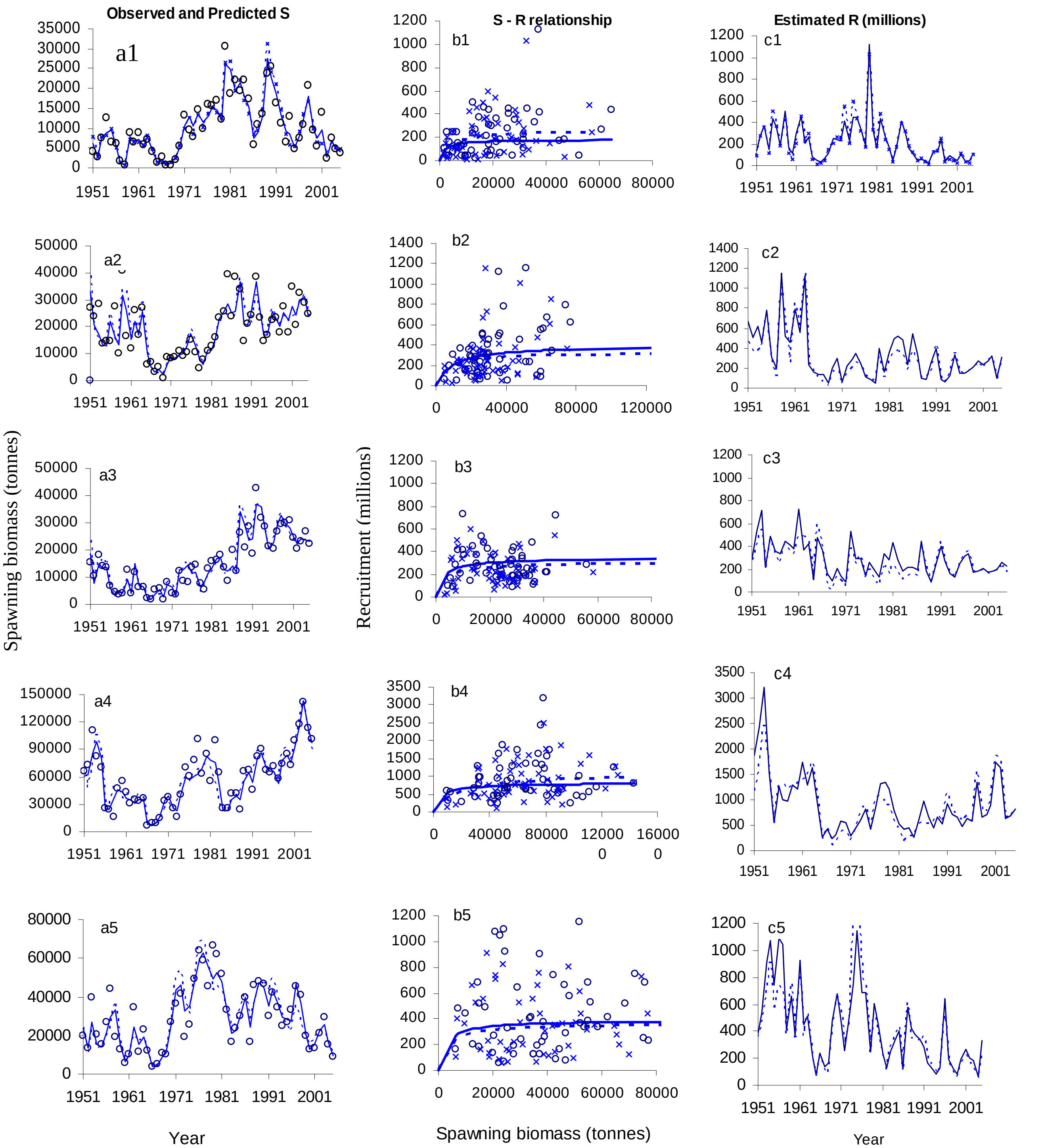

Figure 2. Panels a1 – a5: show observed (circles) and estimated spawning biomass for five stocks; b1 – b5: plots of estimated spawning biomass and recruitments with fitted B-H curve; c1 – c5: show estimated recruitment. The solid line represents estimates from the assessment accounting for variable M and dashed line for constant M. The stocks QCI, PRD, CC, SOG, and WCVI are represented in the panels by numerals 1 to 5, respectively.

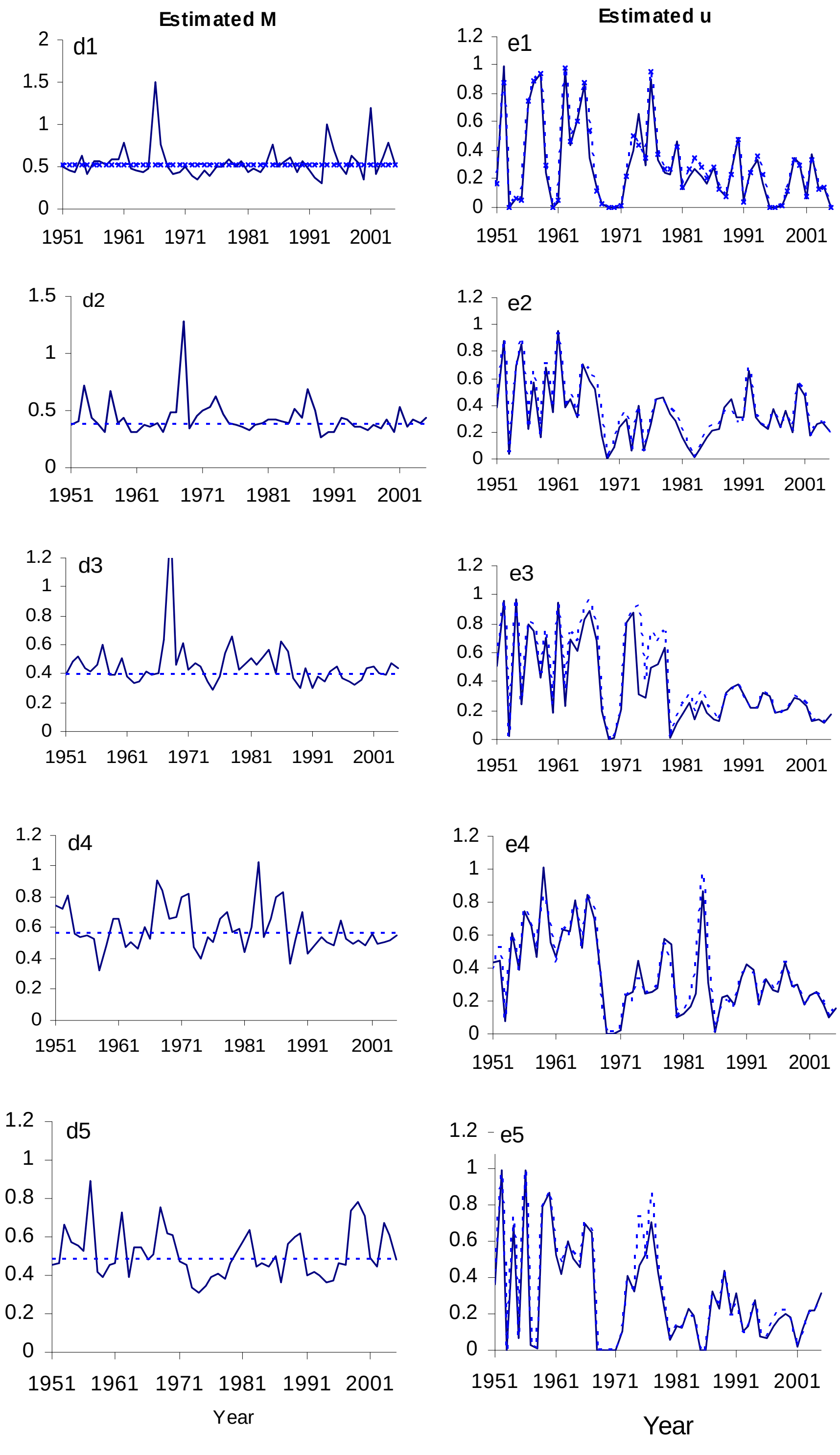

Figure 3. Panels d1 – d5: show estimated natural loss for five stocks; e1 – e5: show estimated exploitation rate for fully recruited fish. The solid line represents estimates from the assessment accounting for variable M and dashed line for constant M. The stocks QCI, PRD, CC, SOG, and WCVI are represented in the panels by numerals 1 to 5, respectively.

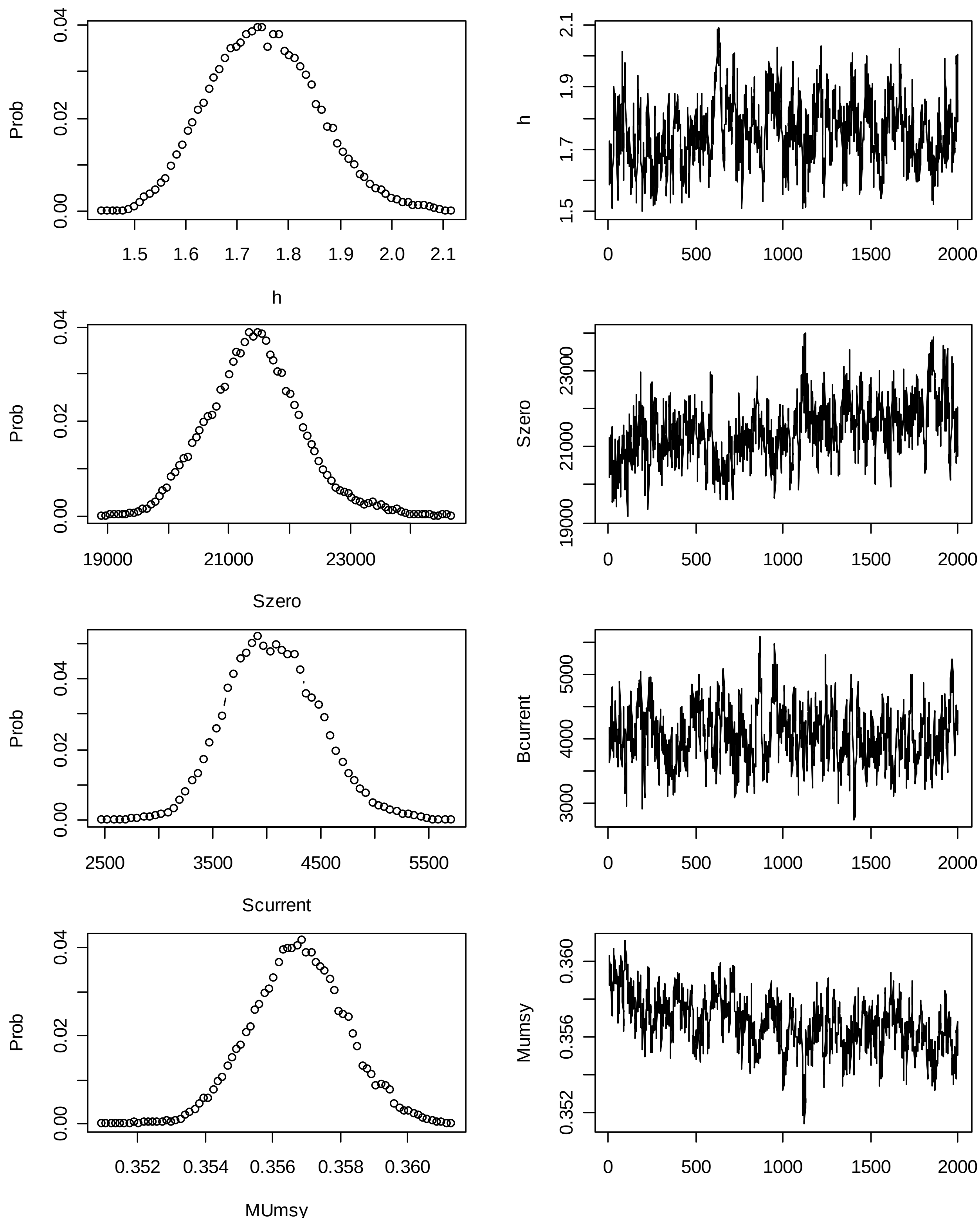

Figure 4. Bayesian posterior distributions and trace plots sub-sampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the exploitation rate generating MSY, from the Ricker model analysis with annually varying M for the Queen Charlotte Islands.

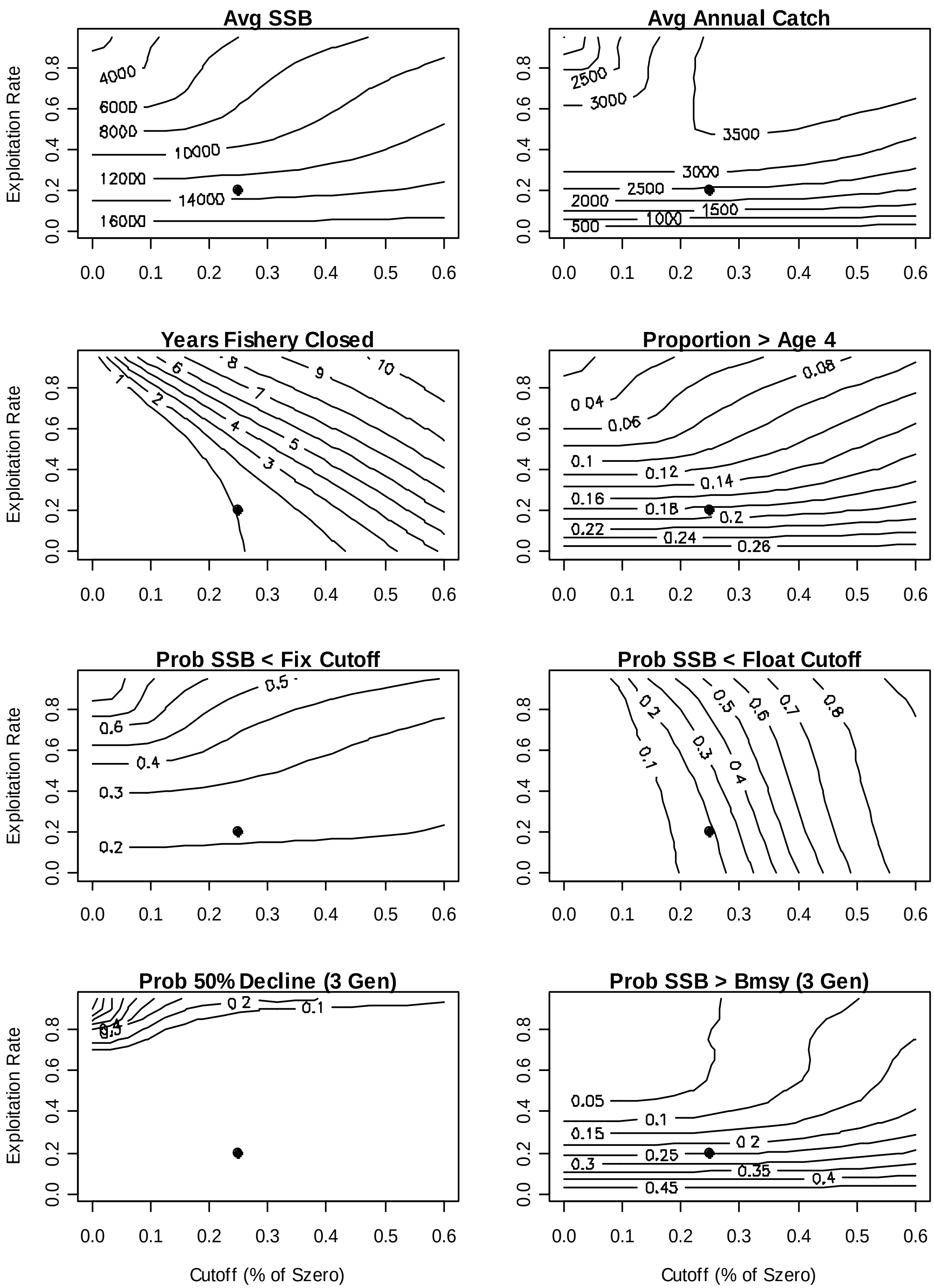

Figure 5. Queen Charlotte Islands contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M. Dots indicate the current harvest policy.

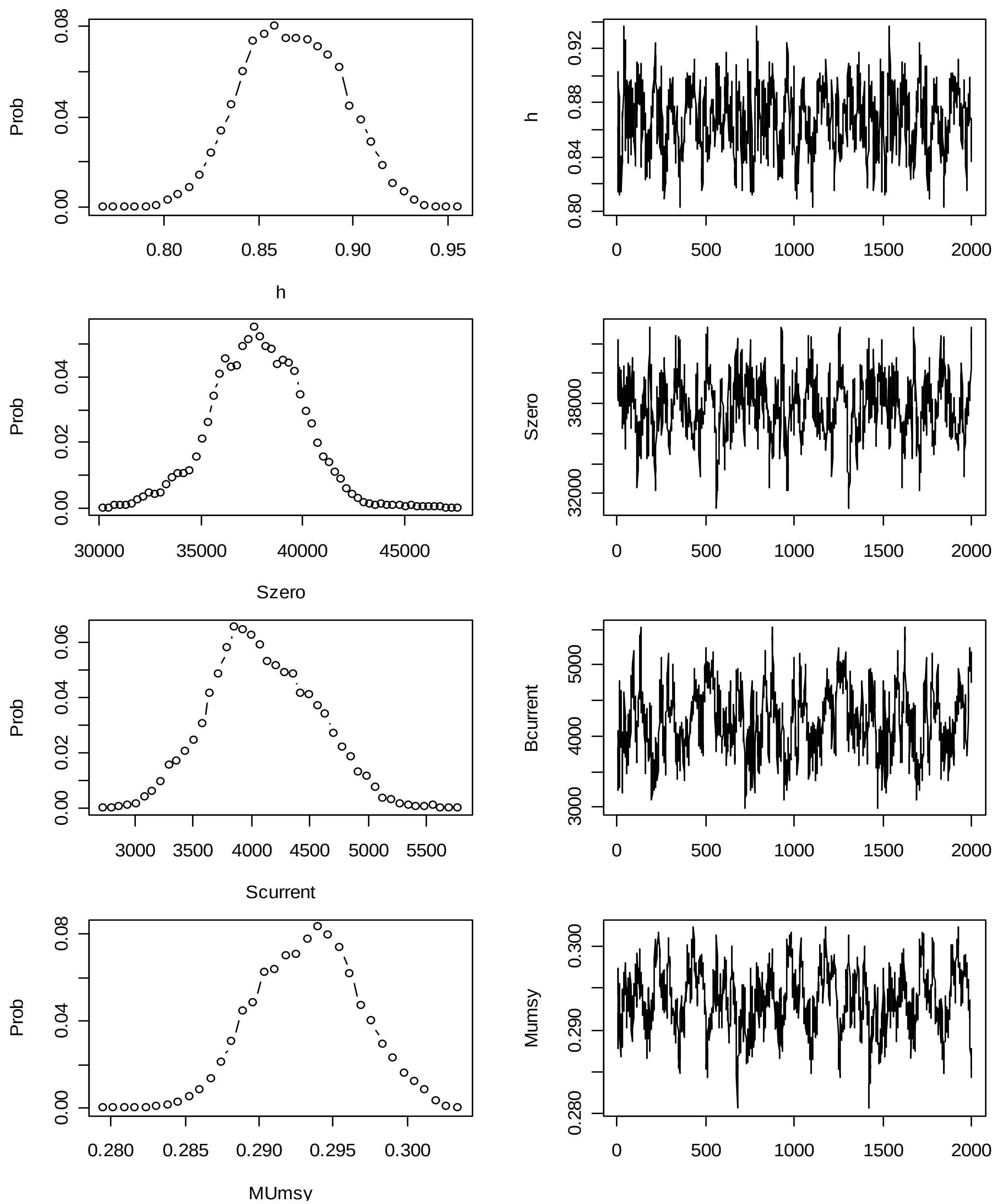

Figure 6. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Beverton-Holt model analysis with annually varying M for the Queen Charlotte Islands.

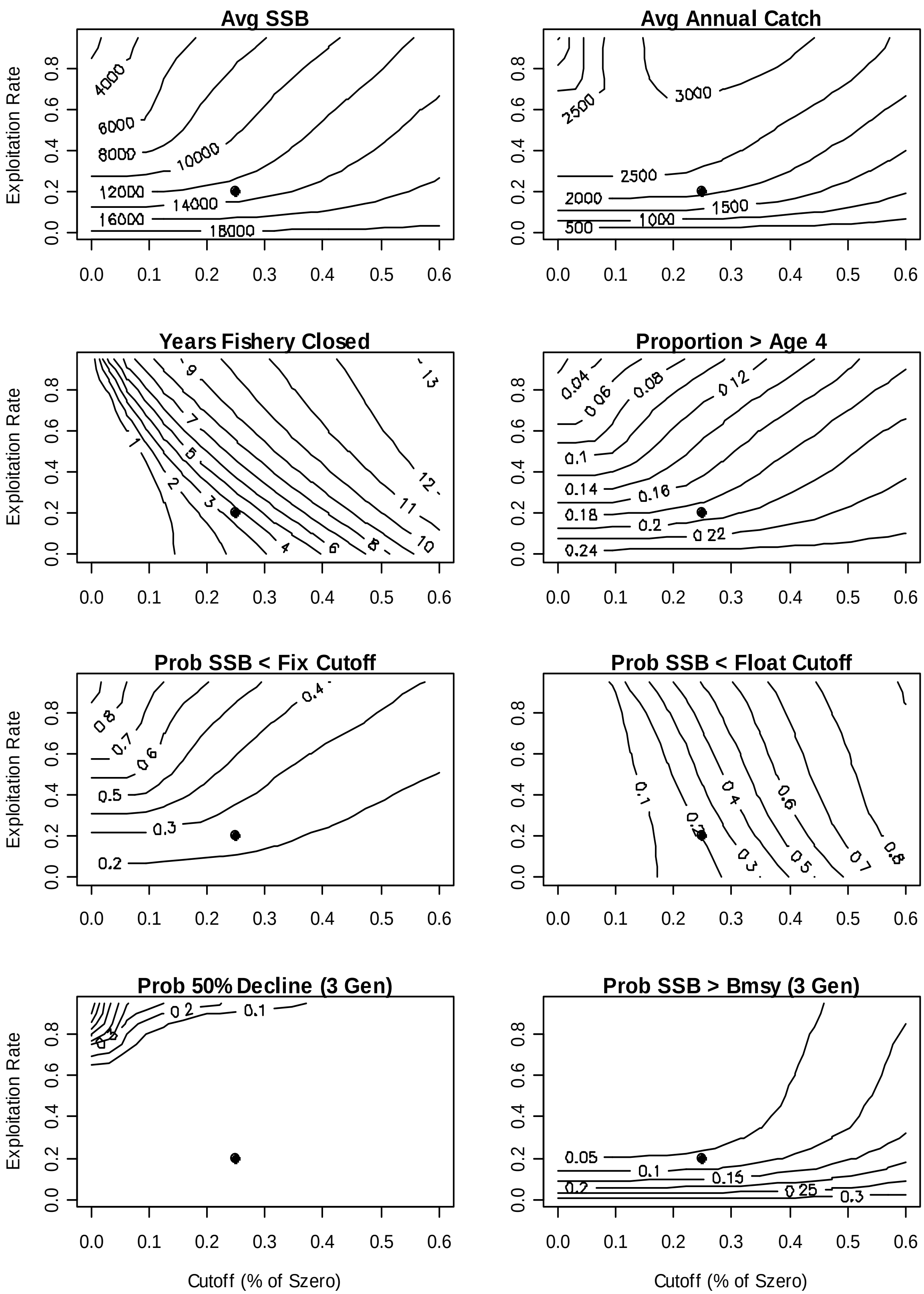

Figure 7. Queen Charlotte Islands contour plots showing results from the eight performance indicators for the B-H S-R function with annually varying M. Dots indicate the current harvest policy.

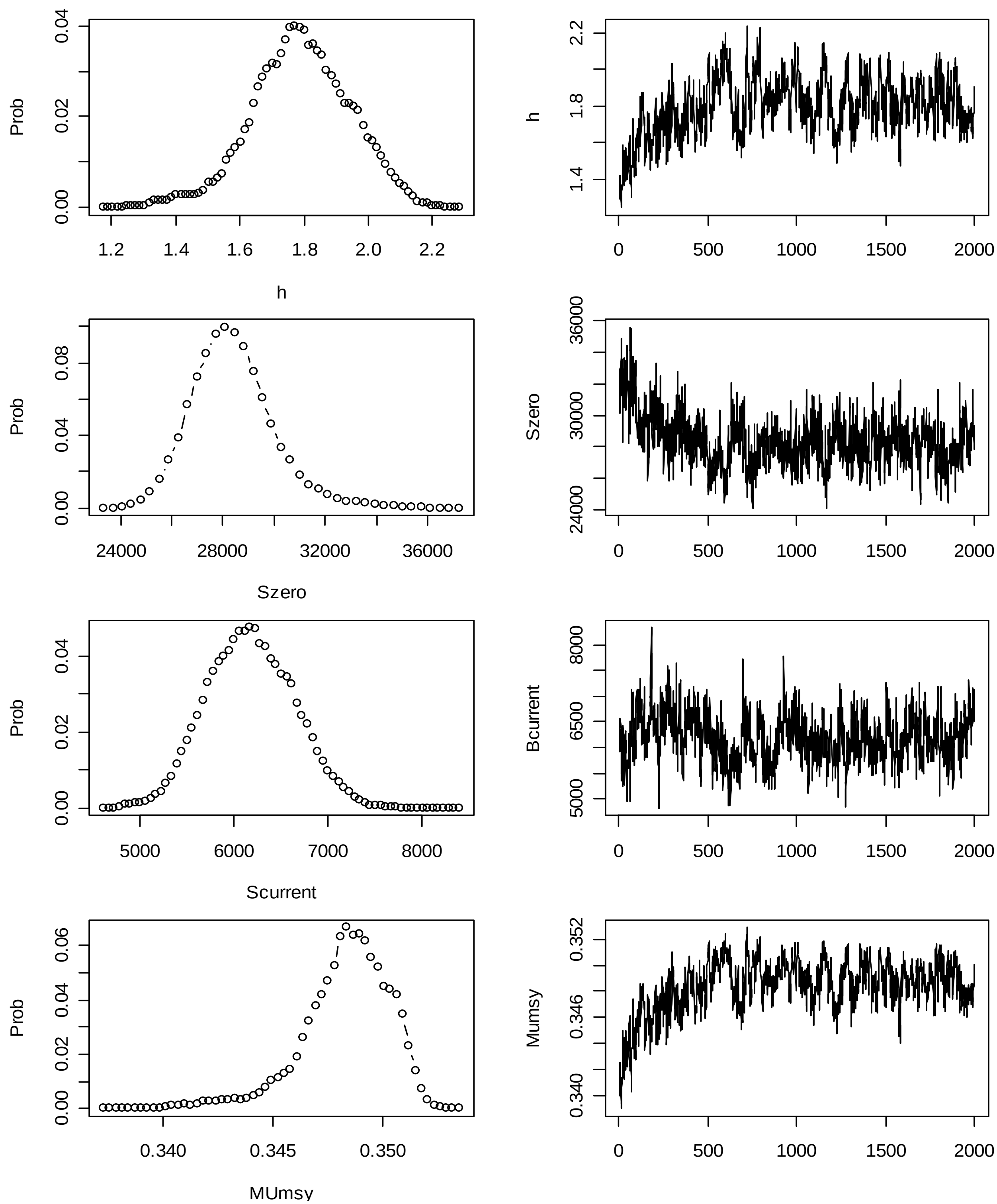

Figure 8. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with constant M for the Queen Charlotte Islands.

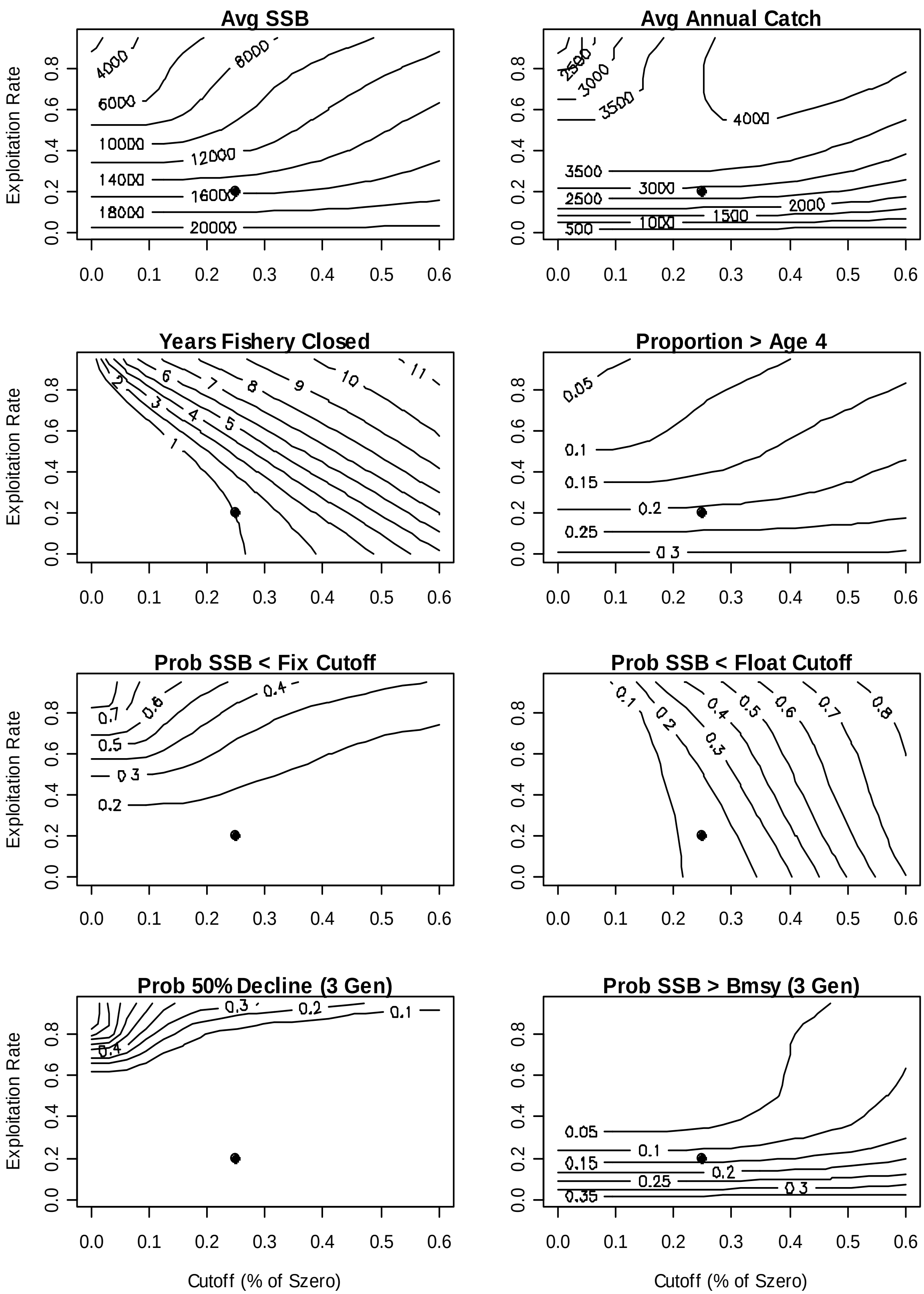

Figure 9. Queen Charlotte Islands contour plots showing results from the eight performance indicators for the Ricker S-R function with constant M. Dots indicate the current harvest policy.

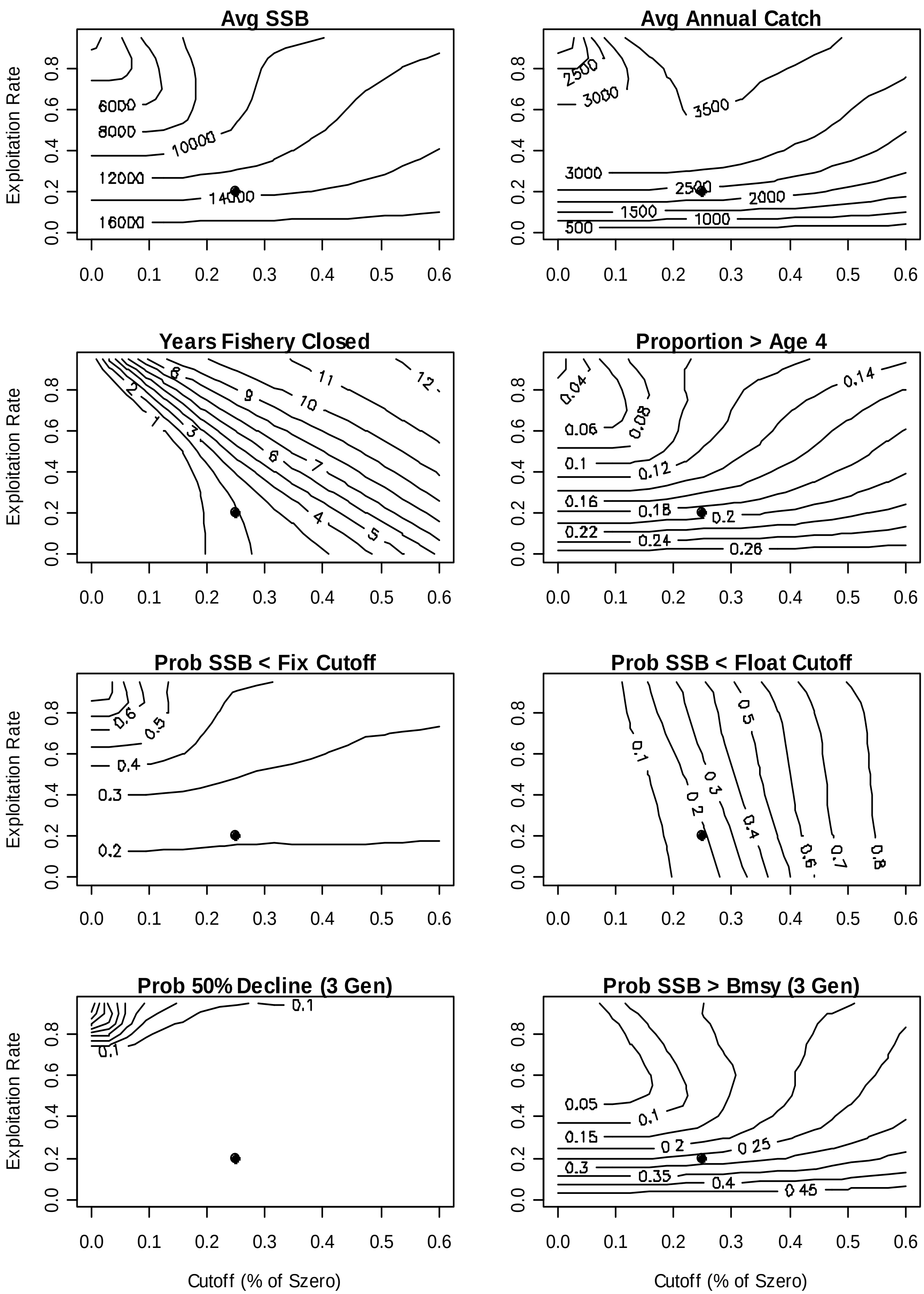

Figure 10. Queen Charlotte Islands contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and an extra year lag in fisheries after rebuilding above cutoff. Dots indicate the current harvest policy.

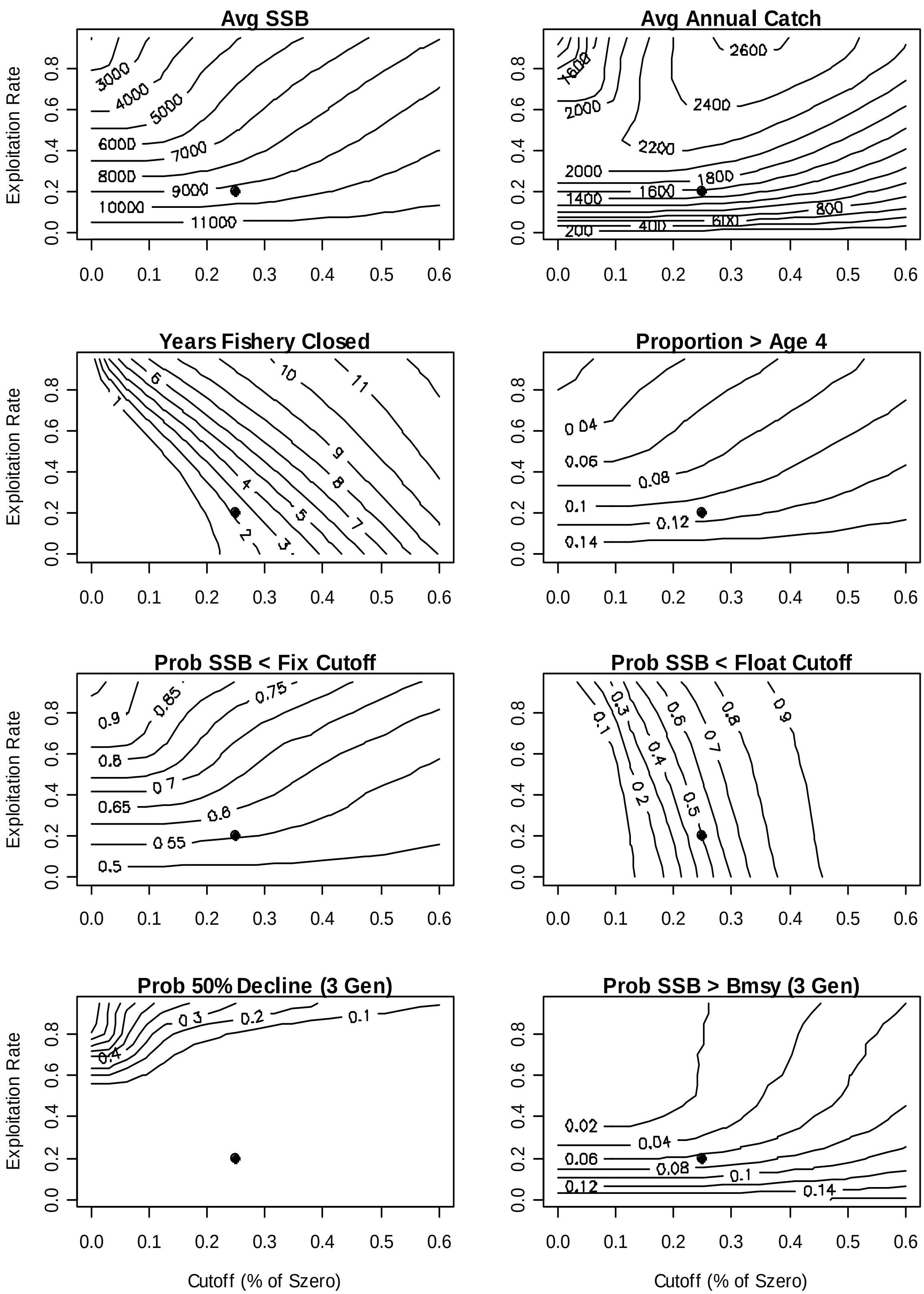

Figure 11. Queen Charlotte Islands contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and reduced survival rate. Dots indicate the current harvest policy.

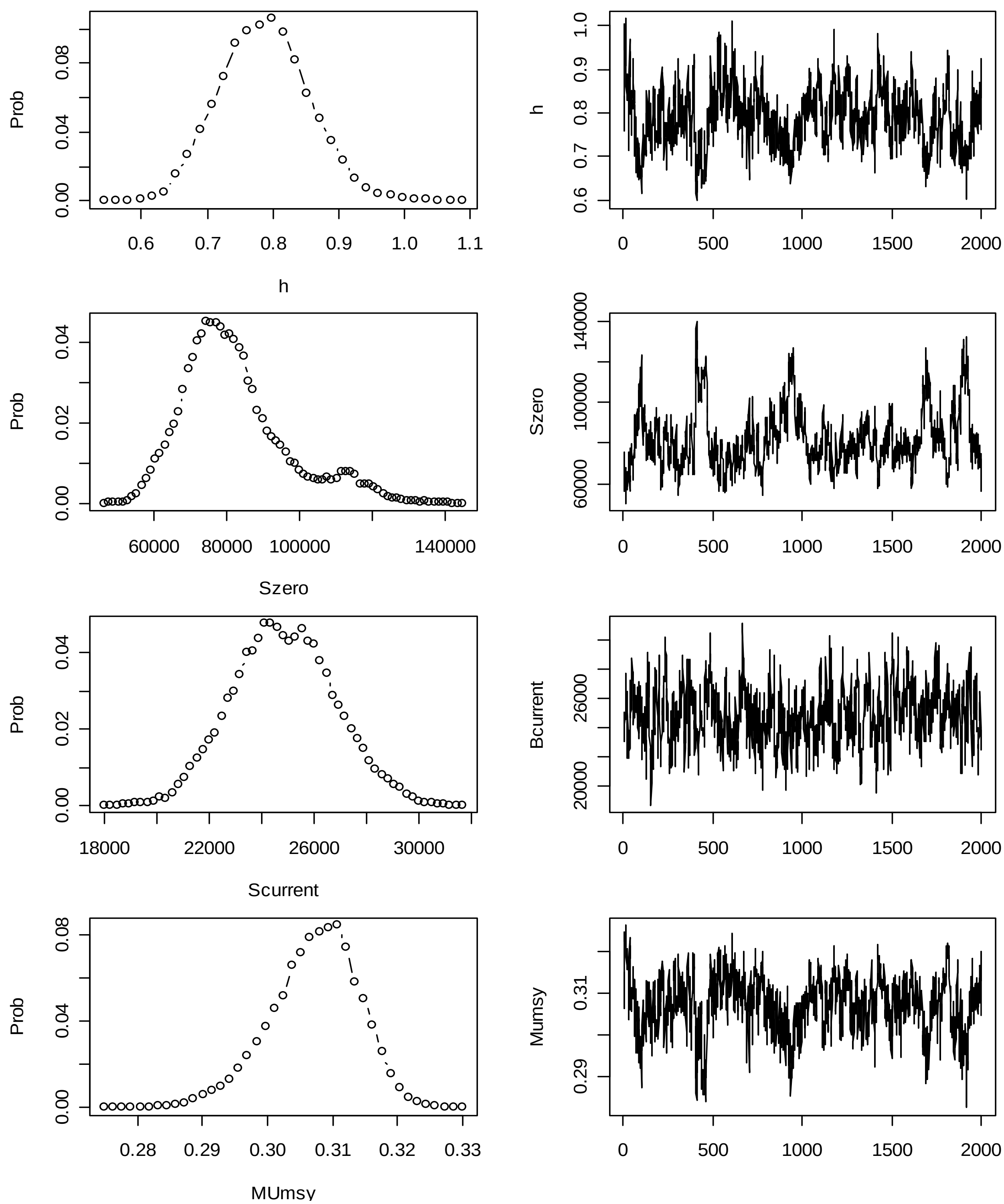

Figure 12. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with annually varying M for the Prince Rupert District.

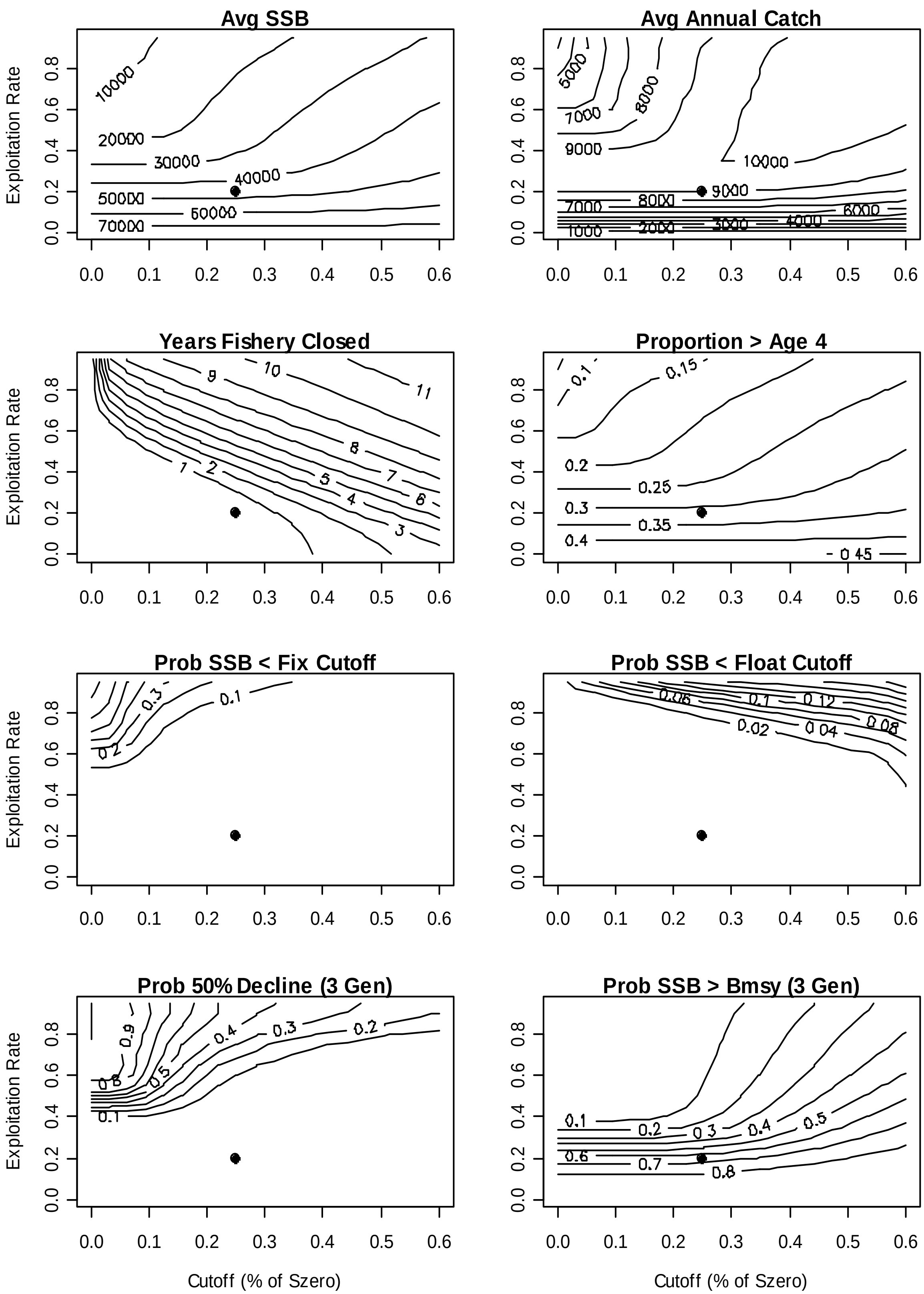

Figure 13. Prince Rupert District contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M. Dots indicate the current harvest policy.

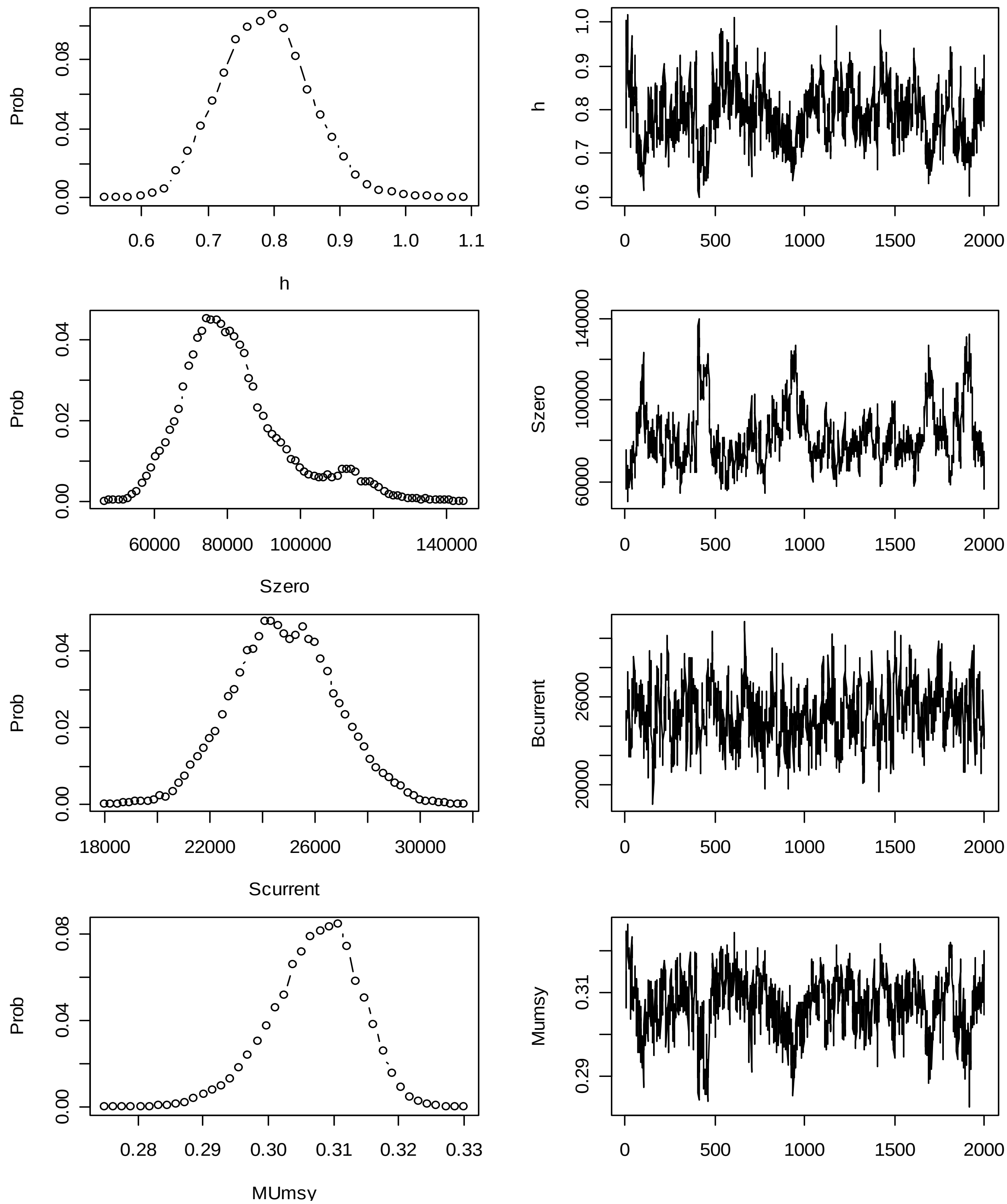

Figure 14. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Beverton-Holt model analysis with annually varying M for the Prince Rupert District.

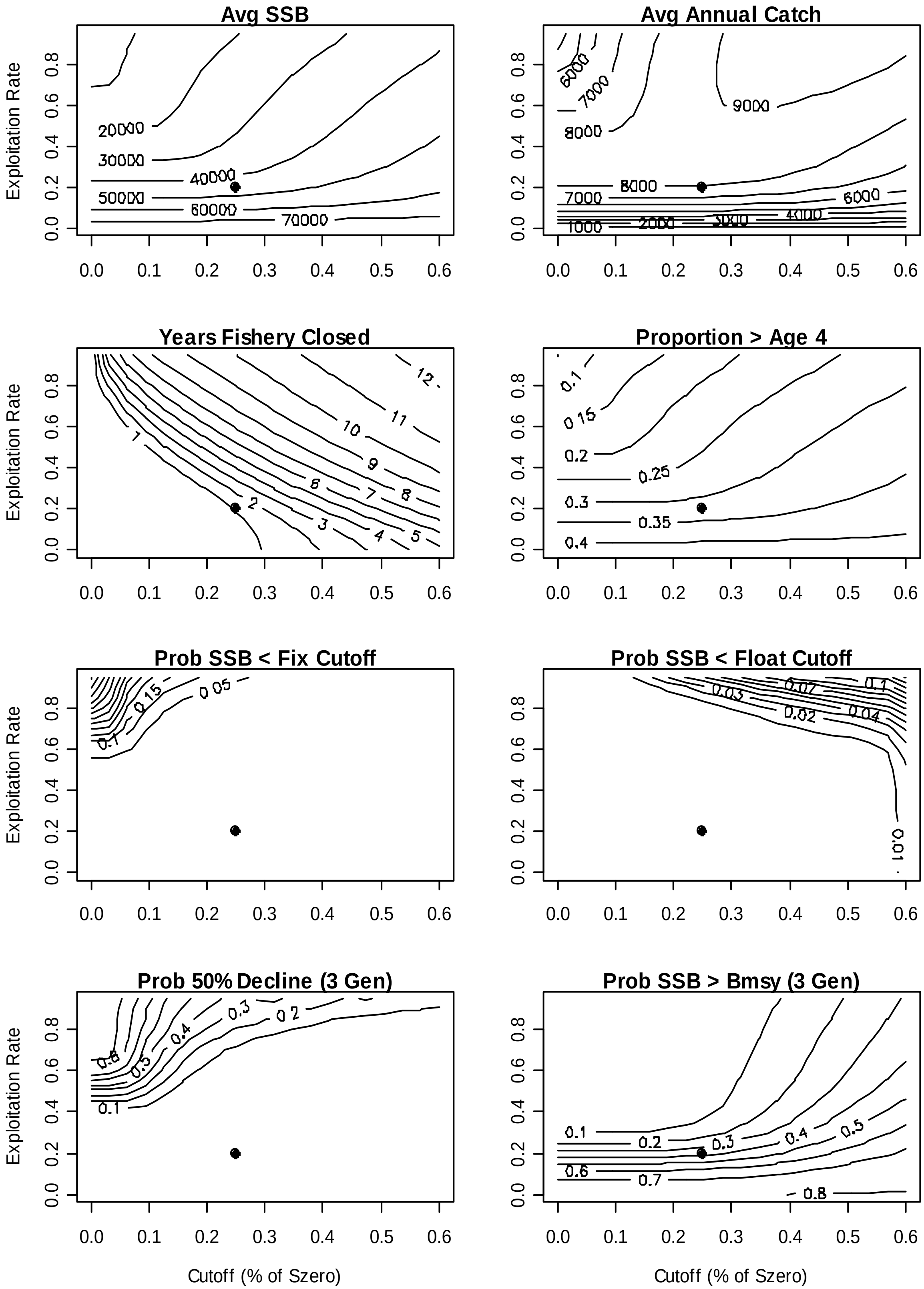

Figure 15. Prince Rupert District contour plots showing results from the eight performance indicators for the Beverton-Holt S-R function with variable M. Dots indicate the current harvest policy.

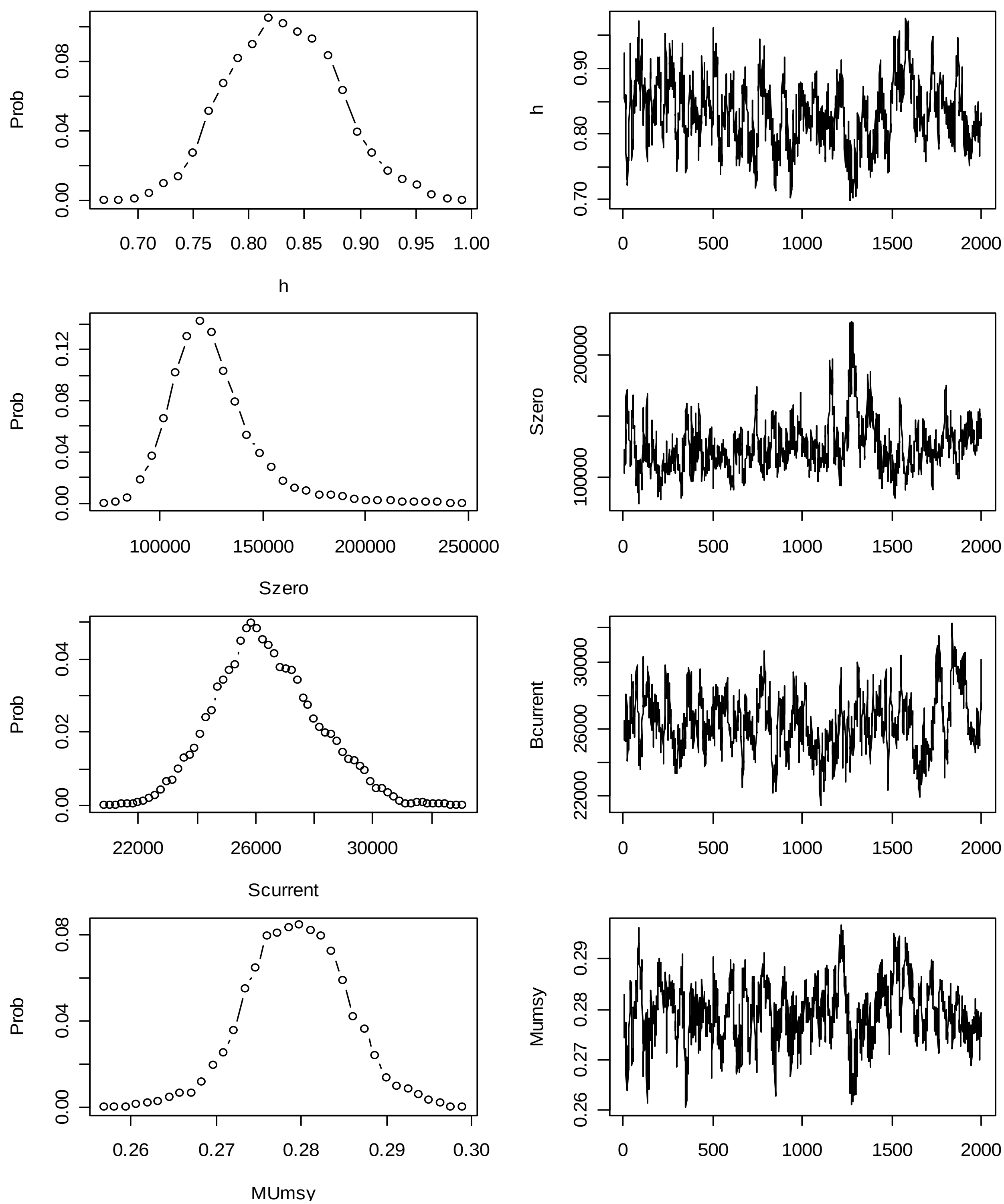

Figure 16. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with constant M for the Prince Rupert District.

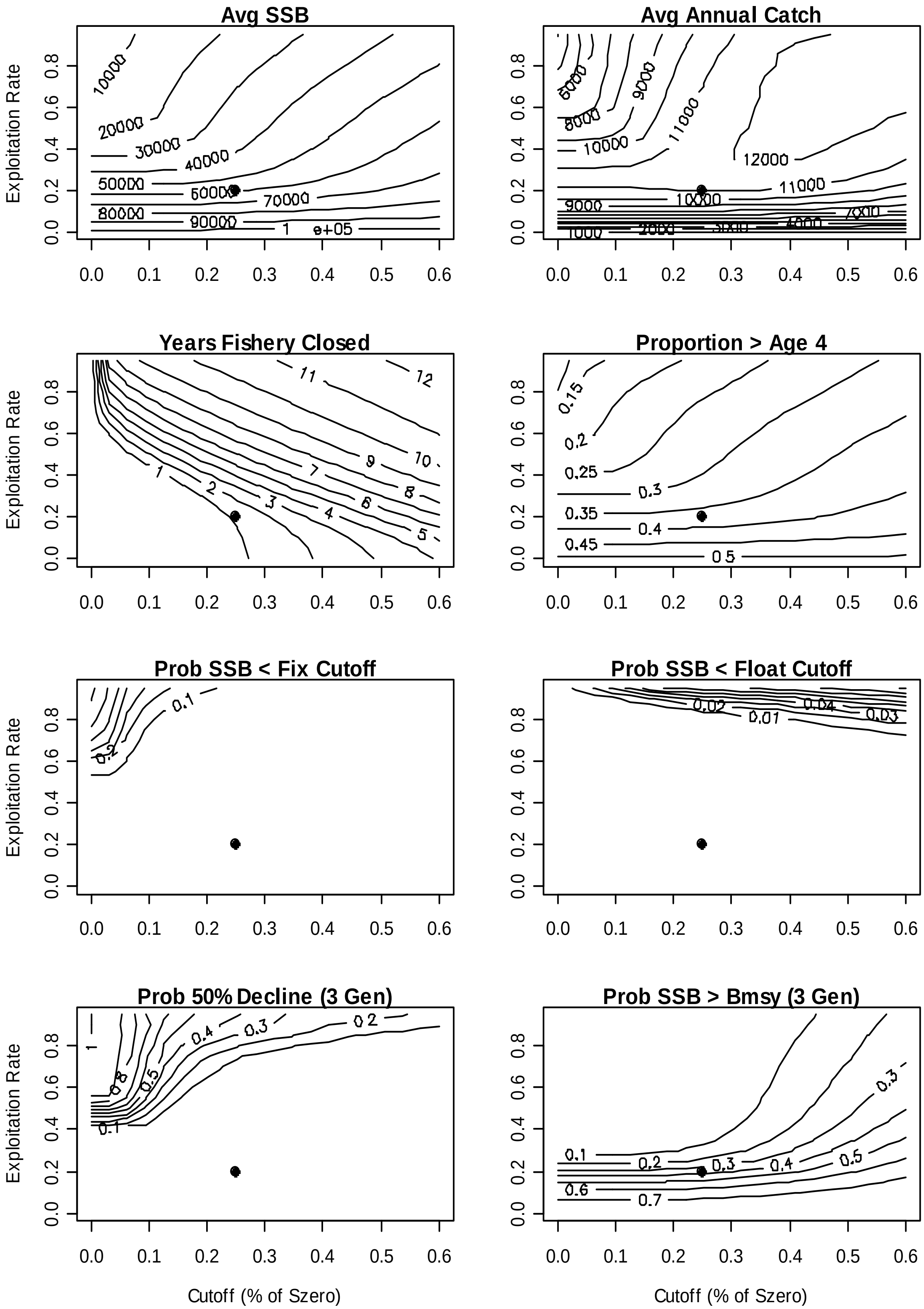

Figure 17. Prince Rupert District contour plots showing results from the eight performance indicators for the Ricker S-R function with constant M. Dots indicate the current harvest policy.

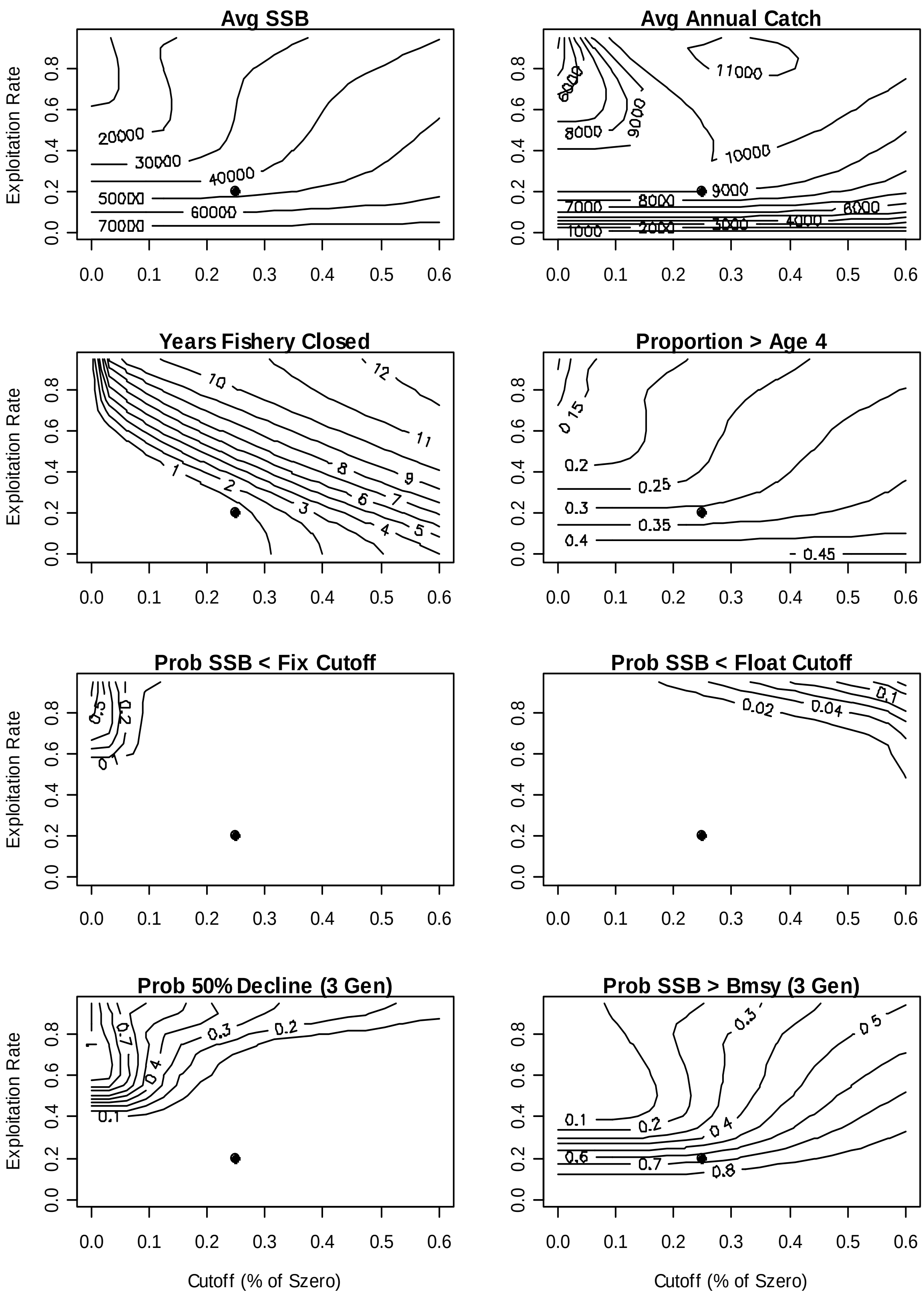

Figure 18. Prince Rupert District contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and an extra year lag in fisheries after rebuilding above cutoff. Dots indicate the current harvest policy.

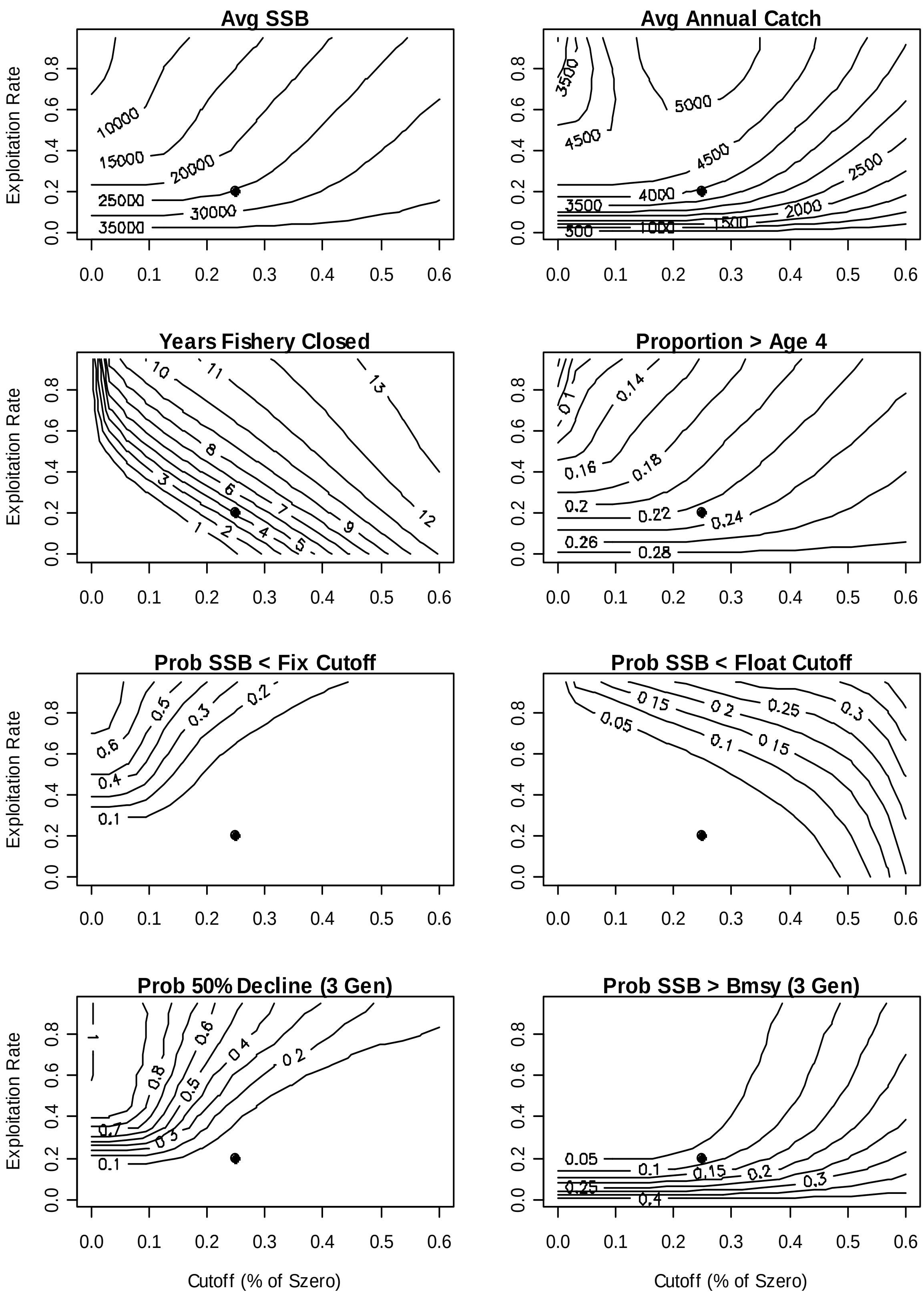

Figure 19. Prince Rupert District contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and reduced survival rate. Dots indicate the current harvest policy.

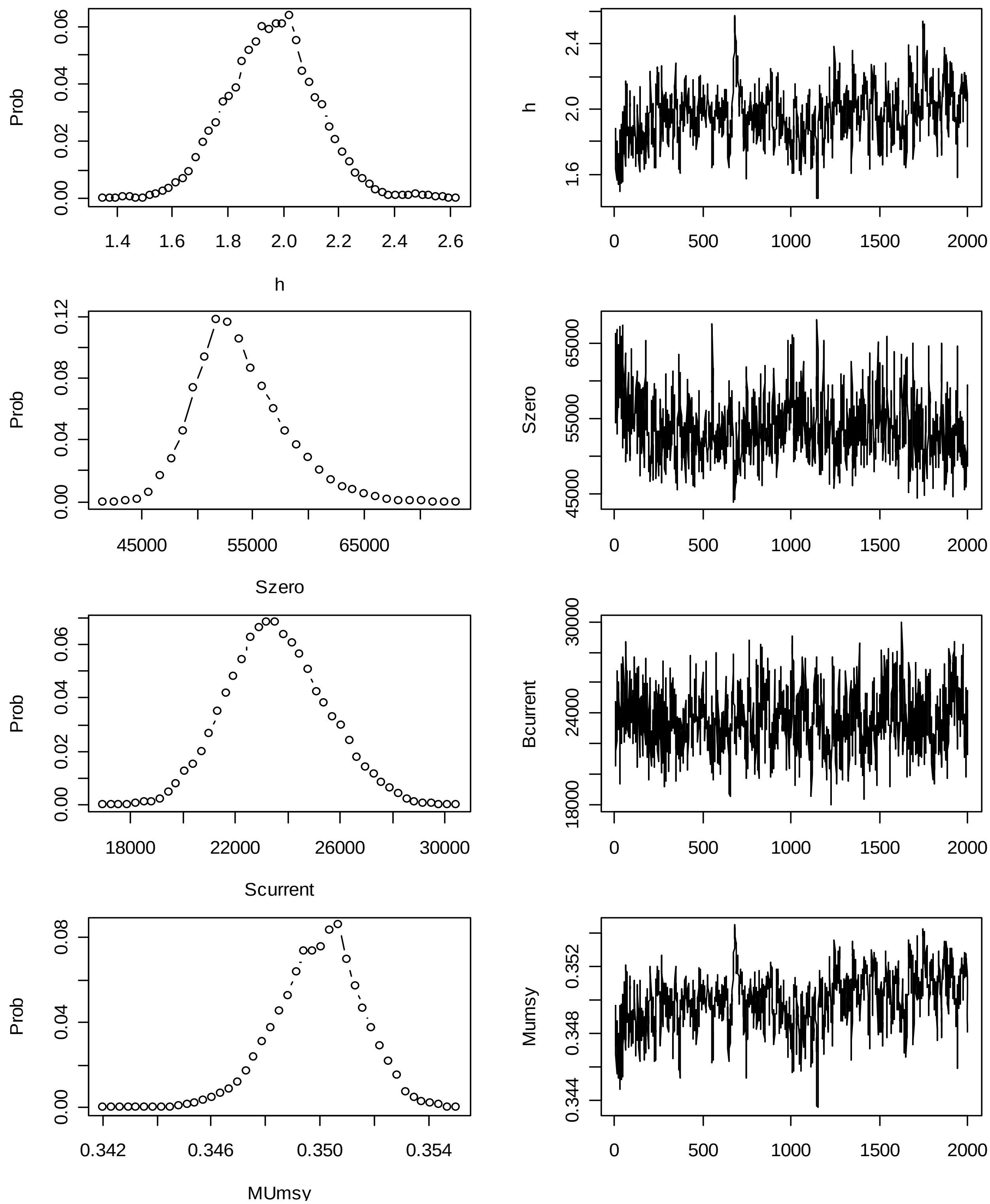

Figure 20. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with annually varying M for the Central Coast.

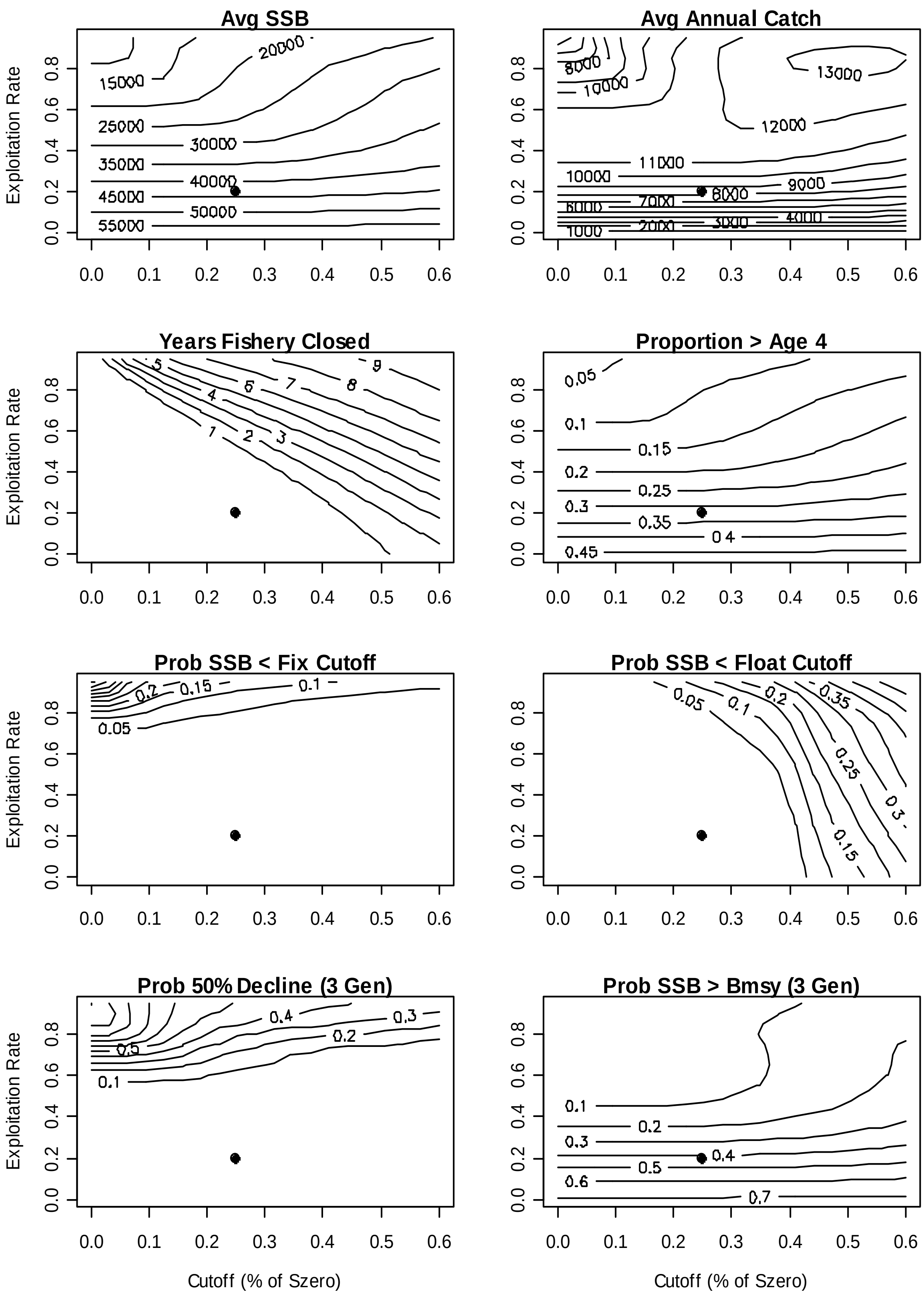

Figure 21. Central Coast contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M. Dots indicate the current harvest policy.

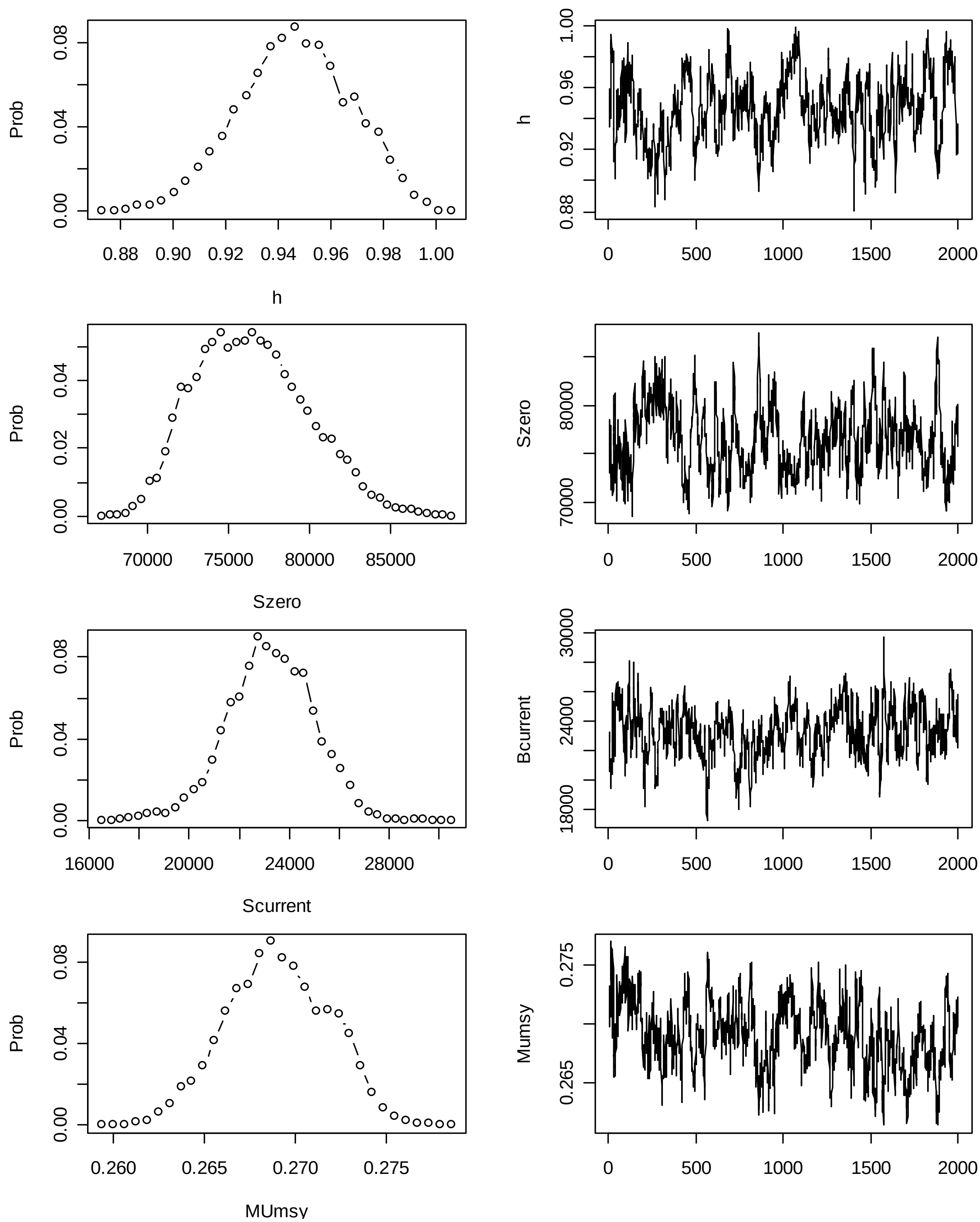

Figure 22. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Beverton-Holt model analysis with variable M for the Central Coast.

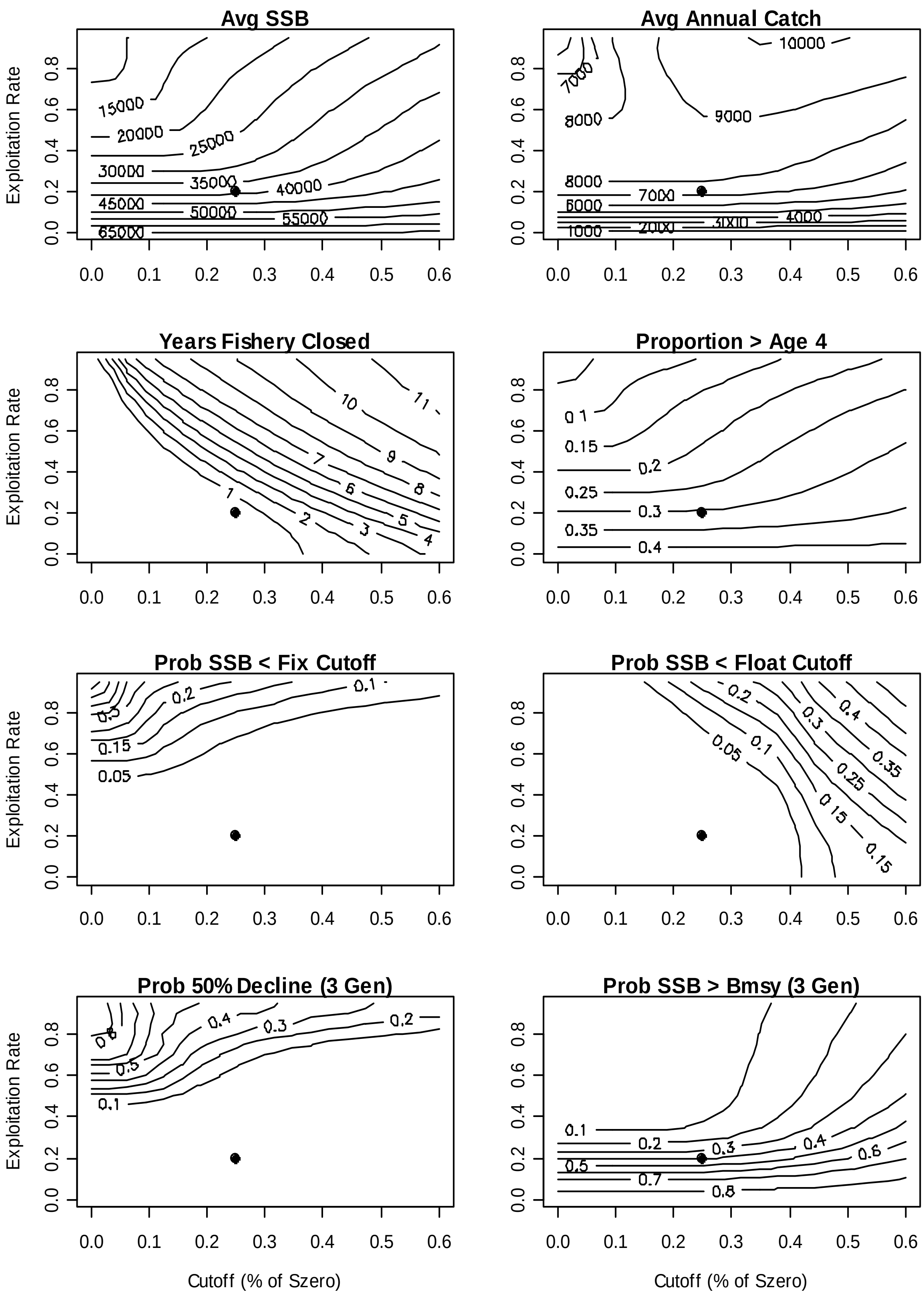

Figure 23. Central Coast contour plots showing results from the eight performance indicators for the Beverton-Holt S-R function with variable M. Dots indicate the current harvest policy.

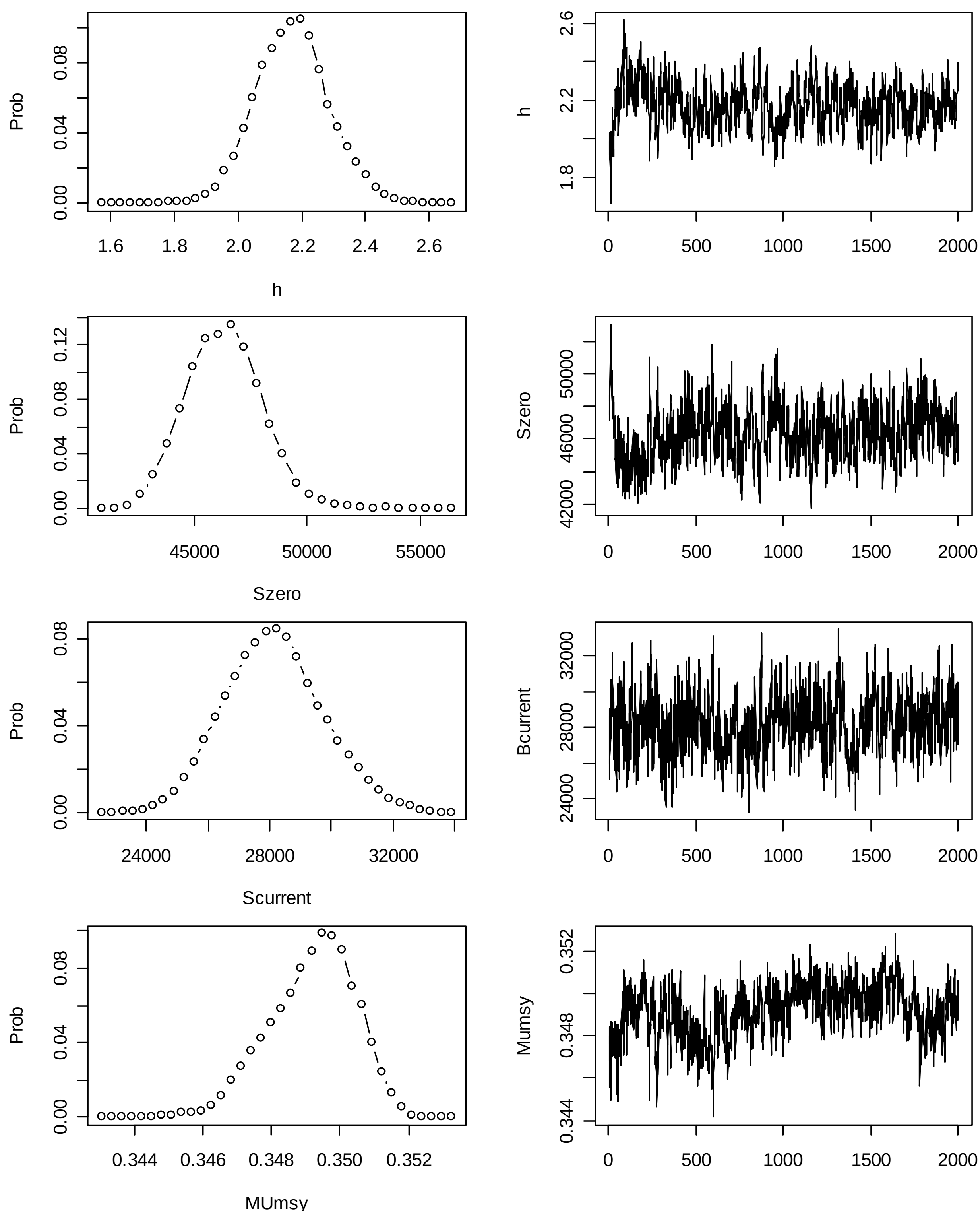

Figure 24. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with constant M for the Central Coast.

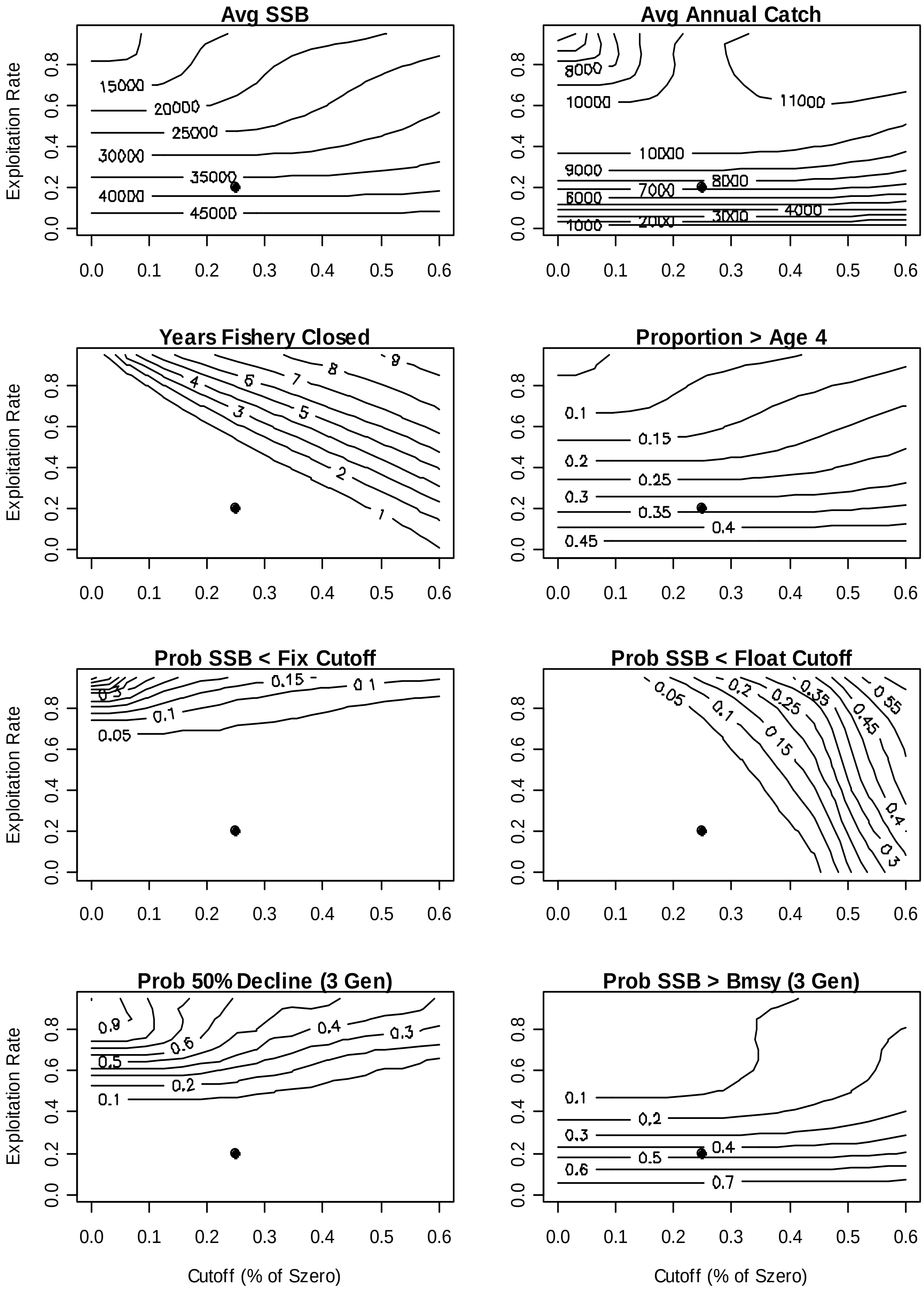

Figure 25. Central Coast contour plots showing results from the eight performance indicators for the Ricker S-R function with constant M. Dots indicate the current harvest policy.

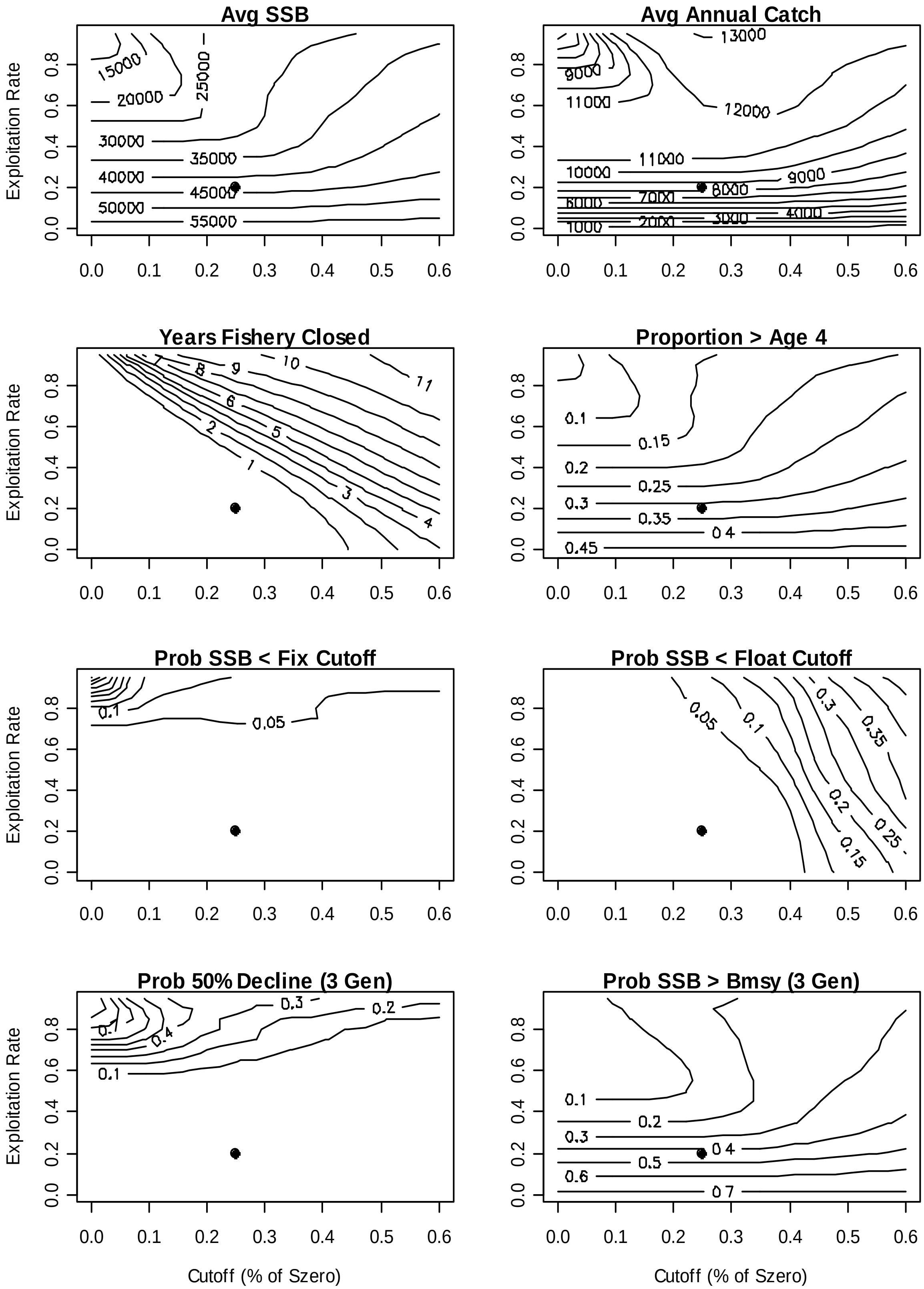

Figure 26. Central Coast contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and an extra year lag in fisheries after rebuilding above cutoff. Dots indicate the current harvest policy.

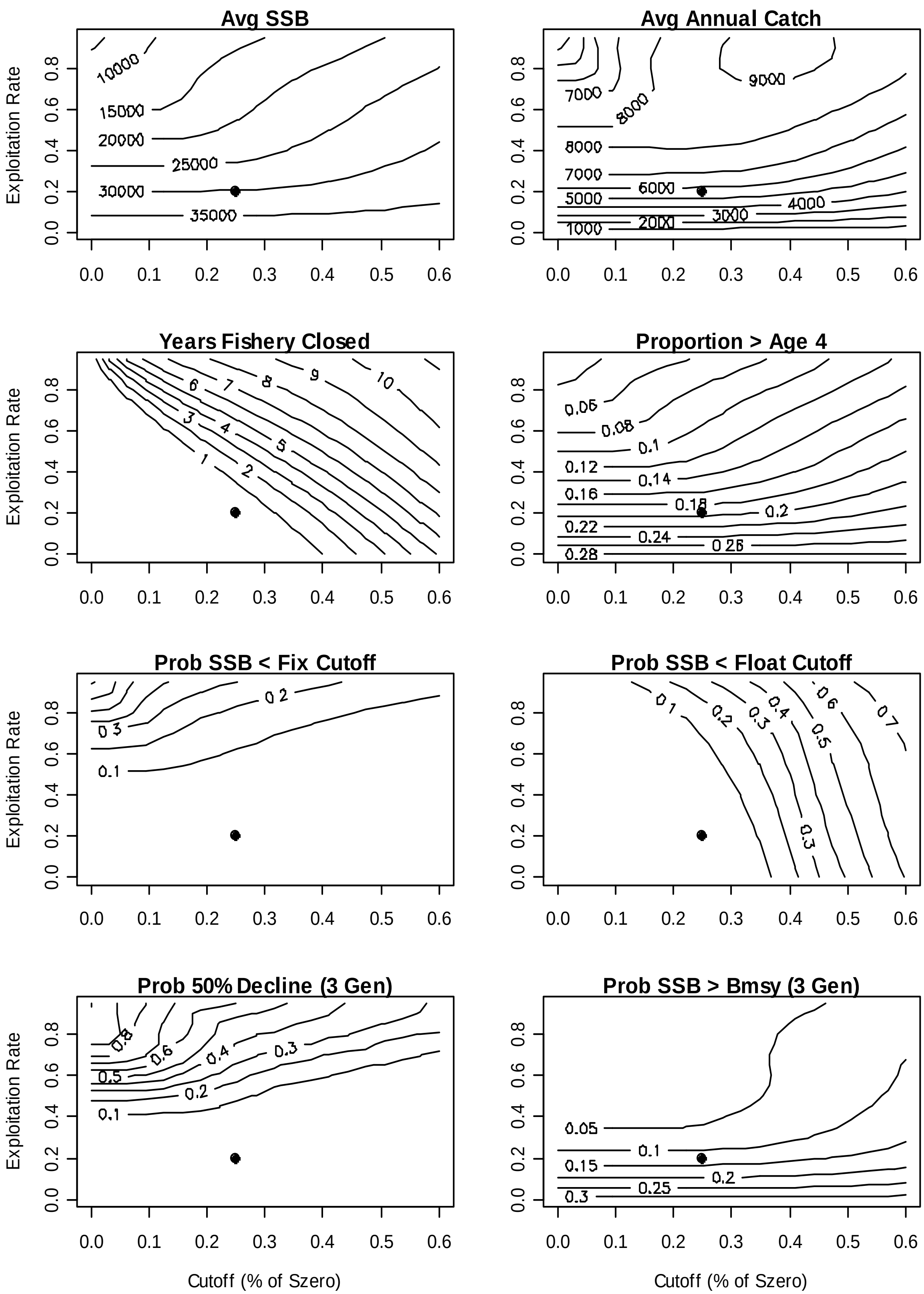

Figure 27. Central Coast contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and reduced survival rate. Dots indicate the current harvest policy.

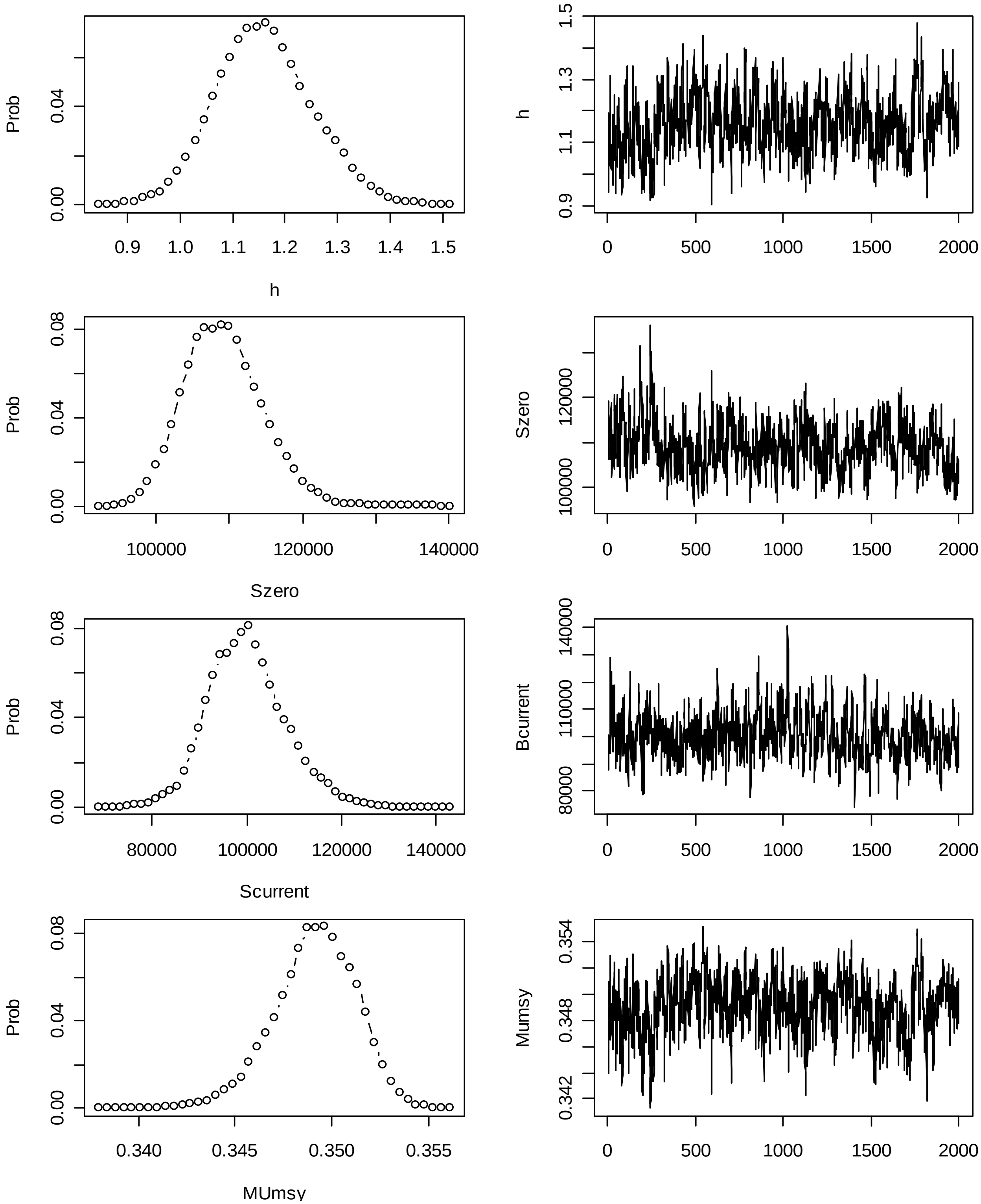

Figure 28. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with annually varying M for the Strait of Georgia.

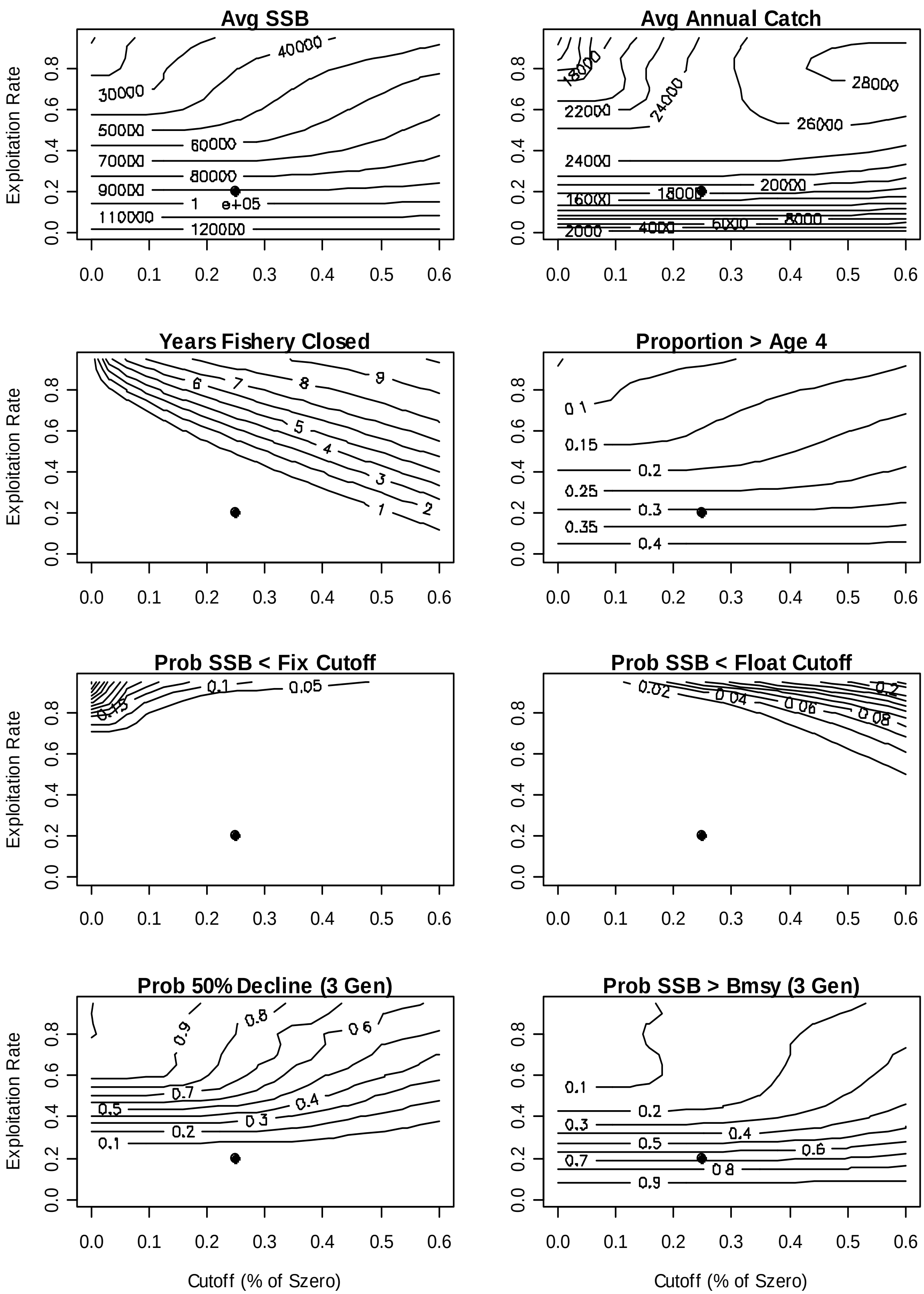

Figure 29. Strait of Georgia contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M. Dots indicate the current harvest policy.

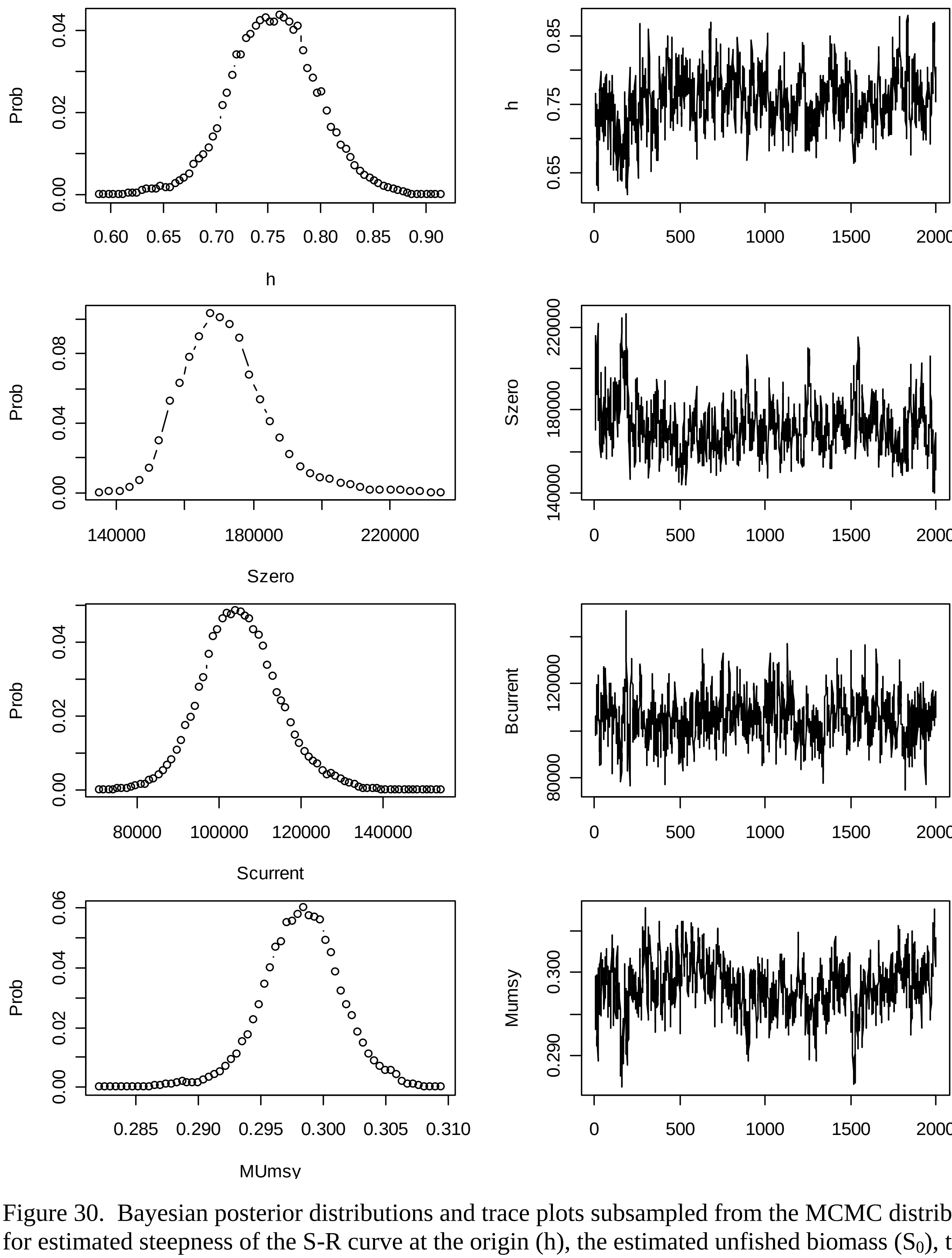

Figure 30. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Beverton-Holt model analysis with annually varying M for the Strait of Georgia.

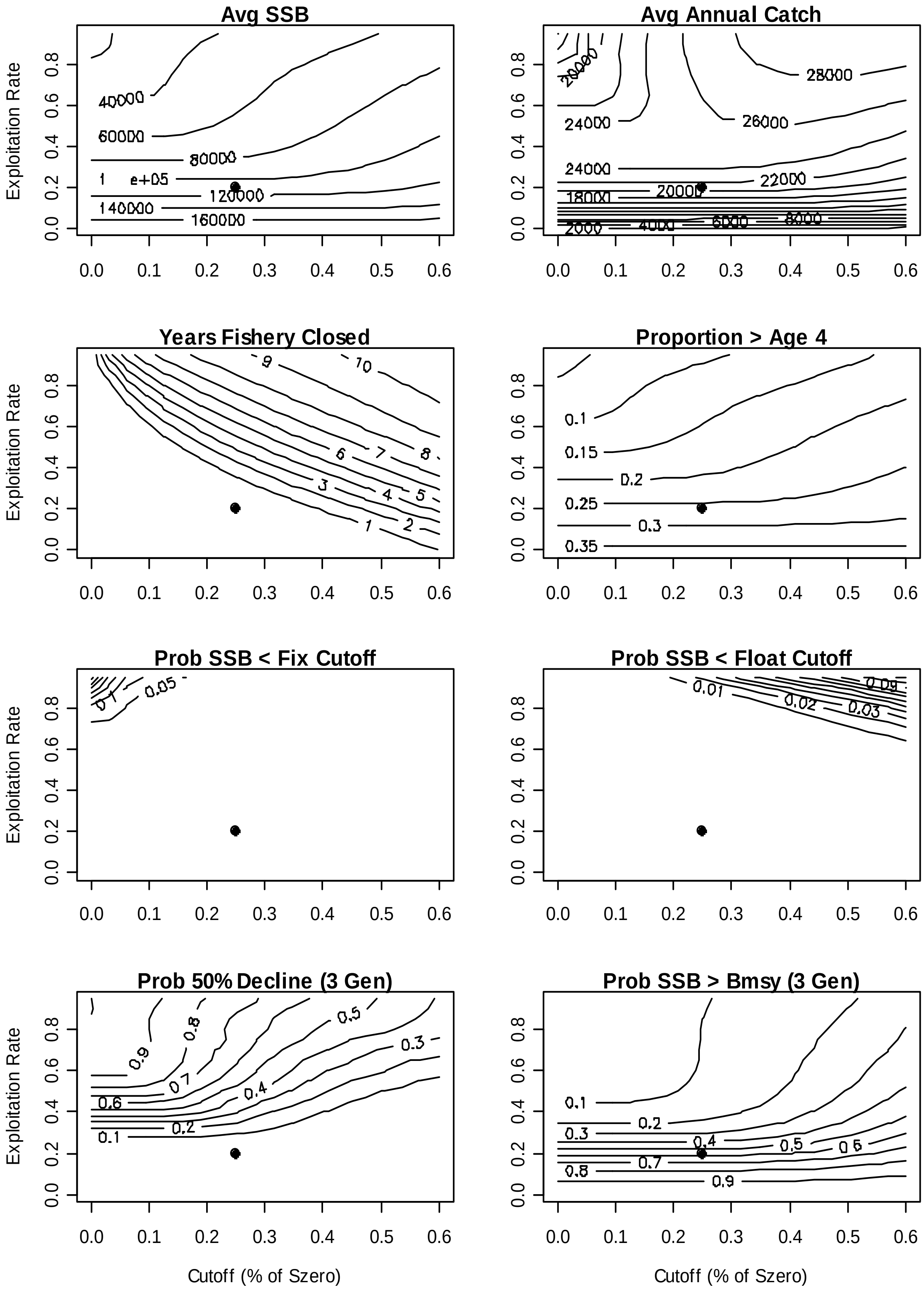

Figure 31. Strait of Georgia contour plots showing results from the eight performance indicators for the Beverton-Holt S-R function with annually varying M. Dots indicate the current harvest policy.

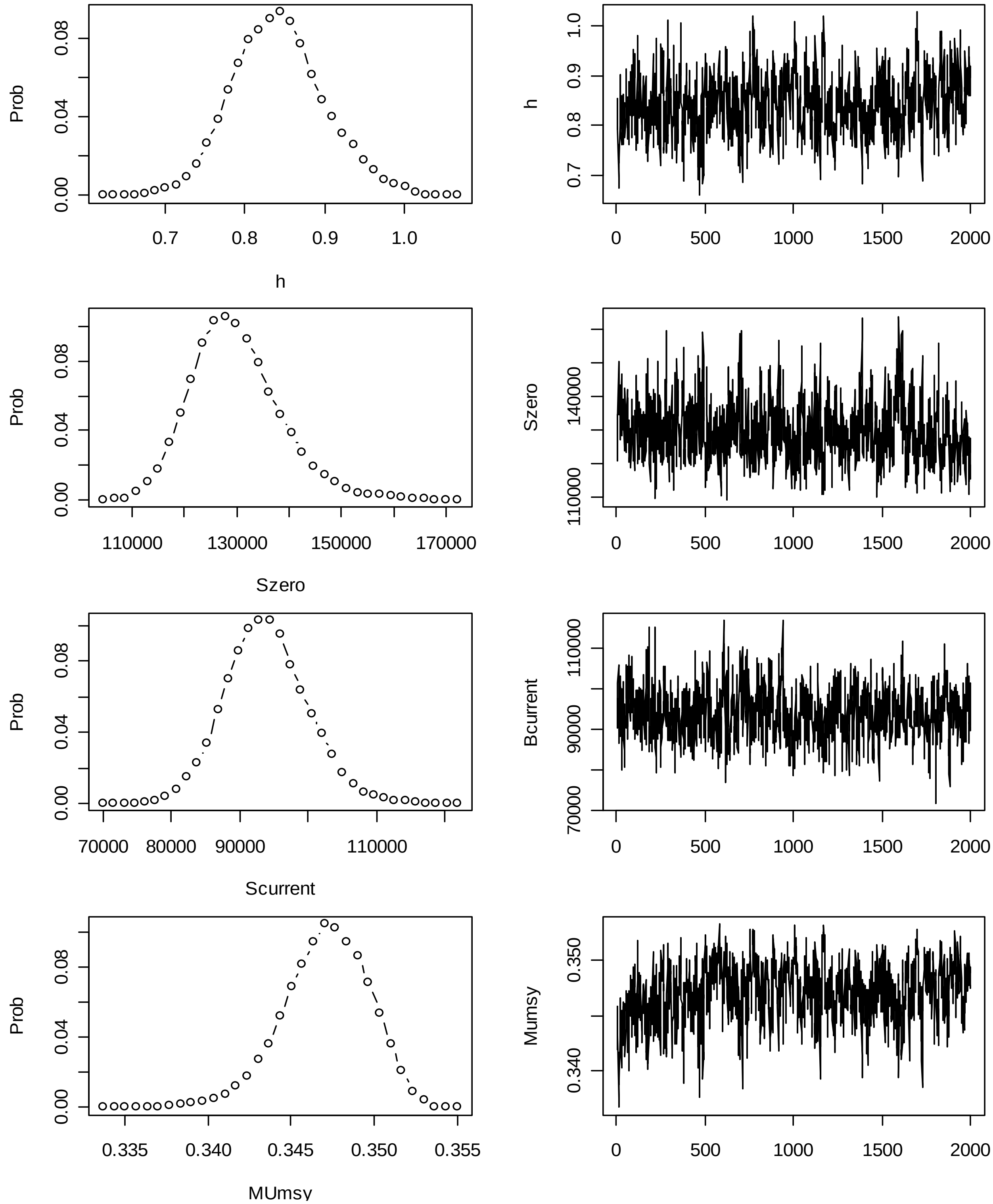

Figure 32. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with constant M for the Strait of Georgia.

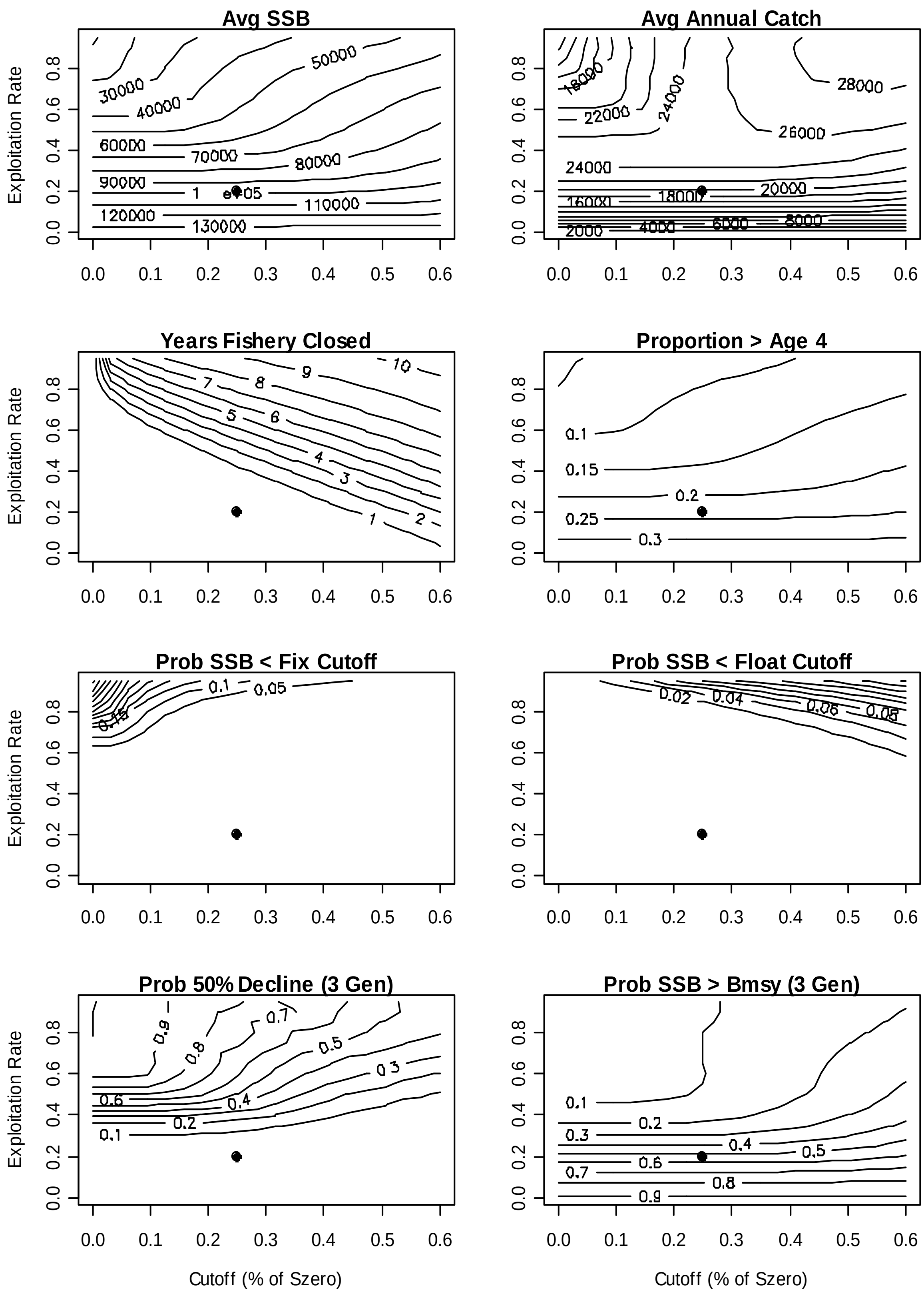

Figure 33. Strait of Georgia contour plots showing results from the eight performance indicators for the Ricker S-R function with constant M. Dots indicate the current harvest policy.

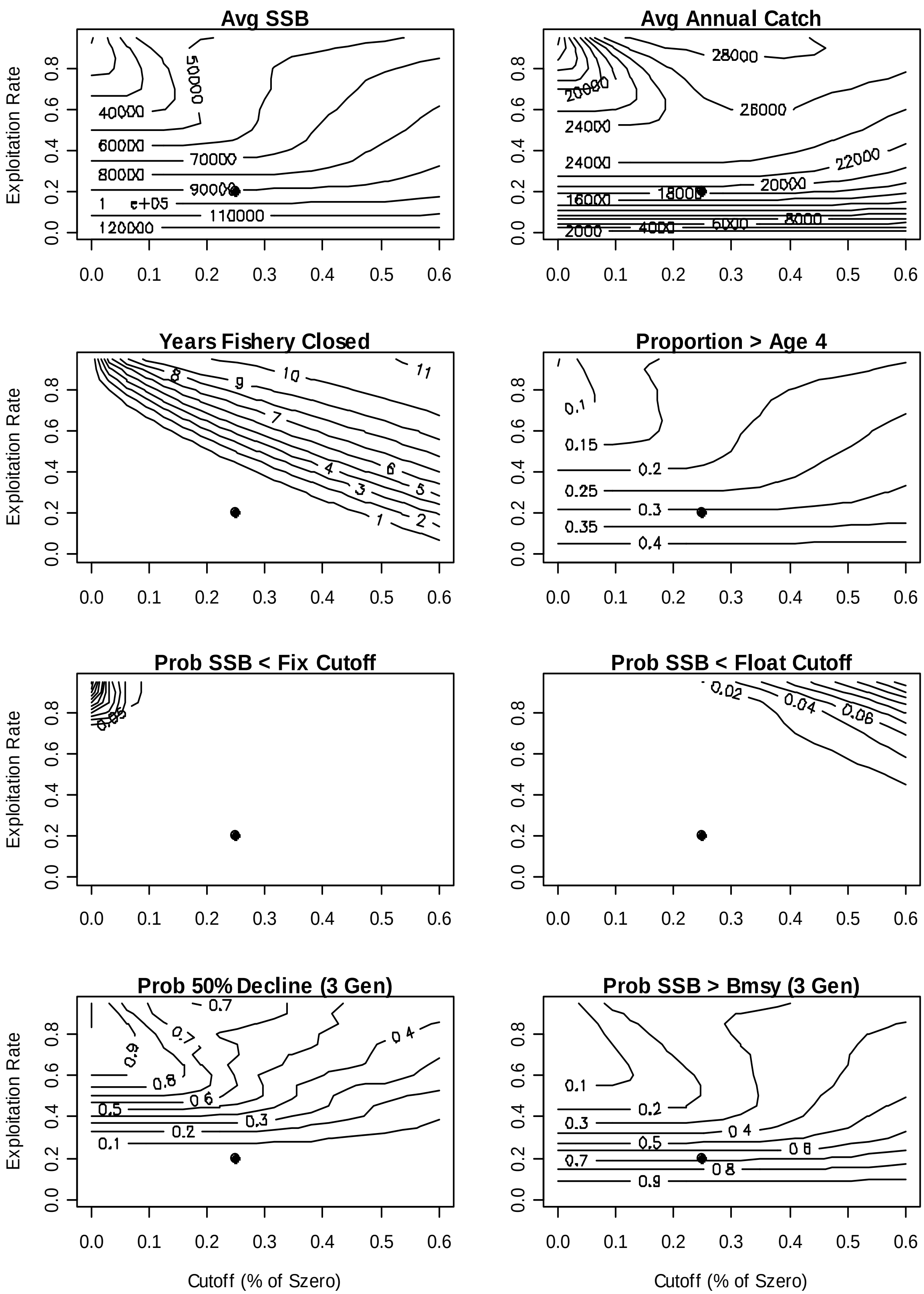

Figure 34. Strait of Georgia contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and an extra year lag in fisheries after rebuilding above cutoff. Dots indicate the current harvest policy.

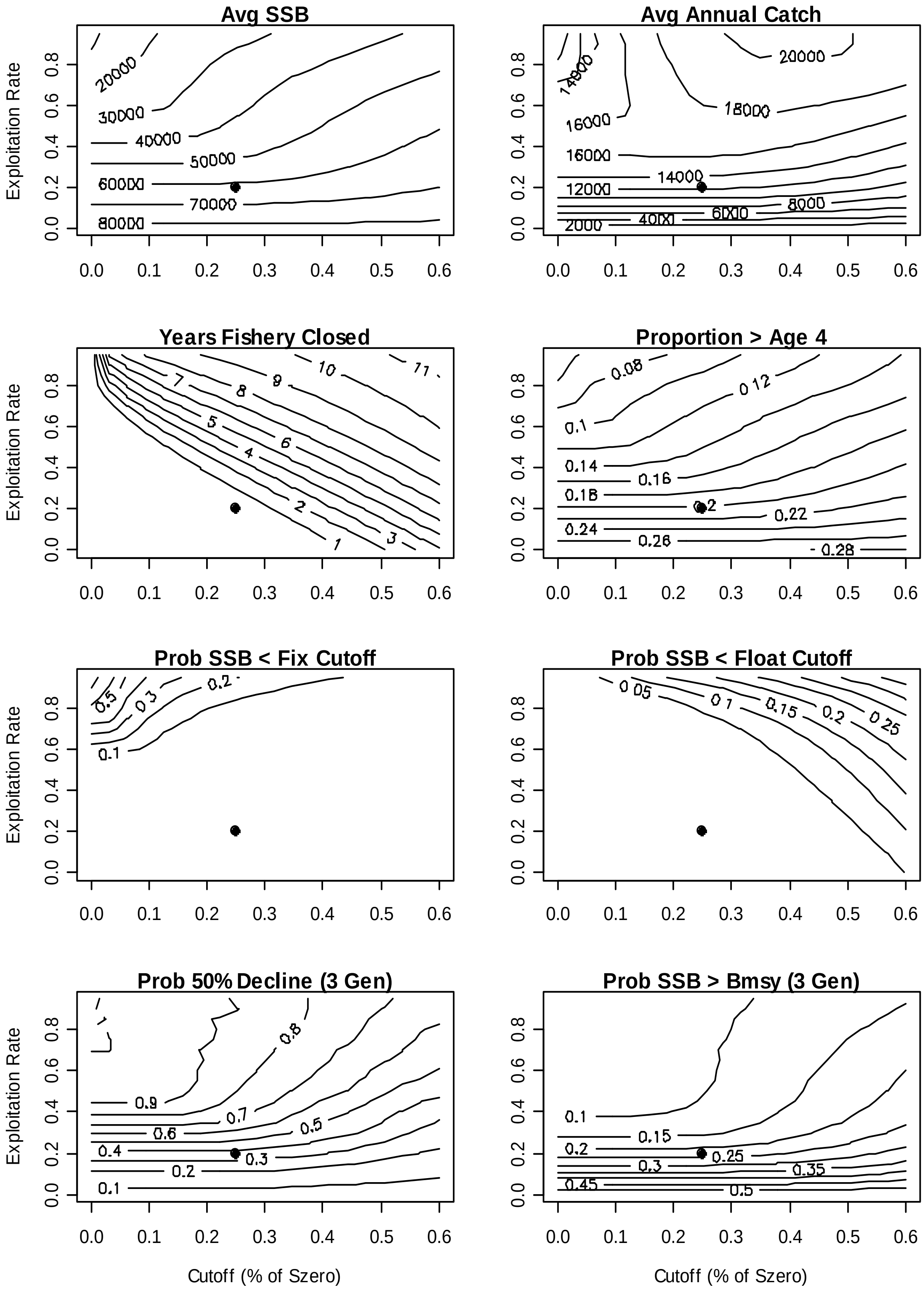

Figure 35. Strait of Georgia contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and reduced survival rate. Dots indicate the current harvest policy.

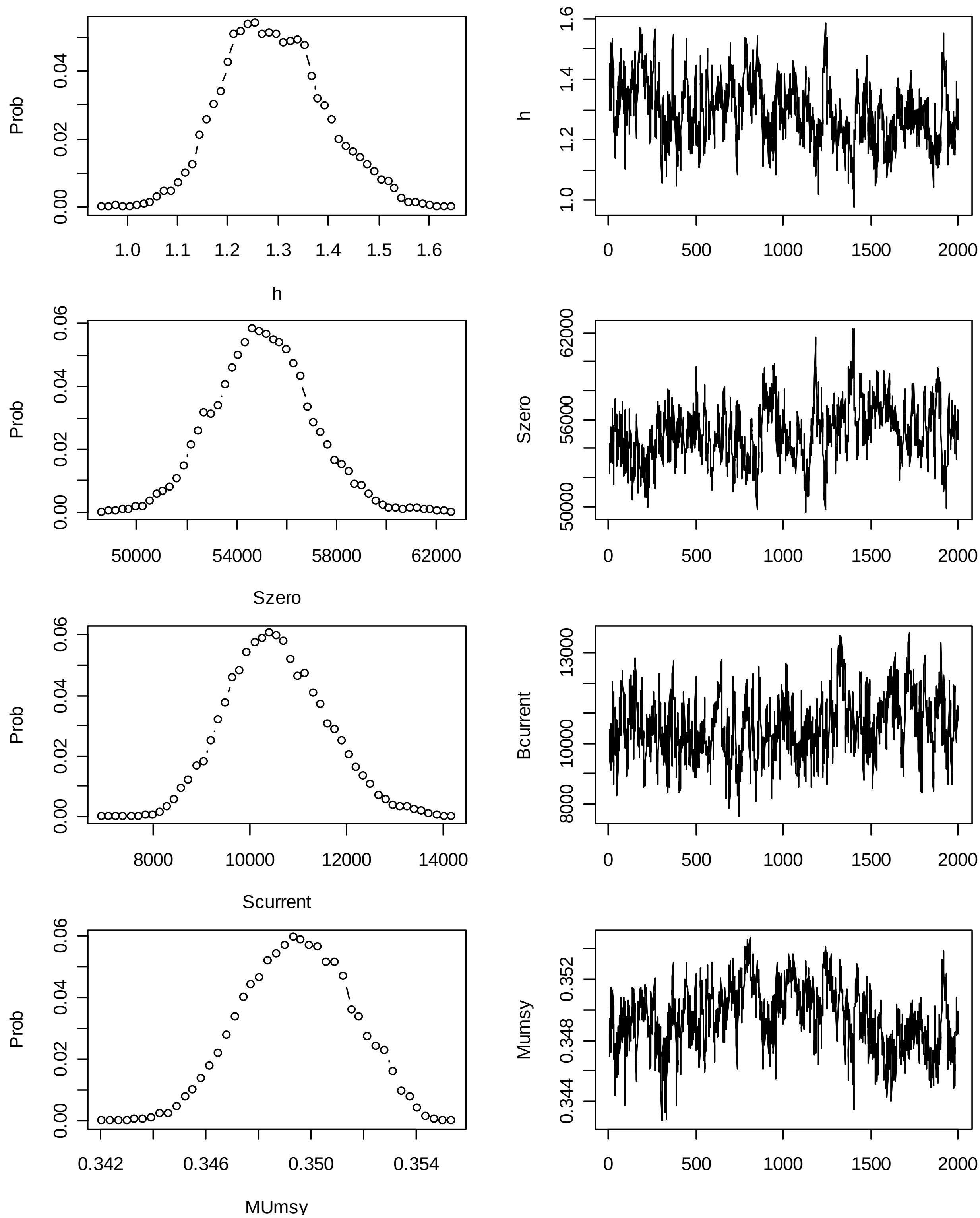

Figure 36. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with annual varying M for the west coast Vancouver Island.

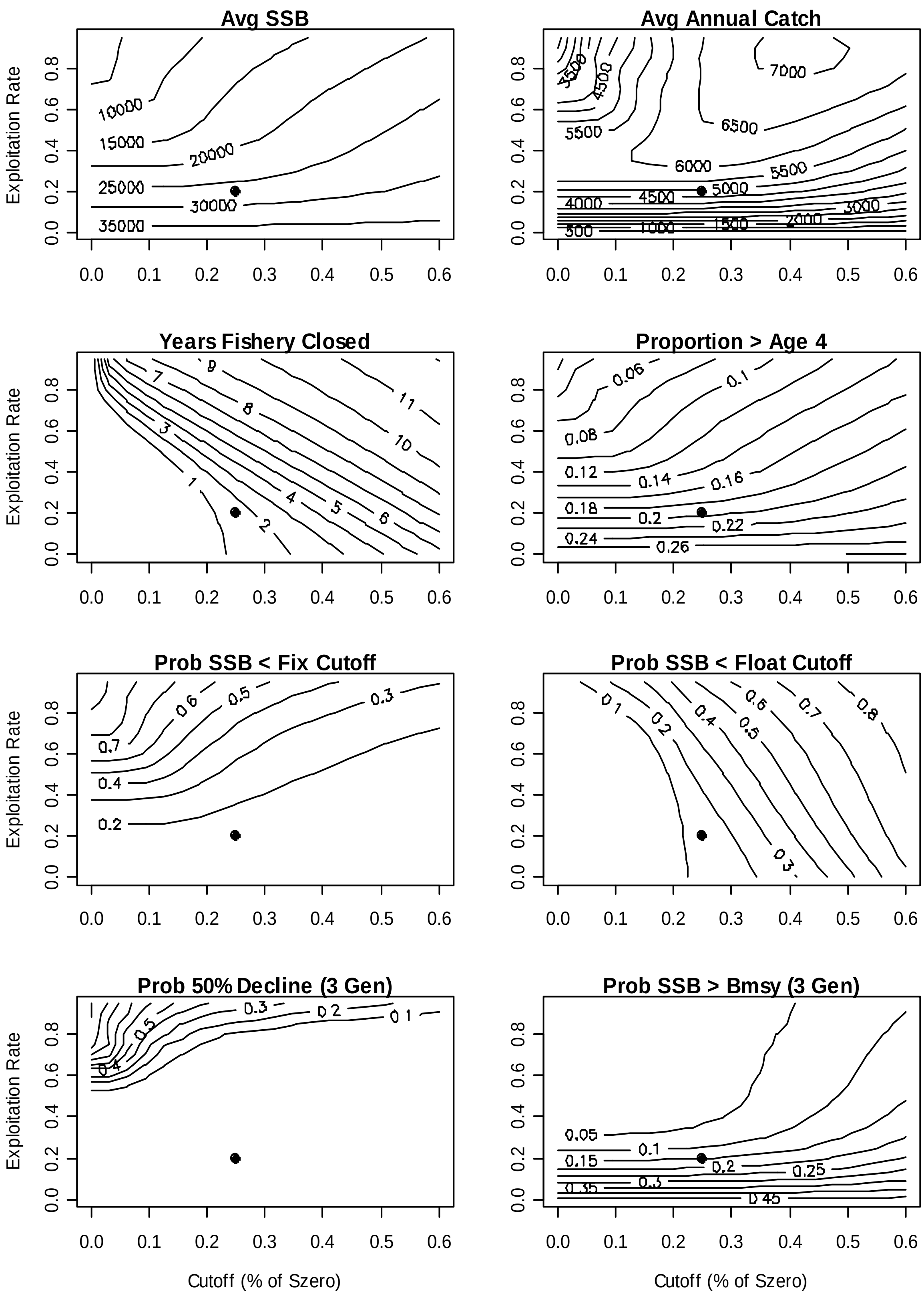

Figure 37. West coast Vancouver Island contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M. Dots indicate the current harvest policy.

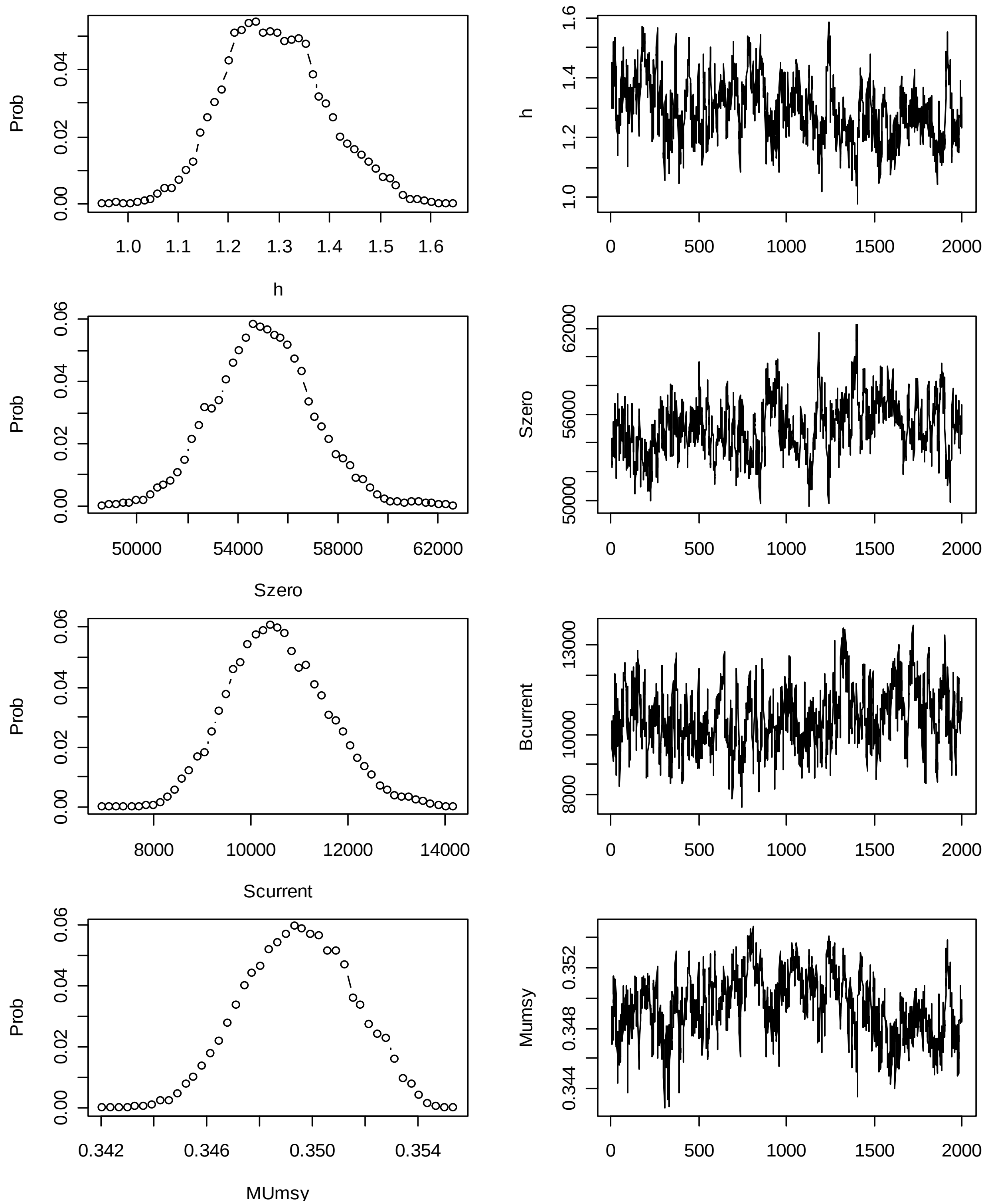

Figure 38. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Beverton-Holt model analysis with annually varying M for the west coast Vancouver Island.

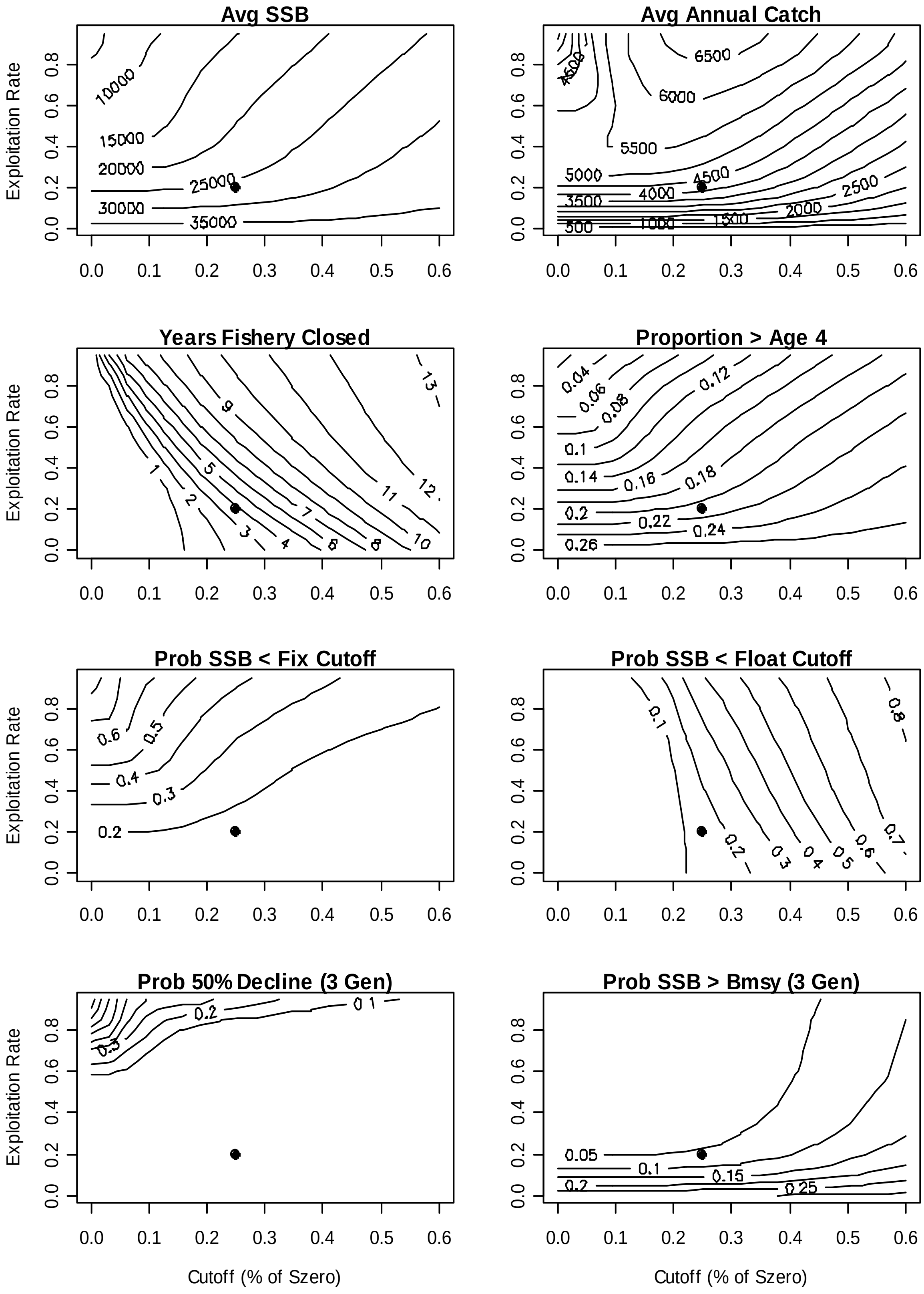

Figure 39. West coast Vancouver Island contour plots showing results from the eight performance indicators for the Beverton-Holt S-R function with variable M. Dots indicate the current harvest policy.

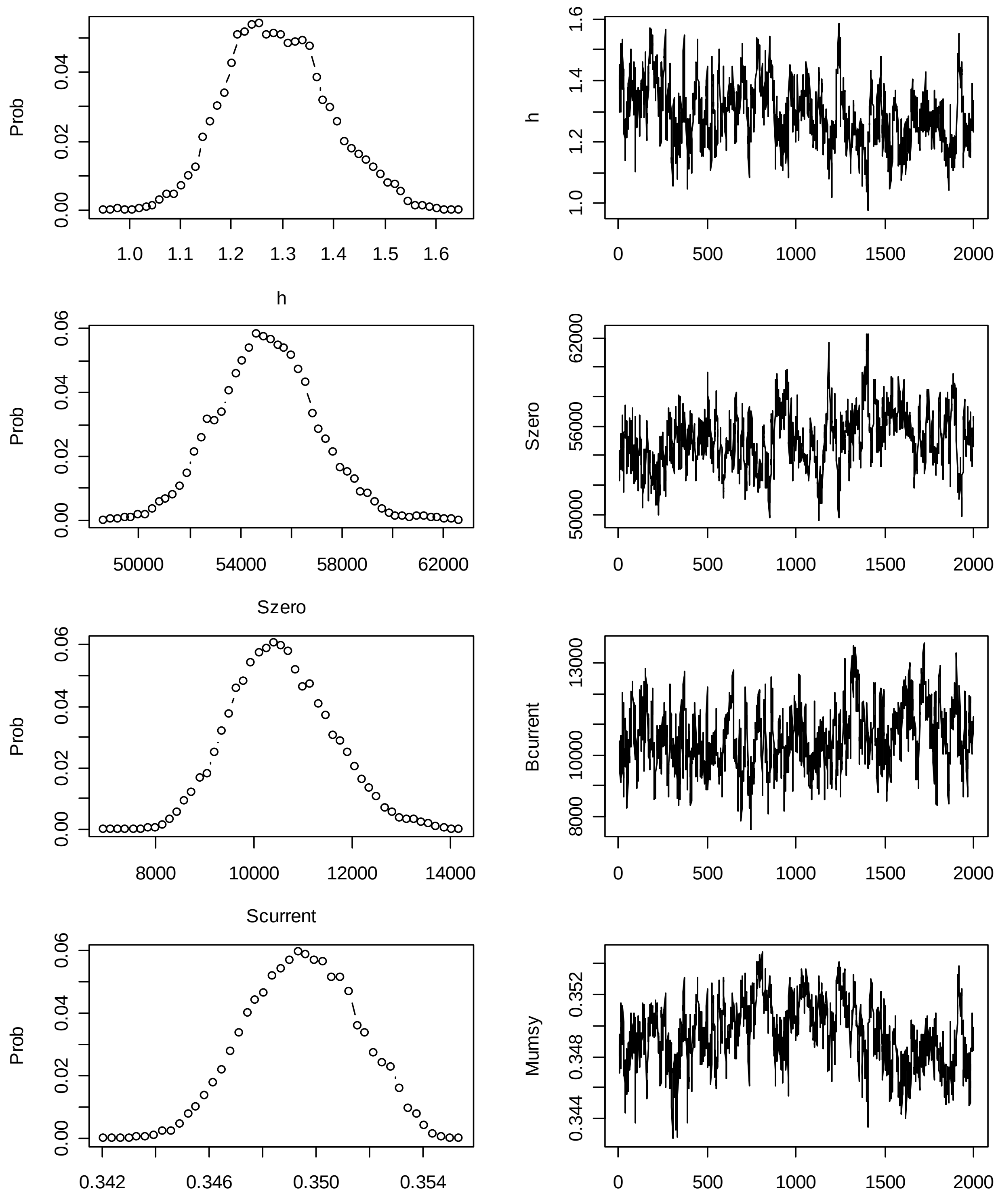

Figure 40. Bayesian posterior distributions and trace plots subsampled from the MCMC distribution for estimated steepness of the S-R curve at the origin (h), the estimated unfished biomass (S_0), the estimated current biomass, and the harvest rate generating MSY, from the Ricker model analysis with constant M for the west coast Vancouver Island.

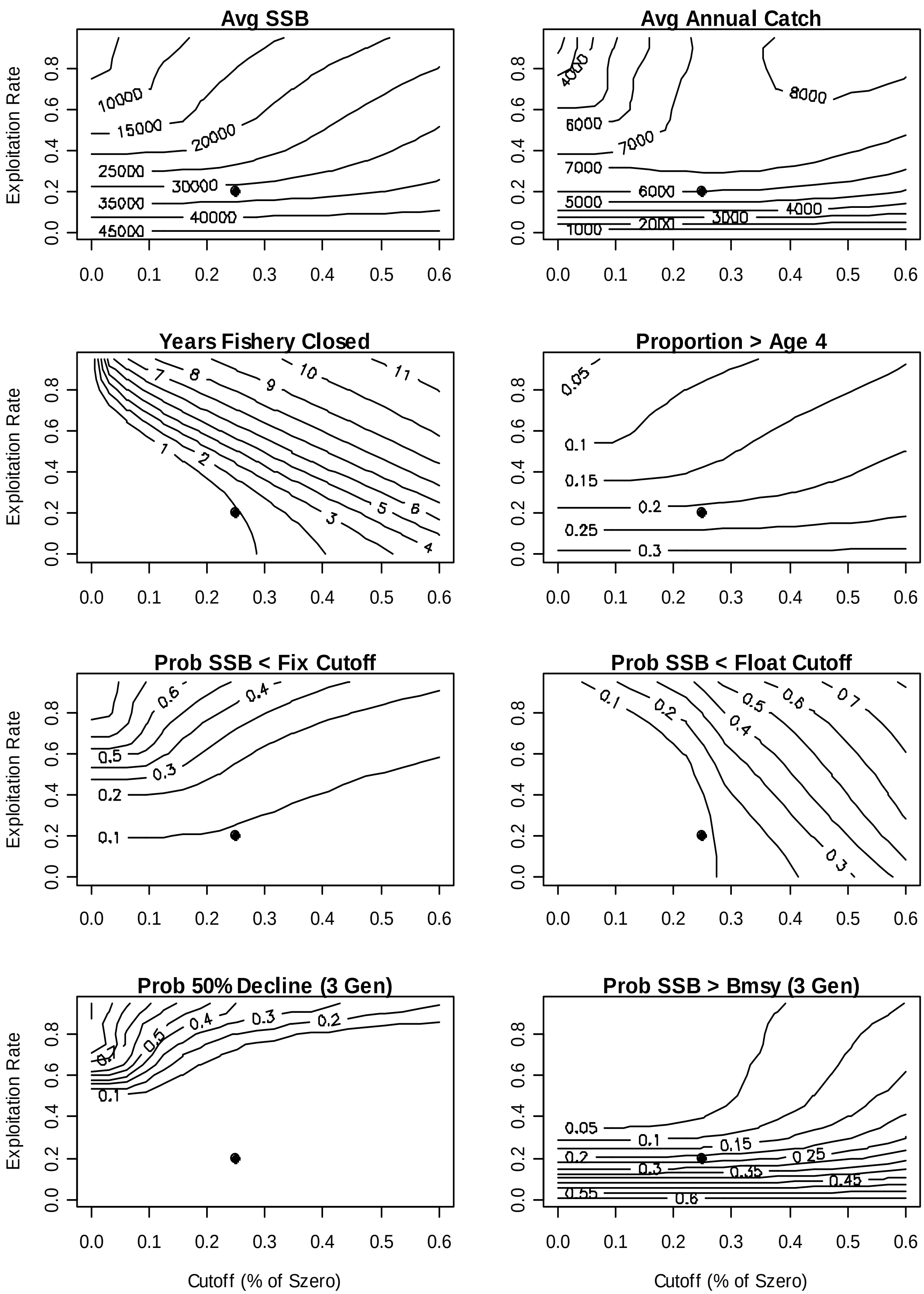

Figure 41. West coast Vancouver Island contour plots showing results from the eight performance indicators for the Ricker S-R function with constant M. Dots indicate the current harvest policy.

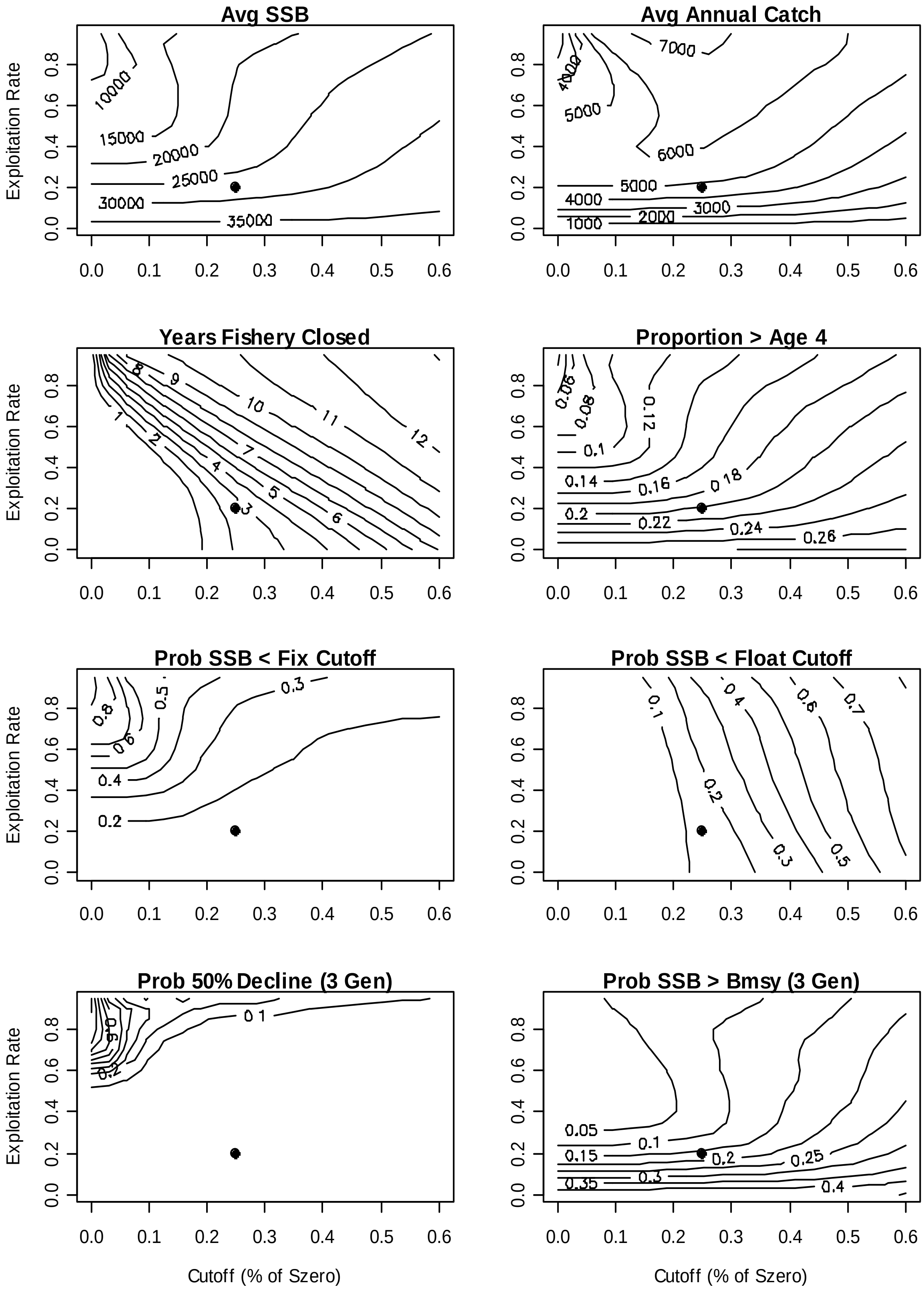

Figure 42. West coast Vancouver Island contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and an extra year lag in fisheries after rebuilding above cutoff. Dots indicate the current harvest policy.

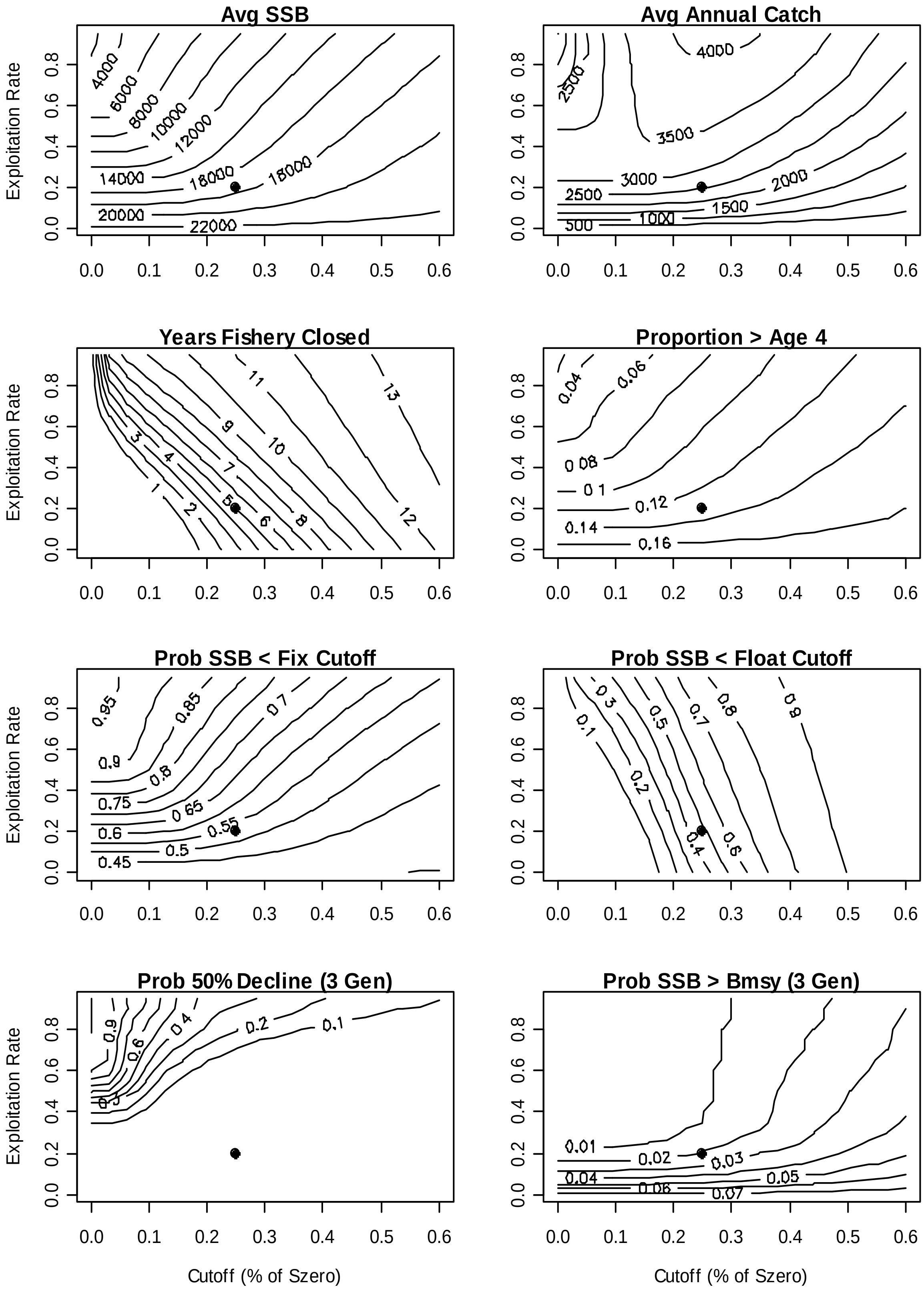

Figure 43. West coast Vancouver Island contour plots showing results from the eight performance indicators for the Ricker S-R function with annually varying M and reduced survival rate. Dots indicate the current harvest policy.

Appendix 1. Notations and equations for the assessment dynamics model

Model notations:

t	Subscript indexing year
a	Subscript indexing age
g	Subscript indexing gear type, 1 = seine; 2 = gillnet
r	Recruitment age or recruitment lag years assumed to be 2 in this study
A	Maximum or plus group age assumed to be 10 in this study
$w_{t,a}$	Average weight at age in year t from sampling
m_a	Average maturity at age from other biological research
$f_{t,a}$	Fecundity at age in year t calculated by $f_{t,a} = m_a w_{t,a}$
$\bar{f}_a$	Average fecundity at age $\bar{f}_a = \sum_{t=1951}^{2005} f_{t,a} \Big/ 55$
$C_{g,t}$	Catch biomass in year t and by gear g
$\hat{C}_{g,t}$	Expected catch biomass year t and by gear g based on the model
$P_{g,t,a}$	Proportion of catch at age a, in year t and by gear g
$\hat{P}_{g,t,a}$	Expected proportion of catch at age a, in year t and by gear g
S_t	Survey spawning biomass index after fishing in year t
$\hat{S}_t$	Expected spawning biomass after fishing in year t
R_0	Virgin recruitment
S_0	Virgin spawning biomass
R_t	Recruitment in year t
$N^*_{t,a}$	Numbers at age at the end of year t after natural loss but before fishing
$N_{t,a}$	Numbers at age at the end of year t after natural loss and fishing
$B_{g,t}$	Commercially exploitable biomass at the end of year t by gear g before fishing
$u_{g,t}$	Exploitation rate by gear g in year t, $u_{g,t} = \dfrac{C_{g,t}}{B_{g,t}}$
$s_{g,t,a}$	Gear-, year- and age- specific selectivity

$\mu_{g,t,a}$ Age-specific exploitation rate by gear g in year t, $\mu_{g,t,a} = u_{g,t} s_{g,t,a}$

M_t Instantaneous natural loss in year t

$\overline{M}$ Average natural loss $\overline{M} = \sum_{t=1951}^{2005} M_t \Big/ 55$

ε_t Recruitment residual for year t

q_t Conversion factor for the spawning biomass index in year t

In initial year (calculated as: $1951-(A-r+1)+r-1=1943$)

(A1.1) $$N_{1943,r} = R_0$$

(A1.2) $$N_{1943,a} = R_0 \prod_{i=r}^{a} e^{-\overline{M}} \qquad r < a < A$$

(A1.3) $$N_{1943,A} = N_{1943,A-1} e^{-\overline{M}} (1 - e^{-\overline{M}})^{-1}$$

(A1.4) $$S_0 = \sum_{a=r}^{A} N_{1943,a} \bar{f}_a$$

In subsequent years with $1943 < t < 1951$

(A1.5) $$N_{t,r} = R_0 \exp(\varepsilon_t)$$

(A1.6) $$N_{t,a} = N_{t-1,a-1} e^{-\overline{M}} \qquad r < a < A$$

(A1.7) $$N_{t,A} = N_{t-1,A-1} e^{-\overline{M}} + N_{t-1,A} e^{-\overline{M}}$$

(A1.8) $$S_t = \sum_{a=r}^{A} N_{t,a} \bar{f}_a$$

Dynamics during years with available data, $1951 \le t \le 2005$

(A1.9) $$N_{t,r} = \overline{R} \cdot \exp(\varepsilon_t)$$

(A1.10) $$N^*_{t,a} = N_{t-1,a-1} e^{-M_{t-1}} \quad \text{with } r < a < A,\ N^*_{t,A} = N_{t-1,A-1} e^{-M_{t-1}} + N_{t-1,A} e^{-M_{t-1}}$$

(A1.11) $$B_{g,t} = \sum_{a=r}^{A} N^*_{t,a} s_{g,t,a} w_{t,a}$$

(A1.12) $$N_{t,a} = N^*_{t,a} (1 - \sum_{g} \mu_{g,t,a})$$

(A1.13) $$S_t = \sum_{a=r}^{A} N_{t,a} f_{t,a}$$

Equations to calculate expected values corresponding to the observed data

(A1.14) $$\hat{P}_{g,t,a} = \frac{N_{t,a} s_{g,t,a}}{\sum_{a=r}^{A} N_{t,a} s_{g,t,a}}$$

(A1.15) $$\hat{S}_t = q_t \sum_{a=r}^{A} N_{t,a} f_{t,a}$$

Appendix 2. Model parameters, priors and likelihood functions.

Parameter notations:

γ_g Gear-specific shape parameter for the logistic selectivity curve

φ_g Average age at which 50% of fish are vulnerable to the specific fishing gear g

h Steepness of the Stock-Recruitment relationship

ρ Correlation coefficient of the recruitment residuals

σ_R, σ_M, and $\sigma_{g,s}$ Standard deviation of the logarithm of the lognormal variability in recruitment, natural loss and selectivity, respectively

ϖ_t, ν_t, and $\varsigma_{g,t}$ Random variability in recruitment, natural loss and selectivity

$\sigma_{C(g,t)}$ and $\sigma_{S(t)}$ Standard deviation of the lognormal distribution for catch biomass and spawning biomass index data

In this study, we fixed the following parameters at their default values:

$$\gamma_g = \begin{cases} 5.0 & \text{if g} = 1 \\ 5.0 & \text{if g} = 2 \end{cases}$$

$$\varphi_g = \begin{cases} 2.3 & \text{if g} = 1 \\ 3.4 & \text{if g} = 2 \end{cases}$$

$$\sigma_M = 0.2$$

$$\sigma_{g,s} = \begin{cases} 0.3 & \text{if g} = 1 \\ 0.3 & \text{if g} = 2 \end{cases}$$

The estimation of various parameters is carried out in a number of phases. If a parameter is not active, it is set at its default value.

Phase 1: $\ln(R_0)$ using locally uniform prior, $U(0.0, 10.0)$

$\ln(\bar{R})$ using locally uniform prior, $U(0.0, 10.0)$

Phase 2: $\varsigma_{g,t}$ using normal prior, $N(0, \sigma_{g,s}^2)$

Phase 3: ϖ_t using normal prior, $N(0, \sigma_R^2)$

Phase 4: ν_t using normal prior, $N(0, \sigma_M^2)$

Phase 5: $\ln(q_c)$ using locally uniform prior, $U(-10.0, 3.0)$

Phase 6: h using a beta distribution $Beta(2, 2)$

ρ using locally uniform prior, $U(-1., 1.0)$

σ_R using normal prior $N(0.6, 0.2^2)$

Penalties:

The negative logarithm of penalties for the stochastic processes of recruitment (Equation A2.1), natural loss (Equation A2.2), and selectivity (Equation A2.3) are included in the overall objective function to constrain their variability.

(A 2.1) $$-\ln PSS_R = \sum_t \left[\frac{(\chi_t - \rho\chi_{t-1})^2}{2\sigma_R^2\sqrt{1-\rho^2}} + \ln(\sigma_R) \right],$$

$$\text{where } \chi_t = \ln(N_{t,r}) - \ln(R_t) + \sigma_R^2 / 2$$

(A 2.2) $$-\ln PSS_M = \sum_t \frac{{\nu_t}^2}{2\sigma_M^2}$$

(A 2.3) $$-\ln PSS_s = \sum_g \sum_t \frac{{\varsigma_{g,t}}^2}{2\sigma_{g,s}^2}$$

Likelihoods:

The model is fit to the survey spawning biomass index by assuming lognormal observation error with known standard deviations.

(A 2.4) $$\ln(S_t \mid parameters) = \prod_t \frac{1}{\sqrt{2\pi}\sigma_{S(t)}} \exp\left(-\frac{[\ln(S_t) - \ln(\hat{S}_t)]^2}{2\sigma_{S(t)}^2} \right)$$

The negative logarithm of the likelihood, ignoring constants, is:

(A 2.5) $$-\ln LL_S = \sum_t \frac{[\ln(S_t) - \ln(\hat{S}_t)]^2}{2\sigma_{S(t)}^2}$$

The model is fit to the proportional catch at age data by assuming multinomial error using slightly modified Fournier et al. (1998) robust likelihood function. The negative logarithm of the likelihood, ignoring constants, is:

(A 2.6) $$-\ln LL_P = \sum_g \sum_t \sum_a \frac{1}{2} \ln\Big[\big(P_{g,t,a}(1-P_{g,t,a}) + 0.1/(A-r+1)\big)\Big]$$

$$-\sum_g \sum_t \sum_a \ln\left[\exp\left\{n_t \frac{-(\hat{P}_{g,t,a} - P_{g,t,a})^2}{2\big(P_{g,t,a}(1-P_{g,t,a}) + 0.1/(A-r+1)\big)}\right\} + 0.01\right],$$

where n_t is the sample size.

Overall objective function:

The overall objective function being minimized to obtain parameter estimates is the sum of the components from Equations (A2.1, A2.2, A2.3, A2.5, and A2.6), and contributions from other non-uniform priors.