# Development, evaluation, and application of a stock assessment framework for the Maine sea urchin stock

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by

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## Executive summary

The green sea urchin (*Strongylocentrotus drobachiensis)* fishery is of great importance to Maine's economy. The fishery took off in the late 1980s as a result of expanding export markets, but has experienced a substantial decline in landings since 1993, probably because of large decreases in urchin stock abundance. Fishery-independent surveys were not conducted until 2001, and no formal stock assessment has been done prior to 2001. The results derived in the 2001 stock assessment (Chen and Hunter, 2003) suggested that the stock biomass in 2001 was only 10% of the stock biomass in 1987 when the fishery started. The stock assessment used in 2001, however, has some unrealistic assumptions in the assessment model, in particular, the assumption that the sea urchin stock-recruitment relationship follows the Beverton-Holt model. The assessment framework developed for the 2001 stock assessment was not thoroughly tested, and we did not know whether it accurately represented the population dynamics of the Maine sea urchin.

In this project we modified the stock assessment framework developed in 2001. The modified stock assessment framework includes a stochastic observation-error length-structured model for describing the dynamics of the sea urchin population. No functional relationship was assumed for the sea urchin stock-recruitment relationship. A robust Bayesian approach is used for estimating fishery parameters because of concerns of possible outliers in fisheries data and mis-specification of priors. A simulation approach was developed to evaluate the performance of the modified model. To test if the performance of the modified stock assessment framework changes with the temporal variations in recruitment, we included in the simulation various scenarios of recruitment patterns (fluctuating, constant, continuous increasing, and continuous decreasing recruitment over years). Using the data collected from the fishery and urchin life history parameters derived from scientific studies, we conducted a formal stock assessment with the modified stock assessment framework for the Maine sea urchin stock. A risk analysis was also done to evaluate the impacts of different levels of landings on the population dynamics of the Maine sea urchins.

This study suggests that the modified stock assessment framework performs well

in estimating key fishery parameters such as exploitable stock biomass, total stock biomass, natural mortality, catchability, and fishing mortality under different scenarios of recruitment patterns. The performance of the modified stock assessment framework in estimating annual recruitment depends on the temporal patterns of recruitment. The assessment framework tends to perform well in estimating recruitment when annual recruitment fluctuates over time, but less well when the annual recruitment is constant, continuous decreasing, or continuous increasing over time. The recruitment of the Maine sea urchin stock is likely to fluctuate over time; being low, high, and low when stock abundance is high, intermediate, and low, respectively. Thus, the recruitment should be well estimated for the Maine sea urchin stock. This study suggests that the modified stock assessment framework can yield reliable estimates of key fisheries parameters that determine the population dynamics of the Maine sea urchin.

The application of this modified stock assessment framework to the Maine sea urchin fishery suggests that the current stock of the Maine sea urchin is approximately 10%-15% of the virgin stock biomass for Management Zone 1 and 15% to 20% of the virgin stock biomass for Management Zone 2. The exploitation rate is much higher than $F_{0.1}$, which is often used as a management target, for both management zones. The low current stock biomass and high exploitation rates suggest that the Maine sea urchin fishery is severely overfished in both zones, and a large reduction in exploitation rate is necessary. The overexploitation for Management Zone 1 is, however, more severe than that for Management Zone 2. The recruitment is regulated by density-related factors. Recruitment is low at high levels of stock abundance, and increases with decreasing stock abundance. However, this compensation process stops after the stock abundance decreases to certain levels. As suggested by this study, further decreases in stock abundance would initialize depensation processes with recruitment decreasing with decreases in stock abundance.

The risk analysis suggests that 750 and 1500 metric tons per year for the next five years for sea urchin landings in Management Zones 1 and 2, respectively, would provide a chance to stop further declines in stock biomasses. A more aggressive management (i.e. landings smaller than 750 and 1500 for Zones 1 and 2, respectively) is, however, needed to rebuild the Maine sea urchin stock. This rebuilding plan is, however, based on the assumption that the population dynamics of the Maine sea urchins will behave in the same way as they have in the past. Unfavorable changes in the ecosystem (e.g. loss of habitats and increased natural mortality due to increased predator abundance in the ecosystem) will call for more aggressive management measures to reduce landings for stock rebuilding. Any favorable changes in the ecosystem will, however, increase the chance of success in stopping further decreases in Maine sea urchin abundance if the recommended landing levels are implemented. This rebuilding plan may also need to be revised when results from the fisheries-independent survey are incorporated into the assessment model.

# Introduction

The green sea urchin, *Strongylocentrotus drobachiensis*, fishery is of great importance to Maine's economy. It is the state's fourth largest fishery by value, worth $20.3 million in 1999. The fishery is managed by limited entry, a minimum size limit, a maximum size limit, and a limited number of opportunity dates that are established each year by recommendation of the sea urchin zone council (SUZC). The fishery is further regulated seasonally by two management zones (Fig. 1) that correspond to variation in spawning along the coast (Vadas et. al., 2002).

The urchin fishery took off in the late 1980s as a result of expanding export markets, and landings peaked in 1992 (Fig. 2). Since 1992, the fishery has experienced substantial declines in landings, mainly resulting from a large decrease in urchin stock abundance. Although this decrease is evident in several studies (Harris et al, 2001; Hunter et al, 2003; Steneck, 1997; Steneck et al, in press, Vavrinec, 2003) and is recognized by the urchin fishing industry, the catch-per-unit-effort (CPUE) data derived from the fishery data have shown no significant decreases, or only slight decreases, over the last 10 years (Fig. 2). No formal stock assessment has been conducted for the fishery prior to this study, and no detailed information is available for the population dynamics of the stock.

Understanding of the urchin stock dynamics is essential, and can be accomplished by developing a population dynamic model, and subsequently, reliable estimation of model parameters with suitable statistical methods (Hilborn and Walters, 1992; Chen and Paloheimo,1998; Walters, 1998). A length-structured population dynamic model is desirable for the fishery because urchins are difficult to age and have large variations in growth among individuals (Quinn and Deriso, 1999; Russell and Meredith, 2000). Bayesian inference was considered for this study in fitting a population dynamic model to data because the use of prior distributions enables the incorporation of prior knowledge of the fishery into parameter estimation and the use of likelihood functions in Bayesian inference makes it easy to incorporate data of various sources and uncertainties associated with the data (Taylor et al., 1996). Bayesian inference provides a systematic approach that explicitly incorporates both uncertainties and risks in analyses (Hilborn et al., 1993).

The Maine Department of Marine Resources implemented a fishery-independent survey program in 2001 (Hunter et al, 2003). Because there were only two years of data available, we did not include the survey data derived from the survey in this study. The stock assessment model developed in this study, however, does have a structure that allows for the use of survey size-composition data and survey abundance indices in the assessment, which will facilitate the incorporation of survey data in future stock assessments.

Data available for this stock assessment study were mainly from the fishery. Outliers are probably present in such data (Chen et al., 2000). Commonly used Bayesian approaches often assume that errors in data follow normal distributions in formulating likelihood functions. This assumption can, however, be violated if there are outliers in fisheries data resulting from abnormal measurement and/or process errors (Chen et al., 1994). The likelihood of having outliers in the urchin data makes the commonly used normal-distribution-based approach undesirable (Fournier et al., 1990; Chen and Fournier, 1999). It is desirable to use an approach that performs as well as the normality-based methods when errors are normally distributed, but performs much better than normality-based methods when there are outliers in stock assessment modeling (Chen et al., 2000). This can ensure the quality of the stock assessment whether there were outliers or not.

There is limited knowledge of the values of some key parameters that characterize urchin stock dynamics. Prior distributions for fisheries parameters can be very inaccurate in fisheries due to the all-too-common problem of stock assessment scientists choosing biased priors (Punt and Hilborn, 1997; McAllister and Kirkwood, 1998) and overly precise priors with prior variances much smaller than their real uncertainties (Adkison and Peterman, 1996; McAllister and Kirkwood, 1998). This is probably true for the urchin fishery. Such a prior mis-specification can result in large errors in stock assessment (Chen et al., 2000). Clearly, a Bayesian stock assessment approach robust to prior mis-specifications is desirable.

In this study we develop, evaluate, and apply a Bayesian stock assessment framework that is robust to outliers and mis-specification of priors to assess the Maine green sea urchin fishery in both Management Zone I (approximately half of the Maine coast, from Western Penobscot Bay southwest to the Maine/New Hampshire border) and Management Zone II (Figure 1).

## Materials and methods

For the Maine sea urchin fishery, fisheries-dependent data available include landed catch, various measures of fishing efforts, and estimates of size composition of the catch for each defined management area. Previous studies in the northwest Atlantic (Meidel and Scheibling,1998; Russell,1998; Vadas et al., 2002) have indicated that large variations in growth exist on both large and small spatial scales for the sea urchin stock. This calls for the development of size-structured models for stock assessment, which can better describe large variations in growth compared with commonly used age-structured models.

A size-structured model was developed to describe the dynamics of the sea urchin stock in each management zone. The model consists of nine submodels: (1) a growth model; (2) a stock-recruitment model; (3) a catch-at-size model; (4) a fishing selectivity model; (5) a maturation model; (6) an observational model relating observed catch per unit of effort (CPUE) estimated from catch and effort data, to CPUE data predicted from the models; (7) an observational model relating the observed catch size compositions to predicted catch size compositions; (8) an observational model relating the observed survey abundance index to the abundance index predicted from the models; and (9) an observational model relating observed survey size composition data to predicted stock size compositions. The first five submodels describe the fishing processes and the processes determining the dynamics of a fish population, and they were used to generate a model fishery. The dynamics of the model fishery was driven by reported catch. Various fisheries statistics such as catch size composition and stock biomass could be predicted from the simulated fishery. The submodels were then fine-tuned for their parameters using the four observational models (i.e. submodels 6 to 9 listed above) by minimizing the differences between observed and predicted fisheries statistics. A detailed description and the mathematical functions of these submodels can be found in Appendix I of this report.

To reduce the complexity of the stock assessment model, the growth model was determined outside the stock assessment modeling process. A growth transition matrix was developed to describe the probability of an urchin growing from one size class to another. Sixty-one size classes were established from 40 mm to 100 mm (midpoint values) with the width of a size class of 1 mm. The development of the growth model is detailed in Appendix II.

The fishery statistics available to this study for use in the observational models include catch per unit of effort (CPUE) data that were estimated from catch and effort data observed from 1987 to 2001 and from 1994 to 2001, respectively, in the fishery (Fig. 2) and size composition data estimated from sampling the catch from 1995 to 2001 (Fig. 3). Note that "2001" refers to the 2001-2002 fall-winter fishing season, etc. The observational models were

(1a) $$I_t = qB_t e^{\varepsilon_t}$$

(1b) $$p_{k,t} = p_{k,t}^{pred} + \phi_{k,t}$$

where $I_t$ is CPUE observed in year t, $B_t$ is the exploitable stock biomass in year t, $p_{k,t}$ is the proportion of urchins in size class k observed in year t, q is the catchability coefficient, $\varepsilon_t$ is an observation error for CPUE often assumed to have a normal distribution $\varepsilon_t \subset N(0, \sigma_I^2)$, and $\phi_{k,t}$ is an observation error often assumed to follow a multinomial distribution. The Bayesian estimator derived from the assumption is, however, sensitive to outliers in data.

As described previously, because data were collected from the commercial fishery, they were likely subject to errors of various sources (e.g. sampling errors and measurement errors; Hilborn and Walters, 1992) and outliers might arise in the data. It was thus desirable to employ a robust Bayesian estimator to fit the model to the data collected from the sea urchin fishery. This can be readily done by adjusting (increasing) the size of tails for probability distribution function in formulating a likelihood function (Chen et al., 2000). The likelihood functions for equations (1a) and (1b) were modified as

(2) $$p(I_t \mid C_t, \boldsymbol{\beta}) = \prod_t \left[ \frac{1.329}{\sqrt{4\pi}} \left( 1 + \frac{[\ln(I_t) - \ln(qB_t)]^{2.5}}{4(\hat{\sigma}_I)^2} \right) \right] \text{ and}$$

(3) $$L(p \mid \boldsymbol{\beta}) = \prod_t \prod_k \frac{1}{\sqrt{2\pi p_{k,t}(1 - p_{k,t}) + 0.1/\Omega}} \exp\left[ \frac{-N_{k,t}(p_{k,t} - \hat{p}_{k,t})^2}{2[p_{k,t}(1 - p_{k,t}) + 0.1/\Omega} + 0.01 \right].$$

$\beta$ in the above equations is a vector of parameters to be estimated. Equation (2) is a likelihood function of t distribution with a degree of freedom of 4. Its tail is slightly thicker than a relevant normal distribution, making it more robust to outliers (Fan and Berger, 1992; Berger, 1994; Chen et al., 2000). The reason that we used 4 degrees of freedom rather than estimating the degrees of freedom in this study was the limited number of data available to the assessment, and previous studies had shown it was difficult to determine the degrees of freedom (Chib et al., 1991; Berger, 1994). The t-function with a degree of freedom of 4 had been used in previous studies (Berger, 1994; Chen et al., 2000). $\hat{\sigma}_I$ in equation (2) is the standard deviation estimated for log CPUE. Subscripts t and k in equation (3) indicate year and length class, $\Omega$ is the number of length classes (= 61 for all years), $p_{k,t}$ is the proportion of urchins in length class k in year t, and $N_{k,t}$ is the effective sample size used to determine the proportion of urchins in year class k in year t. The 0.01 term in the second part of the likelihood (eq. 3) increases the thickness of tails, making the likelihood less sensitive to outliers. The $0.1/\Omega$ term prevents the variance from approaching zero as the $p_{i,t}$ value approaches zero or one (Fournier et al., 1990).

All parameters were assumed to have non-informative priors described by uniform distributions. To make the priors robust to prior mis-specifications, Cauchy distribution functions, instead of log or log-normal functions, were used to describe prior distributions for h and M (Berger, 1994; Chen et al., 2000). Priors used in this study are presented in Table 1.

Posterior distributions of the model parameters were estimated using the Markov Chain Monte Carlo (MCMC) simulation approach. The Hastings-Metro algorithm was used. The simulation was started from the parameters at the mode of the posterior distribution which was identified by minimizing the total objective function, which includes the negative log likelihood components and the prior probability contributions. The lag between samples was 200. The model was implemented in AD Model Builder (Fournier, 1996). Detailed descriptions on estimating posterior distributions can be found in Fournier (1996). Half a million simulations were run to estimate the posterior distribution of model parameters (Chen et al. 2000).

Using the posterior distributions derived for fishery parameters in Bayesian analyses, we conducted a risk analysis on the impacts of different fishing intensities (i.e. different catch levels) on the sea urchin population (Hilborn and Walters 1992). The flowchart for the development of the stock assessment framework is presented in Figure 4.

### A simulation study for evaluating the proposed sea urchin stock assessment model

To determine whether the developed model can realistically reproduce the model parameters and sea urchin population dynamics, a simulation study was conducted. The simulation included the following steps: (1) using catch and CPUE data collected in the sea urchin fishery and biological information (e.g. growth and maturation) to simulate an urchin fishery with known population dynamics; (2) applying the developed stock assessment framework to the simulated urchin fishery to estimate population and fishery parameters and urchin stock dynamics such as natural mortality, fishing mortality, recruitment, spawning stock biomass, and exploitable stock biomass; (3) comparing the parameters and population dynamics used to create the simulated sea urchin fishery (i.e. step 1) with the parameters and population dynamics estimated by applying the developed assessment framework to the simulated sea urchin fishery. Small differences in the comparisons (i.e. step 3) indicate that the developed stock assessment framework is likely to represent the true patterns of sea urchin population dynamics, and thus is reliable.

Using the population dynamic models to be evaluated in simulating the sea urchin fishery may bias the simulation results toward over-rating the performance of the population model to be tested because the same model is used in simulating the fishery and in estimating the fishery parameters. To avoid this problem, an individual-based approach was used to simulate the sea urchin fishery. The flowchart of this approach is presented in Fig. 5. Detailed descriptions using an individual-based approach in simulating the sea urchin fishery are presented as follows.

Instead of using the models for aggregate dynamics of a sea urchin stock, we used a probabilistic approach to simulate the lives of individual sea urchins. This can be accomplished by expressing various components of the model equations as random Bernoulli trials. For example, rather than calculating the number of sea urchins that survive natural mortality by

$$N_{t+1} = N_t e^{-M}$$

where M is the instantaneous rate of natural mortality, we simulated natural mortality acting on $N_t$ individual sea urchins,

$$\textit{for}\ 1\ \textit{to}\ N_t : \textit{if}\ U(0,1) \leq 1 - e^{-M}\ \textit{then}\ N_{t+1} = N_t - 1$$

where U(0,1) is a uniform distributed random number between 0 and 1. We refer to this approach as an individual-based fisheries simulator.

This simulator simulates the life of each sea urchin in a population subject to the fishery. The data generated by the simulator were based on a set of population dynamics parameters estimated for the sea urchin fishery and a specific catch history.

An initial population of N individuals was generated randomly with size-frequency chosen in proportion to the initial size structure. The maturity status of a sea urchin was randomly selected in proportion to the number of mature animals in that size class.

Each year, a certain number of recruits were added to the population. Four scenarios were considered for temporal patterns of recruitment, constant, fluctuating, declining, and increase over time (Fig. 5). Bookkeeping was done by examining each individual and adding it to the legal biomass and spawning stock biomass where appropriate. The exploitation rate was calculated as the proportion of the catch of the legal biomass.

Each time step (i.e. year), each sea urchin had a probability of being caught in the fishery, dying of natural mortality, or growing and maturing. When a sea urchin was caught in the simulated fishery, its size was recorded to generate catch and size frequency data. Catch per unit of effort for the fishery was generated as a constant proportion of the total weight of legal sea urchins in the population. Illegal catch was assumed to be zero in the simulation study.

Errors that arise in the simulation are a result of the random sampling associated with the simulated Bernoulli trials for all life history and fishery processes and differences in how the natural mortality and fishing mortality occur (Fig. 5). No extra observation or process errors were included in this simulation study.

The data simulated by this individual-based simulator were then analyzed using the models developed for the sea urchins. This test would evaluate the validity of the models. If a model yields large biases and errors in estimating parameters in our four recruitment scenarios, it is not suitable. Otherwise, we can conclude that the model performs well in identifying population dynamics of sea urchins in Maine.

## Assessing the Maine sea urchin stock using the proposed stock assessment framework

The proposed stock assessment framework was applied to the data collected by the Maine DMR and scientists of the University of Maine for the assessment of the Maine sea urchin stock. The assessment was done separately for Management Zone 1 and Zone 2. The data used in the assessment included (1) sea urchin landings data from 1987 to 2001; (2) CPUE data from 1994 to 2001; (3) size composition data of landed sea urchins; (4) subsample sizes for estimating size compositions of landed sea urchins; (5) minimum and maximum legal sizes; (6) length-at-age data (i.e., growth data); (7) size-specific maturation data (i.e., proportion of sea urchin mature for a given size); and (8) length-weight data from catches.

Because of concerns about possible underestimation of landings in the Maine sea urchin fishery, two sets of landings data were provided by the DMR and used in the assessment. The data with landings adjusted upward to account for underreporting are referred to as "Data set A" as opposed to observed data.

Although a fishery-independent survey program was initialized in 2001, this assessment did not include the data collected in the survey. The survey data were used in a spatial statistical model (Grabowski et al. 2003), developed independently of the stock assessment model described in this report, for the assessment of sea urchin stock abundance. The exclusion of the fishery-independent survey data in the stock assessment model proposed in this project is to facilitate the comparisons of the stock assessment results derived from the proposed stock assessment model and the spatial statistical model.

The input data used for the stock assessment using the proposed assessment framework are described in Appendix III.

## Results and discussion

## Simulation study

The first simulation scenario considered recruits fluctuating over time, being low in the beginning of the fishery, increasing with landings, and then decreasing quickly after reaching the peak. This mimics the temporal variations in recruits of the Maine sea urchin fishery over time. Recruits were low in the early stage of the fishery due to high density, but increased with the reduction of population density due to high landings in the urchin fishery, followed by a large decrease in recruits probably due to the removal of spawning stock biomass (Fig. 2). The recruits estimated using the proposed stock assessment model were rather consistent with the recruits used in simulating the fishery (Fig. 6). Other key fishery statistics, including exploitable stock biomass, total stock biomass, exploitation rate, and CPUE, estimated using the proposed stock assessment model, were also consistent with the "true" values used in simulating the sea urchin fishery (Fig. 6).

To determine whether the stock assessment model could respond to different patterns of recruitment in the assessment, we included a few simulation scenarios where the recruitment in the simulated fishery was assumed to increase, decrease, and be constant over the stock assessment time period. We then applied the stock assessment model to these simulated fisheries with different patterns of recruitment. When the recruitment decreased over time (Fig. 7), the recruits estimated using the proposed model could capture the trend of changes in recruitment, but with some errors (Fig. 7). The other fishery statistics estimated using the proposed model were, however, rather consistent with the "true" values incorporated in the simulation (Fig. 7). When the recruitment increased over time (Fig. 8), the recruits estimated using the proposed model could capture the trend, but with large errors in some years (Fig. 8). The other fishery statistics estimated using the proposed assessment model were consistent with the "true" values built in the simulation (Fig. 8). The largest errors in estimating recruitment occurred when the recruitment was assumed to be constant over time (Fig. 9). It is obvious that the assessment model yields large errors in recruitment. Surprisingly, the stock assessment yielded other key fishery statistics consistent with the "true" values used in the simulation, despite large errors in estimating recruitment (Fig. 9). There are three reasons for this consistency. Firstly, unlike recruitment, the estimates of other key fishery statistics (i.e. total biomass, exploitable biomass, exploitation rate, and CPUE) are all based on biomass, rather than number. Because the length-weight relationship is exponential, weights of newly recruited individuals are much smaller than those of big ones, and total weights of new recruits only make up a small proportion of the total biomass. Variations in estimated natural mortality among different scenarios also reduced the impacts of differences in "true" and estimated recruitments (Table 2). Secondly, the total recruitment over the test period was approximately the same for different recruitment scenarios. Thus, the total contributions from recruitment to the stock biomass over the test period would be similar among different recruitment scenarios. As a result, the outputs of individual-based sea urchin simulations yielded similar outputs in the simulated fishery among different recruitment scenarios (Figs 6, 7, 8, and 9), which resulted in similarities in estimated fishery parameters and statistics among different recruitment scenarios in the simulation. Thirdly, we used the same initial values to start the estimation for different scenarios of recruitment in the simulation, which might influence the estimation of the key fishery parameters. Nevertheless, the consistency of the "true" values used in simulating the fishery and values estimated using the proposed assessment model in all simulation scenarios considered in this study indicates that the proposed assessment method can capture the dynamics of the sea urchin stock. However, this study only considered some random errors. More extensive studies may, however, need to be done to evaluate possible impacts of mis-reporting of catch and CPUE data on assessing the stock using the proposed model.

The "true" size composition data of landings that were built in the simulation were compared with the size composition of landings predicted using the proposed stock assessment model. For the four simulation scenarios with different recruitment patterns, the largest differences in the "true" and "predicted" occurred in the small size classes (Figures 10- 13). This was especially true for the size classes that were close to the minimum legal size. The size composition data of landings predicted were almost identical to the "true" size composition of landings for the large size classes (Figures 10-13). This suggests that the model can predict size compositions of landings well for large sea urchins, and less well for sea urchins with sizes of close to the minimum legal size. However, if we looked at the magnitudes of differences in figures 10-13 (i.e. Y-axis in the figures), they were all very small, suggesting that even the largest differences in the "true" and "predicted" size compositions were small, suggesting the proposed stock assessment model predicts size composition of landings well. This suggests that the proposed model fits the data well.

Overall, the simulation study included in this study suggests that the proposed stock assessment model performs well with the simulation scenarios considered in this study. We can conclude that the proposed stock assessment can reproduce the patterns of sea urchin population dynamics.

## Applications of the proposed model to the Maine sea urchin fishery

For each management zone, two sets of the data were used in the assessment. One set of data included landings reported to the Maine DMR, and the other included landings adjusted for possible underreporting (Tables 3 and 4). For each management zone, both data sets (i.e. Data set 1 and Data set 1A for Zone 1; and Data set 2 and Data set 2A for

Zone 2), which are identical except for the landings, were used in the assessment.

## Management Zone 1

The results for Management Zone 1 are summarized in Table 5. The estimates of natural mortality were almost identical between data sets 1 and 1A. Virgin stock biomass (i.e. stock biomass at the beginning of the fishery, i.e. 1987) estimated based on data set 1A was higher than that estimated based on data set 1. The assessment based on data set 1A also yielded higher estimates for recruitment in 2001, and total stock biomass and exploitable stock biomass in 2002 which was the last year included in the assessment (Table 5). Estimates of the depletion rate, defined as the ratio of current stock biomass versus virgin stock biomass, were similar between the two sets of data. For both sets of data, this assessment suggests that current exploitable (legal) stock biomass is less than 10% of the virgin biomass and that current total stock biomass is less than 20% of the virgin stock biomass. This suggests a significant decrease in stock abundance in Management Zone 1 over the period of 1987 to 2002. The maximum sustainable yield (MSY) and stock biomass that yields maximum sustainable yield (i.e., $B_{MSY}$) estimated from data with adjusted landings were higher than those estimated from data with reported landings. The adjusted landings in 2001 were higher than the median value of MSY estimated based on data with reported landings, but were almost identical to that estimated from data with adjusted landings. The median value of total stock biomass of 5,641 mt in 2002 was, however, much lower than that of $B_{MSY}$. This suggests that the stock had been overfished. The exploitation rate, which is the proportion of stock biomass that is removed in the fishery, in 2001 was close to 0.4 (i.e. 40%), much higher than the $F_{0.1}$ value which is often used as a target fishing mortality (about 2.5 time higher; Table 5). This indicates overfishing. This assessment suggests that the sea urchin stock in Management Zone 1 has been overfished, and if the current exploitation rate continues, the stock would not be able to recover from the current status. A large reduction in landings is necessary in order for the stock to recover.

The plots of time series of total stock biomass and exploitable stock biomass showed a continuous decrease since 1987 (Fig. 14). The large decrease in exploitable biomass in 1995 results from the adaptation of the minimum legal size, which excludes sublegal sized sea urchins being included in the exploitable biomass. The recruitment was lower early in the fishery (Fig. 14), probably due to the fact that the stock was a virgin stock biomass with high densities. Recruitment increased in the late 80s and early 90s, probably as a result of reduction in stock biomass (thus lower population density) due to increased landings in the fishery. The recruitment reached its peak in 1993, followed by a large and sudden reduction in the next two years (Fig. 14). The reduction in recruitment slowed down in the recent years, but current recruitment was very low (only about 10% of the highest level in 1993), compared with the historical levels (Fig. 14). This suggests that the stock was recruitment overfished. The low recruitment might result from many factors such as low success rate of fertilization due to low population density caused by overexploitation (i.e. Allee effects), changes in the ecosystem, and loss of habitats. Because recruitment is a key for the recovery of the fishery, more studies are needed to identify key factors that limit the recruitment of the Maine sea urchin population.

The posterior distributions of the key fishery parameters are presented in Fig. 15. Noninformative (i.e. we assumed prior distributions of parameters follow uniform distributions) priors were used in the Bayesian estimation. The resultant posterior distributions followed either normal or log-normal (i.e. with a long tail on the right side of the distribution; Fig. 15), which differed from uniform distributions assumed for the priors. This suggests that data are informative in estimating the model parameters.

The plot of spawning stock biomass (SSB) and recruitment estimated using the maximum likelihood method indicates that population density may be a key factor in regulating recruitment (Fig. 16). When SSB was high (e.g. 1989), the recruitment was low, followed by increases in recruitment with reductions in SSB. After SSB fell below certain levels, recruitment no longer increased with decreasing SSB, rather recruitment started to decrease with SSB (Fig. 16). Thus, at high levels of SSB, the sea urchin stock experienced compensation (i.e. recruitment increased with decreased SSB), and after SSB dropped to a certain level, the stock experienced depensation (i.e. recruitment decreased with decreased SSB).

Similar results were observed in the assessment using the data with adjusted landings (i.e. Data set 1A). The results for data set 1A are summarized in Table 6 and figures 17, 18, and 19. The results based on the adjusted landings tended to be more optimistic about the estimation of the current status of the fishery. However, the results were consistent with the results based on reported landings in that the stock had been severely overfished with low stock biomass, and the current exploitation rate was too high. Current recruitment was also very low compared with historical levels.

## Management Zone 2

The key fishery parameters and statistics estimated for the sea urchins of Management Zone 2 are summarized in Table 6. The estimated natural mortality was almost identical for data sets 2 and 2A. Virgin stock biomass (i.e. stock biomass at the beginning of the fishery, i.e. 1987) estimated based on data set 2A was higher than that estimated based on data set 2. The assessment based on data set 2A also yielded higher estimates for recruitment in 2001, and total stock biomass and exploitable stock biomass in 2002 (Table 6). Estimates of the depletion rate, defined as the ratio of current stock biomass versus virgin stock biomass, were similar between the two sets of data. For both sets of data, this assessment suggests that current exploitable (legal) stock biomass was slightly more than 10% of the virgin biomass and that current total stock biomass was over 20% of the virgin stock biomass. Although both are higher than those for Management Zone 1, the depletion rates of 0.12 and 0.25 still suggest a significant decrease in stock abundance in Management Zone 2 over the period of 1987 to 2002. The maximum sustainable yield (MSY) and stock biomass that yields maximum sustainable yield ($B_{MSY}$) estimated from data with adjusted landings were higher than those estimated from data with reported landings. The landings of Management Zone 2 in 2001 were higher than the median value of MSY. The median value of total stock biomass of 7,076 mt in 2002 was, however, lower than that of $B_{MSY}$, although the difference between $B_{MSY}$ and total biomass in 2002 is smaller than that for Management Zone 1. This suggests that the Zone 2 stock has been overfished, but less severely compared with the stock of Management Zone 1. The exploitation rate, which is the proportion of stock biomass that is removed in the fishery in 2001 is over 0.5 (i.e. 50%), much higher than the $F_{0.1}$ value, which is often used as a target fishing mortality (Table 6). This indicates overfishing. This assessment suggests that the sea urchin stock in Management Zone 2 has been overfished, and if the current exploitation rate continues, the stock would not be able to recover from the current status. A large reduction in landings is necessary in order for the stock to recover.

The plots of time series of total stock biomass and exploitable stock biomass show an initial increase early in the fishery, followed by large decreases (Fig. 20). This is very different from that for Management Zone 1. The initial increase in stock biomass may likely result from the large increases in recruitment for the same time period (Fig. 20). It may also result from increases in fishing areas in this management Zone in the initial time period of fishery development. The recruitment was lower early in the fishery (Fig. 20), probably due to the fact that the stock was a virgin stock biomass with high densities. The recruitment increased in the late 80s and early 90s, probably as a result of reductions in stock biomass (thus lower population density) due to increased landings in the fishery, and was followed by a continuous reduction (Fig. 20). The reduction in recruitment slowed down in the recent years, but current recruitment was very low (less than 20% of the highest level), compared with the historical levels (Fig. 20). This suggests that the stock was recruitment overfished. The low recruitment might result from many factors such as low success rate of fertilization due to low population density caused by overexploitation (i.e. Allee effects), changes in the ecosystem, and loss of habitats. Because recruitment is a key factor for the recovery of the fishery, more studies are needed to identify key factors that limit the recruitment of the Maine sea urchin population. Recruitment in Management Zone 2 was, however, higher than that for Management Zone 1. This might explain why the overexploitation for Management Zone 2 was less severe than that for Management Zone 1.

The posterior distributions of the key fishery parameters are presented in Fig. 21. Noninformative priors (i.e. prior distributions of parameters were assumed to follow uniform distributions) were used in the Bayesian estimation. The resultant posterior distributions followed either normal or log-normal (i.e. with a long tail on the right side of the distribution; Fig. 21). This suggests that data are informative in estimating the model parameters.

The plot of spawning stock biomass (SSB) and recruitment estimated using the maximum likelihood method indicates that population density may be a key factor in regulating recruitment (Fig. 22). When SSB was high (i.e. late 80s and early 90s), the recruitment fluctuated greatly among years. This was different from that for

Management Zone 1, which showed an increase (Figs. 15 and 22). Such a difference perhaps resulted from the fact that the stock abundance of Management Zone 1 decreased since the start of the fishery (Fig. 14), while the stock abundance in Management Zone 2 increased in the first few years of the fishery before decreasing (Fig. 20). After 1993, recruitment started to decrease with SSB. Thus, in high levels of SSB, the sea urchin stock in management Zone 2 experienced compensation (i.e. recruitment increased with decreased SSB), and then depensation (i.e. recruitment decreased with decreased SSB).

Similar results were observed in the assessment using the data with adjusted landings (i.e. Data set 2A). The results for data set 2A were summarized in Table 6 and figures 23, 24, and 25. The results based on the adjusted landings tended to be more optimistic about the estimation of the current status of the fishery. However, the results were consistent with the results based on reported landings in that the stock had been severely overfished with low stock biomass, and the current exploitation rate was too high. The current recruitment was also low compared with historical levels.

## An evaluation of model goodness of fit

To assess the goodness of fit of the model to the data, we plotted the observed and predicted size composition of landings and CPUE values for both Management Zone 1 and Management Zone 2. For both zones, size compositions of landings predicted with the proposed model were close to size compositions of landings observed in the fishery (Figs 26, 27, 28, and 29), and this was particularly true for the large sizes of urchins. CPUEs predicted with the proposed model were higher than observed CPUEs early in the fishery, but lower than observed CPUEs in more recent years, indicating lack of fit for CPUE data. CPUEs are notorious for their lack of association with stock abundance (Hilborn and Walters 1992). Stock abundance of sea urchins had shown large decreases in both management zones. The changes in CPUE were, however, very small, indicating CPUE is not a reliable indicator of the Maine sea urchin stock abundance. Future stock assessments should include the abundance index estimated in the fishery-independent survey program. The changes in stock assessment after including the fishery-independent abundance index should be carefully evaluated to identify the possible impacts of the lack of a reliable abundance index on this assessment.

## A risk analysis of different management options (i.e. different catch levels)

We used the results based on adjusted landings for both Management Zones in assessing the impacts of different catch levels on the dynamics of sea urchin stocks in the next five years (i.e. from 2002 to 2006). For each zone, we made both deterministic and probabilistic projections on the impacts of different catch levels.

For the deterministic projections, the exploitable and total stock biomass of Management Zone 1 would decrease if landings were higher than 750 metric tons per year for the next 5 years (Fig. 30). Recruitment had a three-year time lag, which is why there is only one estimate for different catch levels from 2002 to 2004. The impacts of different landings on recruitment could only be detected after 2004. Similar to the total and exploitable stock biomass, recruitment would decrease if catch levels were over 750 metric tons per year for the next five years (Fig. 30). The deterministic analysis thus suggests that landings should be below 750 metric tons per year for the next five years in order to give the urchin stock of Management Zone 1 a chance to stop further declines in stock biomass.

For Management Zone 2, the deterministic analysis suggests that the exploitable and total stock biomass would stop decreasing if landings were below 1500 metric tons per year for the next five years (Fig. 31). Recruitment would also increase with such a landing level.

Using the posterior distributions of the key fishery parameters estimated using the Bayesian method, we conducted a risk analysis which provides us with the probability of some key fishery statistics/parameters at the end of the five-year period being higher or lower than their current values under different levels of landings. The three key fishery statistics we evaluated in this study are exploitable stock biomass, total stock biomass, and recruitment.

The results of risk analysis are summarized in figure 32 for Management Zone 1. The probability of the total stock biomass in 2006 being lower than that in 2002 was approximately 40%, 35%, 20%, 10%, and 5% for landings of 1000, 750, 500, 350, and 250 metric tons, respectively (Fig. 32). The probability of the exploitable stock biomass being lower than that in 2002 was approximately 40%, 35%, and 10% for landings of 1,000, 750, and 500 metric tons, respectively. When landings were below 500 metric tons, the chance of exploitable stock biomass in 2006 being lower than that in 2002 was minimal (Fig. 32). For recruitment, the probability of its value in 2006 being lower than that in 2002 was approximately 65%, 60%, 55%, 50%, and 50% for landings of 1000, 750, 500, 350, and 250 metric tons, respectively (Fig. 32). Thus, for Management Zone 1, if we used the result derived in the deterministic analysis, i.e. setting landings at 750 metric tons per year for the next five years, the chances of having the total biomass and exploitable stock biomass in 2006 higher than those in 2002 were both 65%, while the chance of recruitment in 2006 being higher than that in 2002 was 40%.

The results of risk analysis are summarized in figure 33 for Management Zone 2. The probability of the total stock biomass in 2006 being lower than that in 2002 was approximately 60%, 10%, 0%, and 0% for landings of 2000, 1500, 1250, and 1000 metric tons, respectively (Fig. 33). The probability of the exploitable stock biomass being lower than that in 2002 was approximately 60%, 5%, 0%, and 0% for landings of 2000, 1500, 1250, and 1000 metric tons, respectively (Fig. 33). For recruitment, the probability of its value in 2006 being lower than that in 2002 was approximately 90%, 85%, 75%, and 70% for landings of 2000, 1500, 1250, and 1000 metric tons, respectively (Fig. 33). Thus, for Management Zone 2, if we used the result derived in the deterministic analysis, i.e. setting landings at 1500 metric tons per year for the next five years, the chances of having the total biomass and exploitable stock biomass in 2006 higher than those in 2002 were 90% and 95%, respectively, while the chance of recruitment in 2006 being higher than that in 2002 was 15%.

The apparent discrepancy between recruitment and stock biomass in the risk analysis (Figs 32 and 33) might be for the following reason. The last year for which the recruitment was estimated with the proposed model was 2001, while the last year for which the stock biomass was estimated was 2002 (i.e. stock biomass is always estimated a year ahead because it is the biomass in the beginning of the year, prior to the removal of catch for the year). The projection of recruitment from 2002 to 2006 was made based on a functional stock-recruitment relationship estimated using the estimated SSB and recruitment from 1989 to 2001. To be consistent with the stochastic analysis of total and exploitable stock biomass, which used biomass in 2002 as the reference for the comparison in the projection, we used recruitment in 2002 as the reference for the comparison in the risk analysis, which might be less reliable than that for stock biomass. If we used recruitment in 2001, which is an estimate (but not a projected value as in 2002), as the reference in the risk analysis, the results for recruitment might be consistent with those for the stock biomass.

In summary, the risk analysis suggests that 750 and 1500 metric tons per year (after adjusting for underreporting) for the next five years (beginning in the 2002-03 fishing season) for sea urchins in Management Zones 1 and 2, respectively, would provide a chance for the two stocks to stop further decreasing their stock biomass. A more aggressive management (i.e. landings are smaller than 750 and 1500 for Zones 1 and 2, respectively) is, however, needed to rebuild the Maine sea urchin stock. This rebuilding plan is, however, based on the assumption that the population dynamics of Maine sea urchins will behave in the same way as they have in the past. Unfavorable changes in the ecosystem (e.g. loss of habitats and increased natural mortality due to increased predator abundance in the ecosystem) will call for more aggressive management measures to reduce landings. Any favorable changes in the ecosystem will, however, increase the chance of success in stopping further decrease in Maine sea urchin abundance if the recommended landing levels are implemented. This rebuilding plan may also need to be revised when results from the fisheries-independent survey are incorporated into the assessment model.

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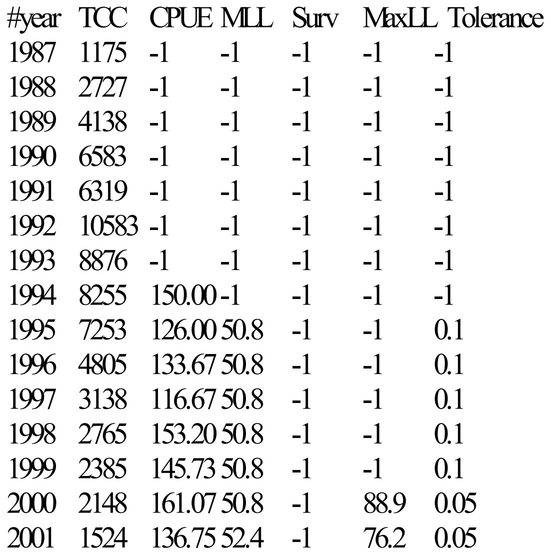
Table 1. Priors used for some key parameters in the Bayesian stock assessment. Explanations of the parameters can be found in Appendix 1. The same priors were used for both Management Zone 1 and Management Zone 2. na = not applicable. The lower and upper boundaries were determined based on sea urchin biology to include possible values for a particular parameter.

| | Boundaries | | | | | |
|---|---|---|---|---|---|---|
| Parameters | Lower | Upper | Distribution | Mean | CV | Initial values |
| M | 0.01 | 0.5 | log-normal | 0.1 | 0.1 | 0.2 |
| Eps | -2.3 | 2.3 | normal | 0 | 0.4 | 0 |
| rho | 0.00001 | 0.99 | uniform | na | na | 0.0001 |
| Rcoff | 5 | 50 | uniform | na | na | 15 |

Table 2. The "true" catchability and natural mortality used in simulating the sea urchin fishery and catchability and natural mortality estimated using the proposed assessment model.

| Recruitment | True | | Estimates | |
|---|---|---|---|---|
| | q | M | q | M |
| Fluctuated | exp(-10) | 0.1462 | exp(-10.3096) | 0.1470 |
| Decreasing | exp(-10) | 0.1462 | exp(-10.2251) | 0.1504 |
| Increasing | exp(-10) | 0.1462 | exp(-10.2640) | 0.1477 |
| Constant | exp(-10) | 0.1462 | exp(-10.3279) | 0.1497 |

Table 3. Fishery statistics for Zone 1 used in the assessment. Year = the year in which the fall-winter fishing season began. TCC = total commercial catch during that fishing season; CPUE = catch per unit of effort; MLL = Minimum legal size; Surv = survey abundance index; MaxLL = maximum legal size; and Tolerance = tolerance to the sublegal urchins in landings. The value of -1 indicates no observation. The TCC values in the upper table (i.e. Data set 1) are the reported landings of Management Zone 1 in the Maine sea urchin fishery. The TCC values in the lower table (i.e. Data set 1A) are the landings of Management Zone 1 adjusted for estimated underreporting.



| #year | TCC | CPUE | MLL | Surv | MaxLL | Tolerance |
|---|---|---|---|---|---|---|
| 1987 | 1175 | -1 | -1 | -1 | -1 | -1 |
| 1988 | 2727 | -1 | -1 | -1 | -1 | -1 |
| 1989 | 4138 | -1 | -1 | -1 | -1 | -1 |
| 1990 | 6583 | -1 | -1 | -1 | -1 | -1 |
| 1991 | 6319 | -1 | -1 | -1 | -1 | -1 |
| 1992 | 10583 | -1 | -1 | -1 | -1 | -1 |
| 1993 | 8876 | -1 | -1 | -1 | -1 | -1 |
| 1994 | 8255 | 150.00 | -1 | -1 | -1 | -1 |
| 1995 | 7253 | 126.00 | 50.8 | -1 | -1 | 0.1 |
| 1996 | 4805 | 133.67 | 50.8 | -1 | -1 | 0.1 |
| 1997 | 3138 | 116.67 | 50.8 | -1 | -1 | 0.1 |
| 1998 | 2765 | 153.20 | 50.8 | -1 | -1 | 0.1 |
| 1999 | 2385 | 145.73 | 50.8 | -1 | -1 | 0.1 |
| 2000 | 2148 | 161.07 | 50.8 | -1 | 88.9 | 0.05 |
| 2001 | 1524 | 136.75 | 52.4 | -1 | 76.2 | 0.05 |

| #year | TCC | CPUE | MLL | Surv | MaxLL | Tolerance |
|---|---|---|---|---|---|---|
| 1987 | 1468 | -1 | -1 | -1 | -1 | -1 |
| 1988 | 3409 | -1 | -1 | -1 | -1 | -1 |
| 1989 | 5173 | -1 | -1 | -1 | -1 | -1 |
| 1990 | 7779 | -1 | -1 | -1 | -1 | -1 |
| 1991 | 7899 | -1 | -1 | -1 | -1 | -1 |
| 1992 | 13228 | -1 | -1 | -1 | -1 | -1 |
| 1993 | 11095 | -1 | -1 | -1 | -1 | -1 |
| 1994 | 10289 | 150.00 | -1 | -1 | -1 | -1 |
| 1995 | 9066 | 126.00 | 50.8 | -1 | -1 | 0.1 |
| 1996 | 6006 | 133.67 | 50.8 | -1 | -1 | 0.1 |
| 1997 | 3766 | 116.67 | 50.8 | -1 | -1 | 0.1 |
| 1998 | 3180 | 153.20 | 50.8 | -1 | -1 | 0.1 |
| 1999 | 2862 | 145.73 | 50.8 | -1 | -1 | 0.1 |
| 2000 | 2523 | 161.07 | 50.8 | -1 | 88.9 | 0.05 |
| 2001 | 1676 | 136.75 | 52.4 | -1 | 76.2 | 0.05 |

Table 4. Fishery statistics for Zone 2 used in the assessment. Year = the year in which the fall-winter fishing season began. TCC = total commercial catch during that fishing season; CPUE = catch per unit of effort; MLL = Minimum legal size; Surv = survey abundance index; MaxLL = maximum legal size; and Tolerance = tolerance to the sublegal urchins in landings. The value of -1 indicates no observation. The TCC values in the upper table (i.e. Data set 2) are the reported landings of Management Zone 2 in the Maine sea urchin fishery. The TCC values in the lower table (i.e. Data set 2A) are the landings of Management Zone 2 adjusted for estimated underreporting.

| #year | TCC | CPUE | MLL | Surv | MaxLL | Tolerance |
|---|---|---|---|---|---|---|
| 1987 | 674 | -1 | -1 | -1 | -1 | -1 |
| 1988 | 666 | -1 | -1 | -1 | -1 | -1 |
| 1989 | 628 | -1 | -1 | -1 | -1 | -1 |
| 1990 | 1355 | -1 | -1 | -1 | -1 | -1 |
| 1991 | 2619 | -1 | -1 | -1 | -1 | -1 |
| 1992 | 7239 | -1 | -1 | -1 | -1 | -1 |
| 1993 | 8283 | -1 | -1 | -1 | -1 | -1 |
| 1994 | 8590 | 219.67 | -1 | -1 | -1 | -1 |
| 1995 | 6474 | 208.00 | 50.8 | -1 | -1 | 0.1 |
| 1996 | 6016 | 203.52 | 50.8 | -1 | -1 | 0.1 |
| 1997 | 4550 | 188.50 | 50.8 | -1 | -1 | 0.1 |
| 1998 | 4811 | 187.86 | 50.8 | -1 | -1 | 0.1 |
| 1999 | 3991 | 175.36 | 50.8 | -1 | -1 | 0.1 |
| 2000 | 3213 | 151.67 | 50.8 | -1 | 88.9 | 0.05 |
| 2001 | 2037 | 130.20 | 52.4 | -1 | 76.2 | 0.05 |

| #year | TCC | CPUE | MLL | Surv | MaxLL | Tolerance |
|---|---|---|---|---|---|---|
| 1987 | 842 | -1 | -1 | -1 | -1 | -1 |
| 1988 | 832 | -1 | -1 | -1 | -1 | -1 |
| 1989 | 785 | -1 | -1 | -1 | -1 | -1 |
| 1990 | 1602 | -1 | -1 | -1 | -1 | -1 |
| 1991 | 3274 | -1 | -1 | -1 | -1 | -1 |
| 1992 | 9048 | -1 | -1 | -1 | -1 | -1 |
| 1993 | 10354 | -1 | -1 | -1 | -1 | -1 |
| 1994 | 10707 | 219.67 | -1 | -1 | -1 | -1 |
| 1995 | 8093 | 208.00 | 50.8 | -1 | -1 | 0.1 |
| 1996 | 7520 | 203.52 | 50.8 | -1 | -1 | 0.1 |
| 1997 | 5459 | 188.50 | 50.8 | -1 | -1 | 0.1 |
| 1998 | 5533 | 187.86 | 50.8 | -1 | -1 | 0.1 |
| 1999 | 4789 | 175.36 | 50.8 | -1 | -1 | 0.1 |
| 2000 | 3775 | 151.67 | 50.8 | -1 | 88.9 | 0.05 |
| 2001 | 2241 | 130.20 | 52.4 | -1 | 76.2 | 0.05 |

Table 5. Summary of the key parameters estimated for Management Zone 1 of the Maine sea urchin fishery using the proposed stock assessment model, with confidence intervals. The table labeled Zone 1 contains the results derived for data with recorded landings, and the table labeled Zone 1A has the results derived for data with landings adjusted for underreporting in the fishery. All the data were provided by the Maine DMR.

### Zone 1

| Parameter | Median | upper 5% | lower 5% |
|---|---|---|---|
| M | 0.162 | 0.184 | 0.142 |
| Biomass 1987 | 33765 | 39724 | 28434 |
| Exploitable B 2002 | 3134 | 6489 | 906 |
| Total B 2002 | 5641 | 11010 | 2522 |
| Recruitment 2001 | 571 | 1077 | 344 |
| EB2002/B1987 | 0.092 | 0.180 | 0.029 |
| TB2002/B1987 | 0.167 | 0.302 | 0.079 |
| MSY | 1842 | 2408 | 1432 |
| Bmsy | 12859 | 15569 | 10525 |
| F0.1 | 0.155 | 0.185 | 0.135 |
| E_rate 2001 | 0.390 | 0.834 | 0.214 |

### Zone 1a

| Parameter | Median | upper 5% | lower 5% |
|---|---|---|---|
| M | 0.161 | 0.183 | 0.142 |
| Biomass 1987 | 41115 | 47927 | 35109 |
| Exploitable B 2002 | 3902 | 7868 | 1067 |
| Total B 2002 | 7446 | 12906 | 3361 |
| Recruitment 2001 | 691 | 1175 | 407 |
| EB2002/B1987 | 0.094 | 0.180 | 0.028 |
| TB2002/B1987 | 0.180 | 0.298 | 0.087 |
| MSY | 2226 | 2875 | 1748 |
| Bmsy | 15570 | 18656 | 12949 |
| F0.1 | 0.155 | 0.180 | 0.135 |
| E_rate 2001 | 0.356 | 0.839 | 0.194 |

Table 6. Summary of the key parameters estimated for Management Zone 2 of the Maine sea urchin fishery using the proposed stock assessment model. The table labeled Zone 2 contains the results derived for data with recorded landings, and the table labeled Zone 2A has the results derived for data with landings adjusted for underreporting in the fishery. All the data were provided by the Maine DMR.

## Zone 2

| Parameter | Median | upper 5% | lower 5% |
|---|---|---|---|
| M | 0.173 | 0.198 | 0.152 |
| Biomass 1987 | 22618 | 27748 | 18433 |
| Exploitable B 200 | 2824 | 6125 | 1088 |
| Total B 2002 | 5180 | 9624 | 2545 |
| Recruitment 2001 | 840 | 1446 | 505 |
| EB2002/B1987 | 0.125 | 0.268 | 0.049 |
| TB2002/B1987 | 0.227 | 0.425 | 0.117 |
| MSY | 1196 | 1702 | 859 |
| Bmsy | 8012 | 10237 | 6217 |
| F0.1 | 0.160 | 0.190 | 0.145 |
| E_rate 2001 | 0.542 | 0.866 | 0.304 |

## Zone 2a

| Parameter | Median | upper 5% | lower 5% |
|---|---|---|---|
| M | 0.173 | 0.196 | 0.152 |
| Biomass 1987 | 28193 | 33917 | 22937 |
| Exploitable B 200 | 3364 | 7311 | 1106 |
| Total B 2002 | 7076 | 12742 | 3525 |
| Recruitment 2001 | 976 | 1626 | 570 |
| EB2002/B1987 | 0.119 | 0.256 | 0.041 |
| TB2002/B1987 | 0.250 | 0.451 | 0.128 |
| MSY | 1492 | 2053 | 1061 |
| Bmsy | 10020 | 12620 | 7735 |
| F0.1 | 0.160 | 0.185 | 0.145 |
| E_rate 2001 | 0.516 | 0.924 | 0.289 |

Figure 1. Management zones for the sea urchin fishery in the state of Maine.

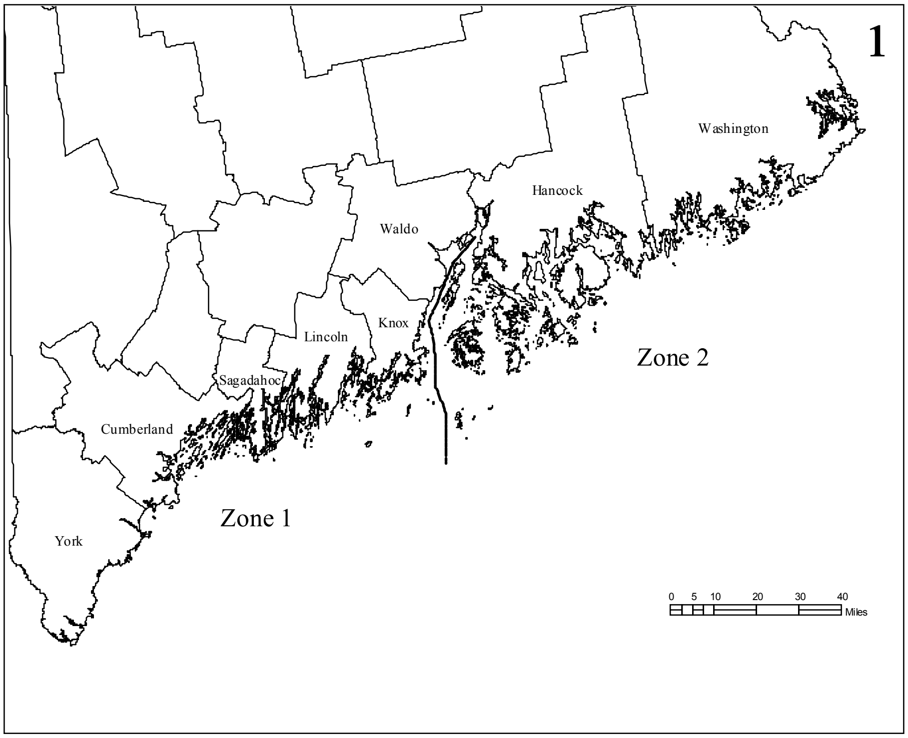


Figure 2. Landings and catch per unit of effort data observed in the Maine sea urchin fishery.

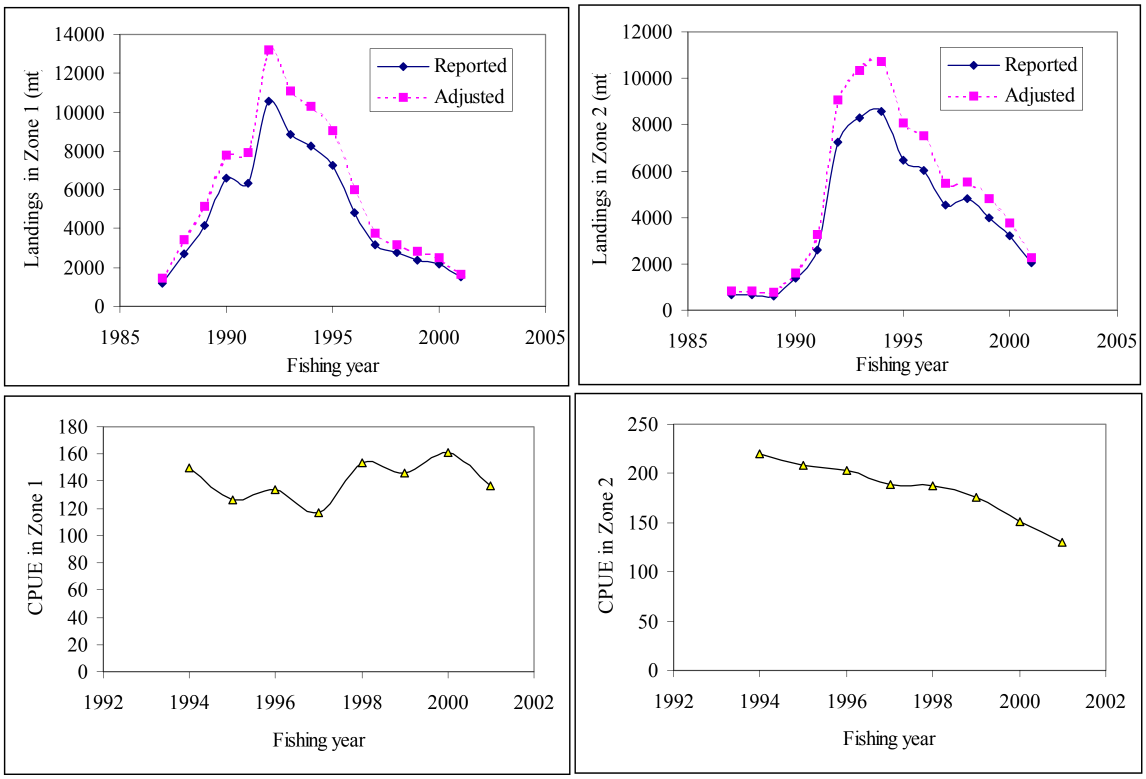


Figure 3. Size composition of landings in the Maine sea urchin fishery, Zone 1 above and Zone 2 below.

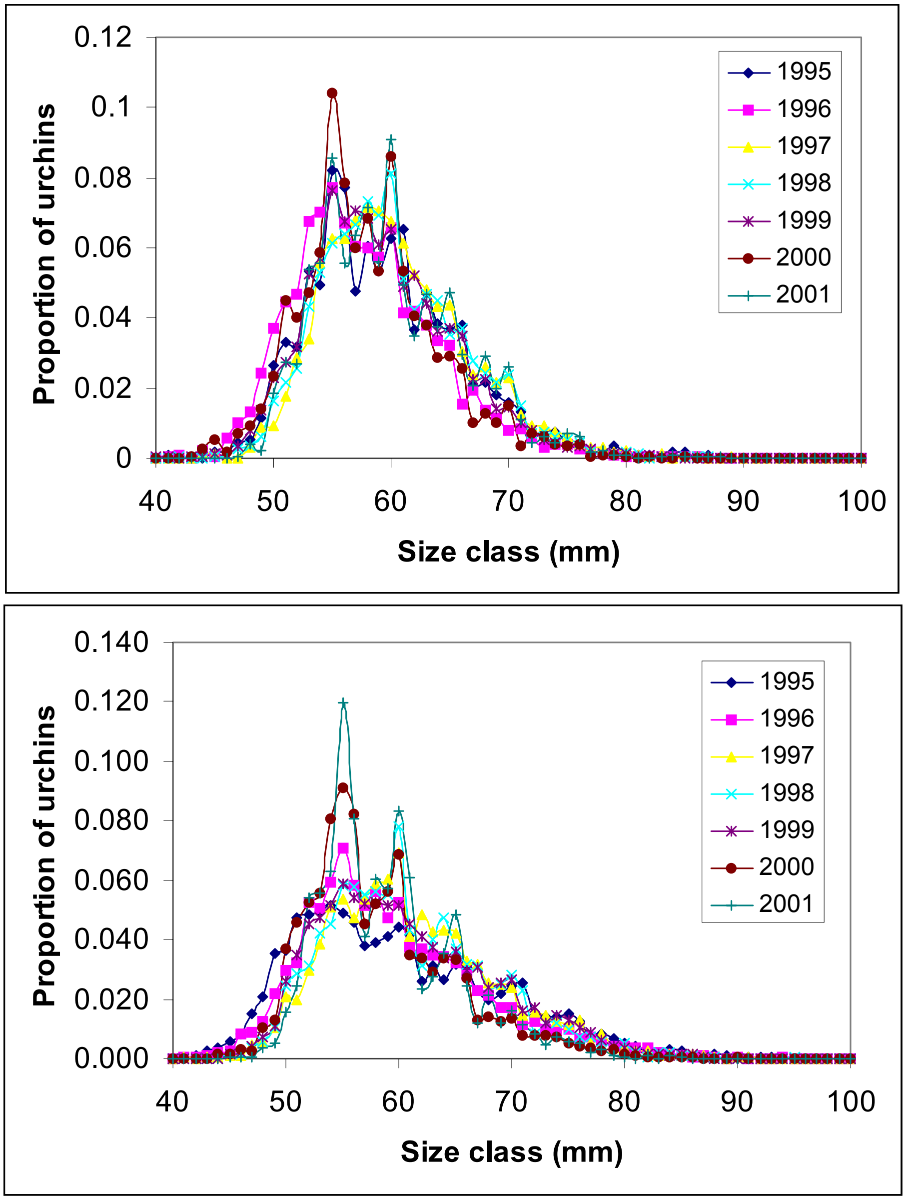
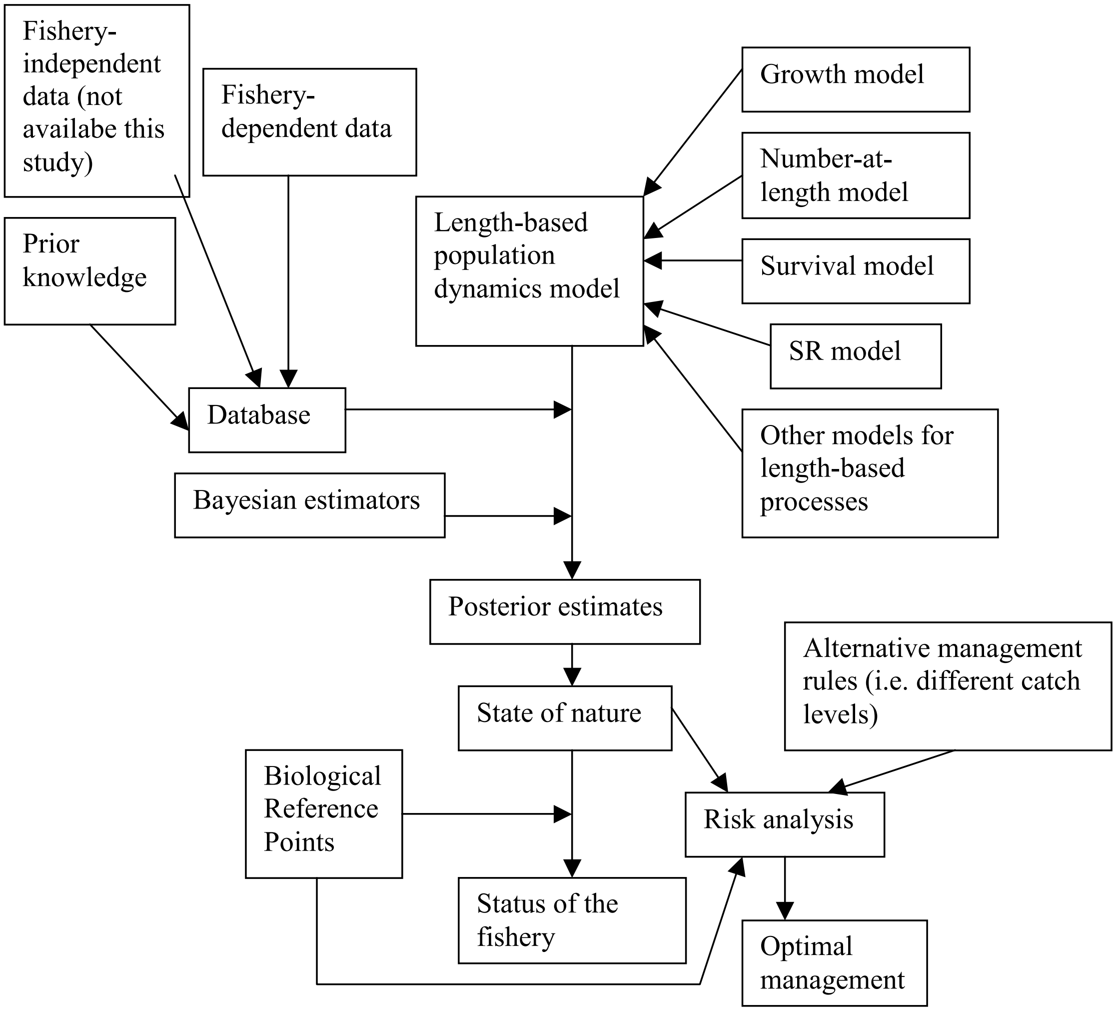


**Figure 4. Flow chart for the stock assessment framework developed in this study**



Flowchart of the Bayesian stock assessment framework

Figure. 5. Flow chart for the individual-based fisheries simulator.

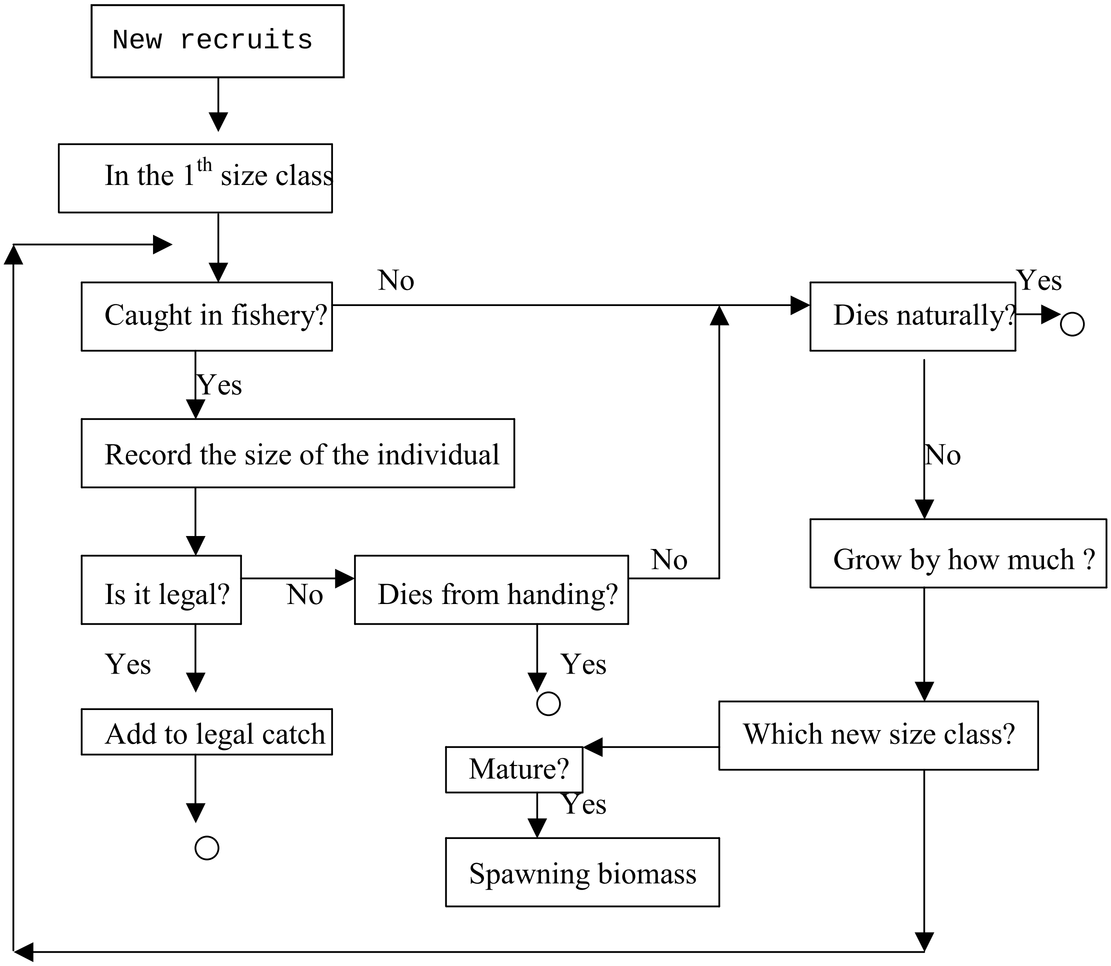


Figure 6. Key fishery statistics built-in in the simulated fishery (i.e. true) and predicted by the proposed stock assessment framework when recruits fluctuate among years.

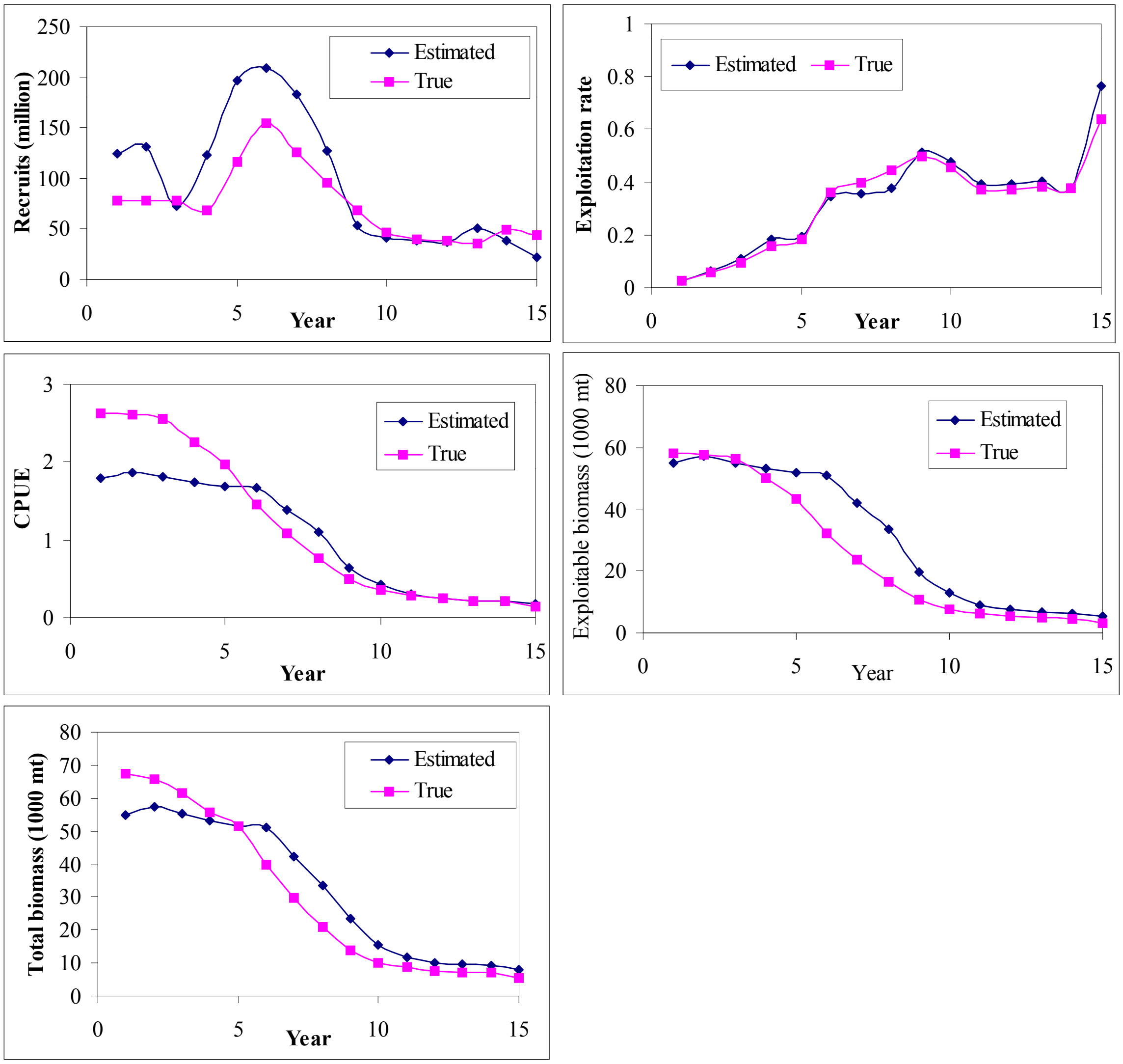


Figure 7. Key fishery statistics built-in in the simulated fishery (i.e. true) and predicted by the proposed stock assessment framework when recruits continue decreasing over time.

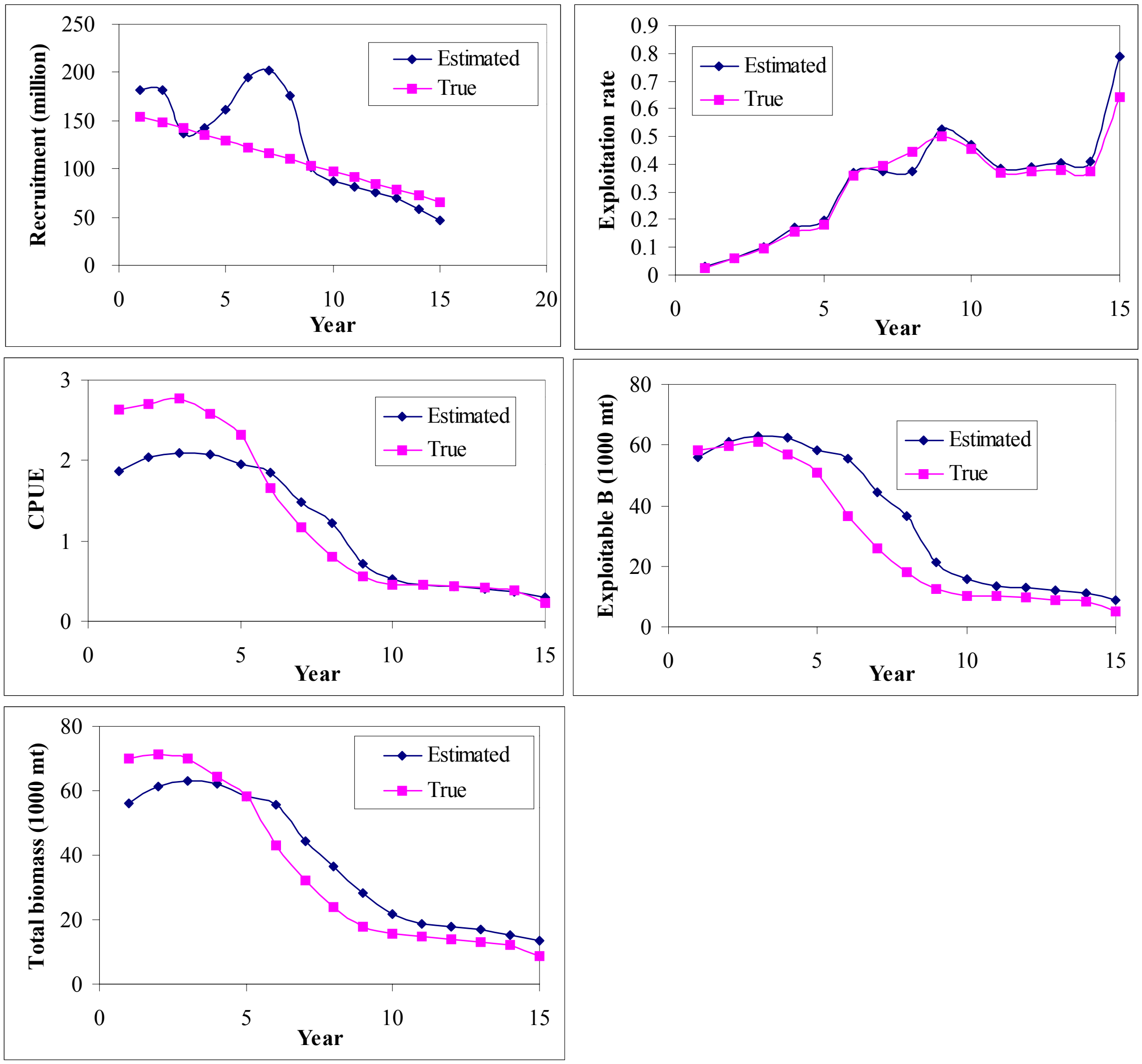


Figure 8. Key fishery statistics built-in in the simulated fishery (i.e. true) and predicted by the proposed stock assessment framework when recruits continue increasing over time.

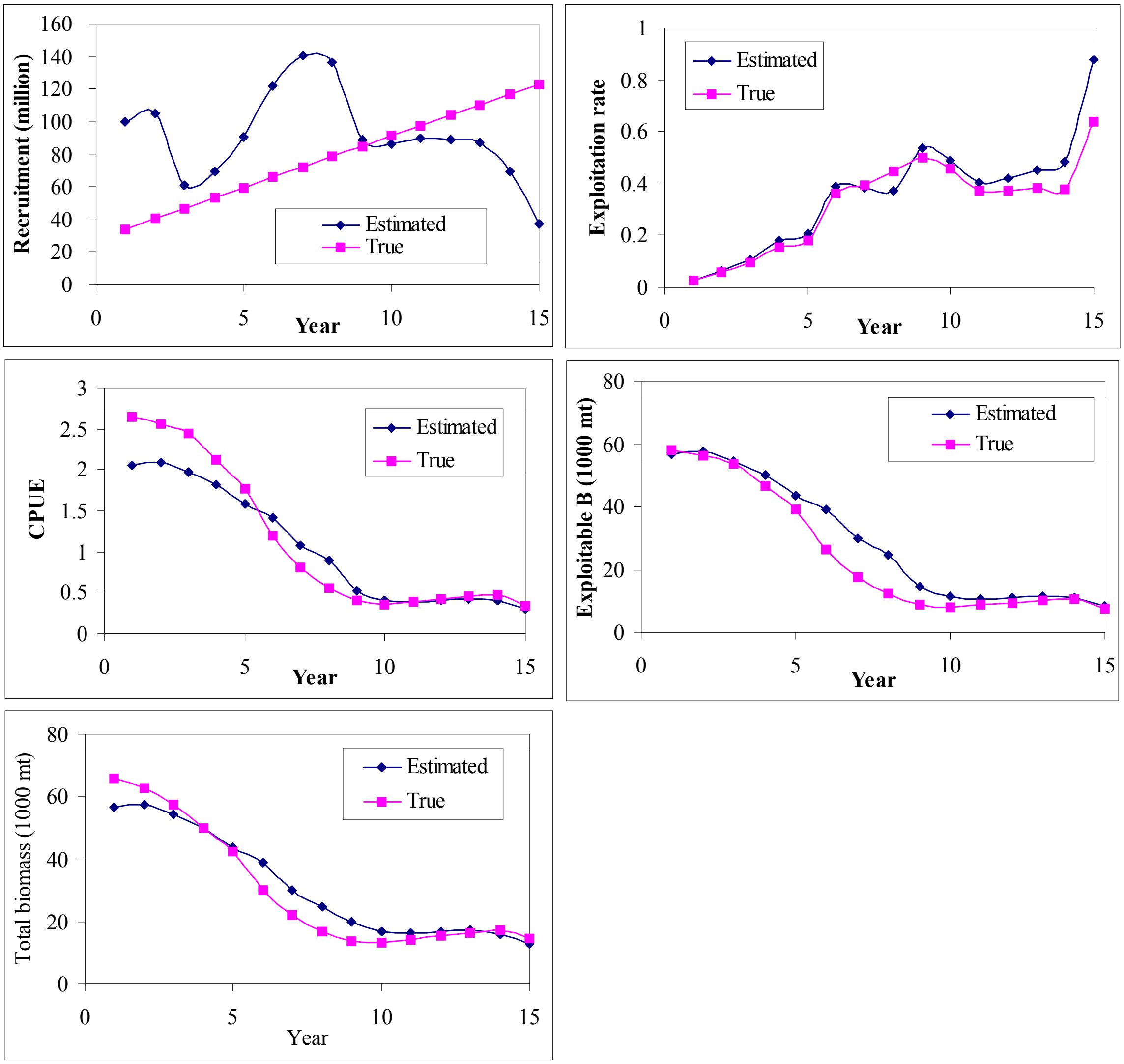


Figure 9. Key fishery statistics built-in in the simulated fishery (i.e. true) and predicted by the proposed stock assessment framework when recruits are constant over time.

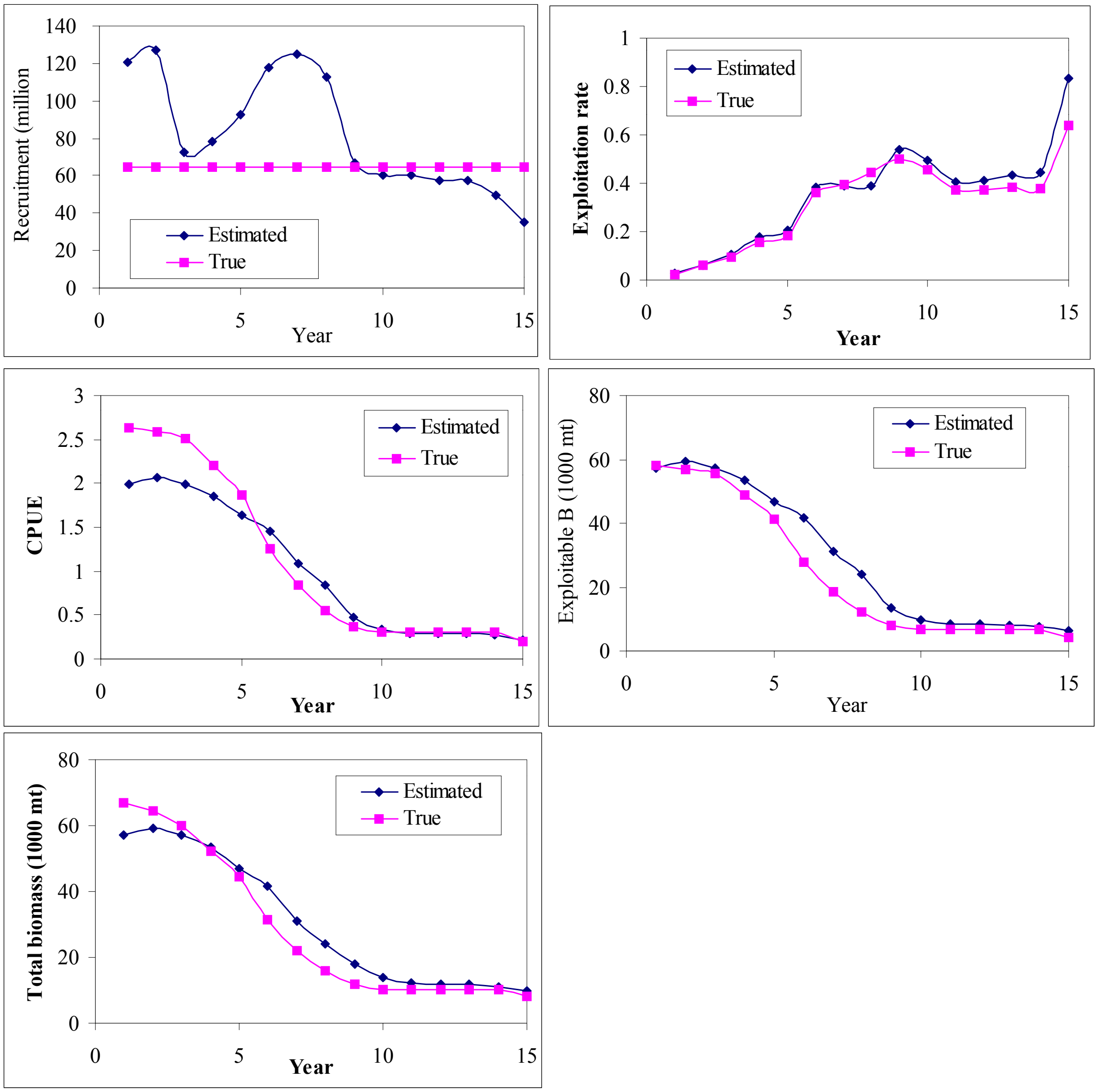


Figure 10. Differences in "true" size composition data and size composition data predicted using the proposed assessment model for the simulation scenario of fluctuating recruitment. The numbers from 1 to 15 listed on the right side of the figure correspond to the years 1987 to 2001, respectively.

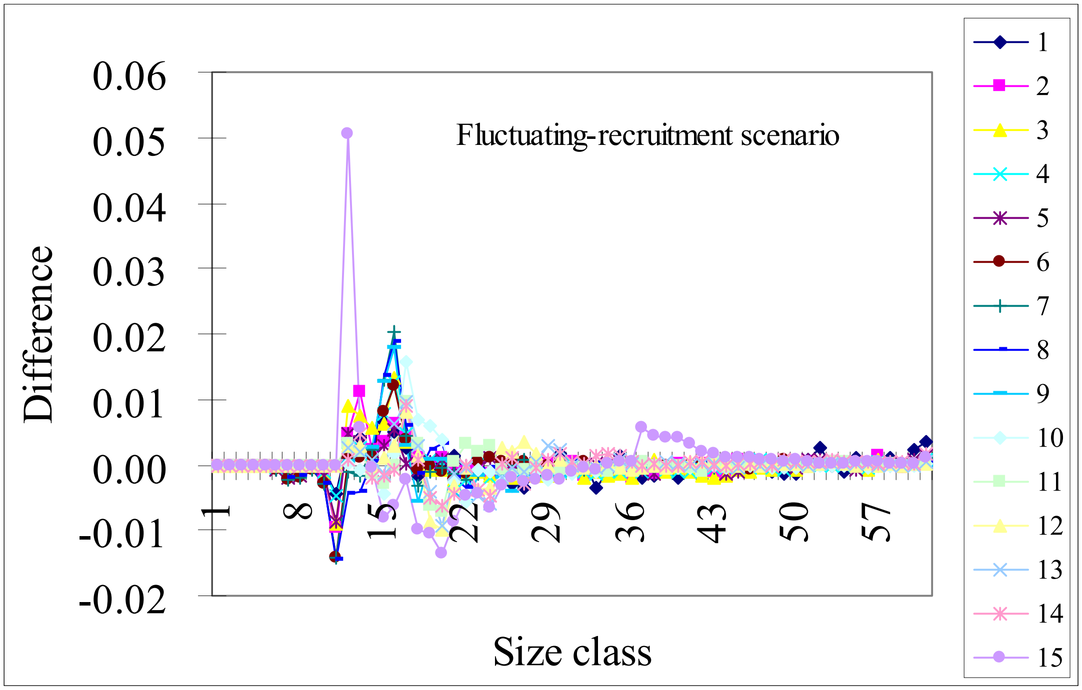


Figure 11. Differences in "true" size composition data and size composition data predicted using the proposed assessment model for the simulation scenario of decreasing recruitment. The numbers from 1 to 15 listed on the right side of the figure correspond to the years 1987 to 2001, respectively.

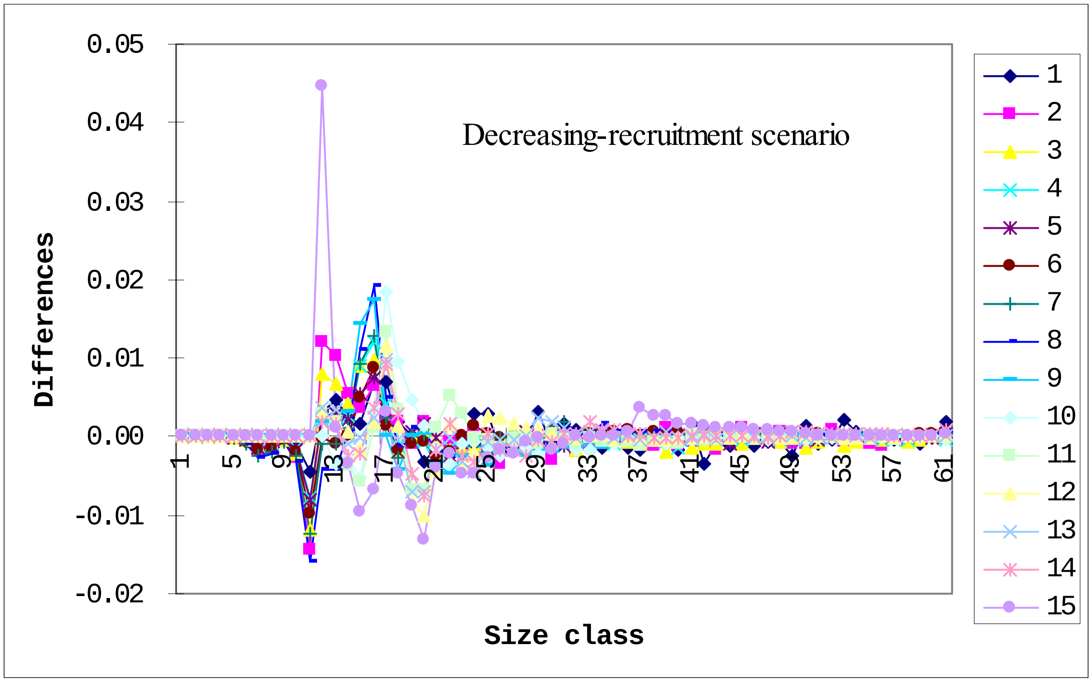


Figure 12. Differences in "true" size composition data and size composition data predicted using the proposed assessment model for the simulation scenario of increasing recruitment. The numbers from 1 to 15 listed on the right side of the figure correspond to the years 1987 to 2001, respectively.

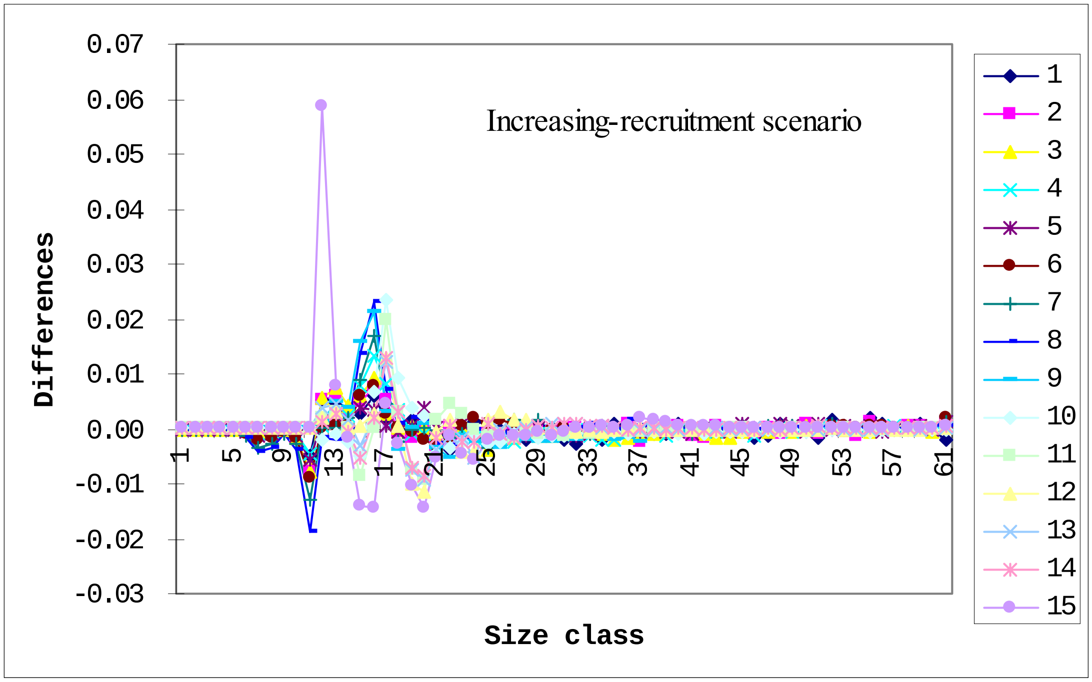


Figure 13. Differences in "true" size composition data and size composition data predicted using the proposed assessment model for the simulation scenario of constant recruitment. The numbers from 1 to 15 listed on the right side of the figure correspond to the years 1987 to 2001, respectively.

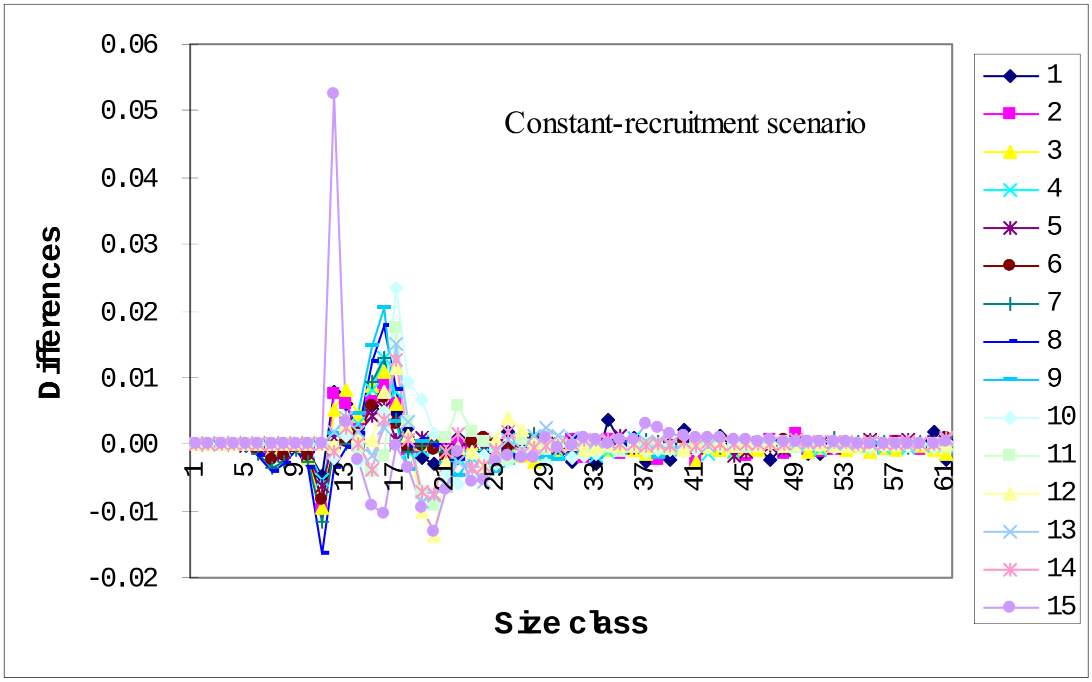


Figure 14. Total stock biomass, exploitable stock biomass, and recruits estimated by applying the proposed stock assessment model to data set 1 (i.e. reported landings) for Management Zone 1. Dashed lines are 5th and 95th percentiles of the Bayesian posterior estimates. The solid line is the median value of the Bayesian posterior estimates.

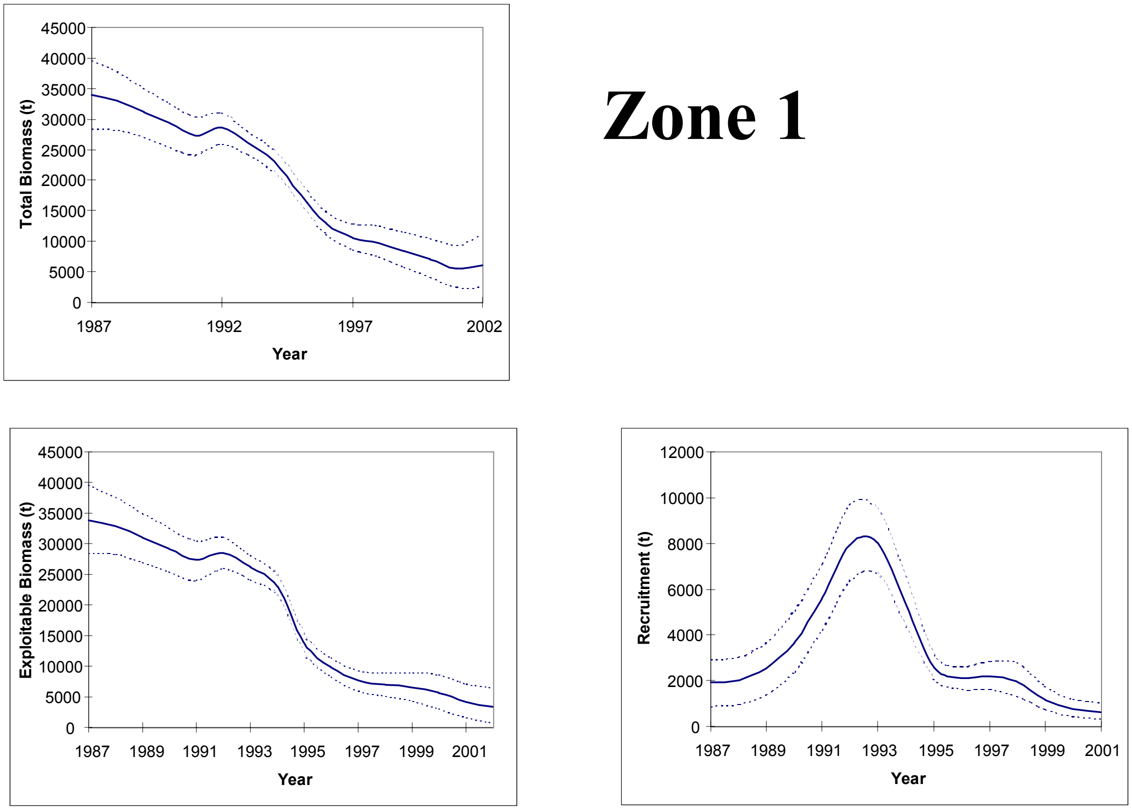


Figure 15. Posterior distributions of some key fishery parameters for Management Zone 1 using the reported landings. The parameters include biomass in 1987 (B1987; stock biomass in the beginning of the fishery); exploitable stock biomass in year 2002 which is the last year included in the assessment (EB2002); total biomass in 2002 (TB2002); depletion rate defined as a ratio of current stock biomass versus stock biomass in the beginning of the fishery (EB2002/B1987 for exploitable biomass and TB2002/B1987 for the total biomass); recruitment in 2001, natural mortality, exploitation rate in 2001 defined as the ratio of catch versus total biomass (Erate 2001), and maximum sustainable yield (MSY).

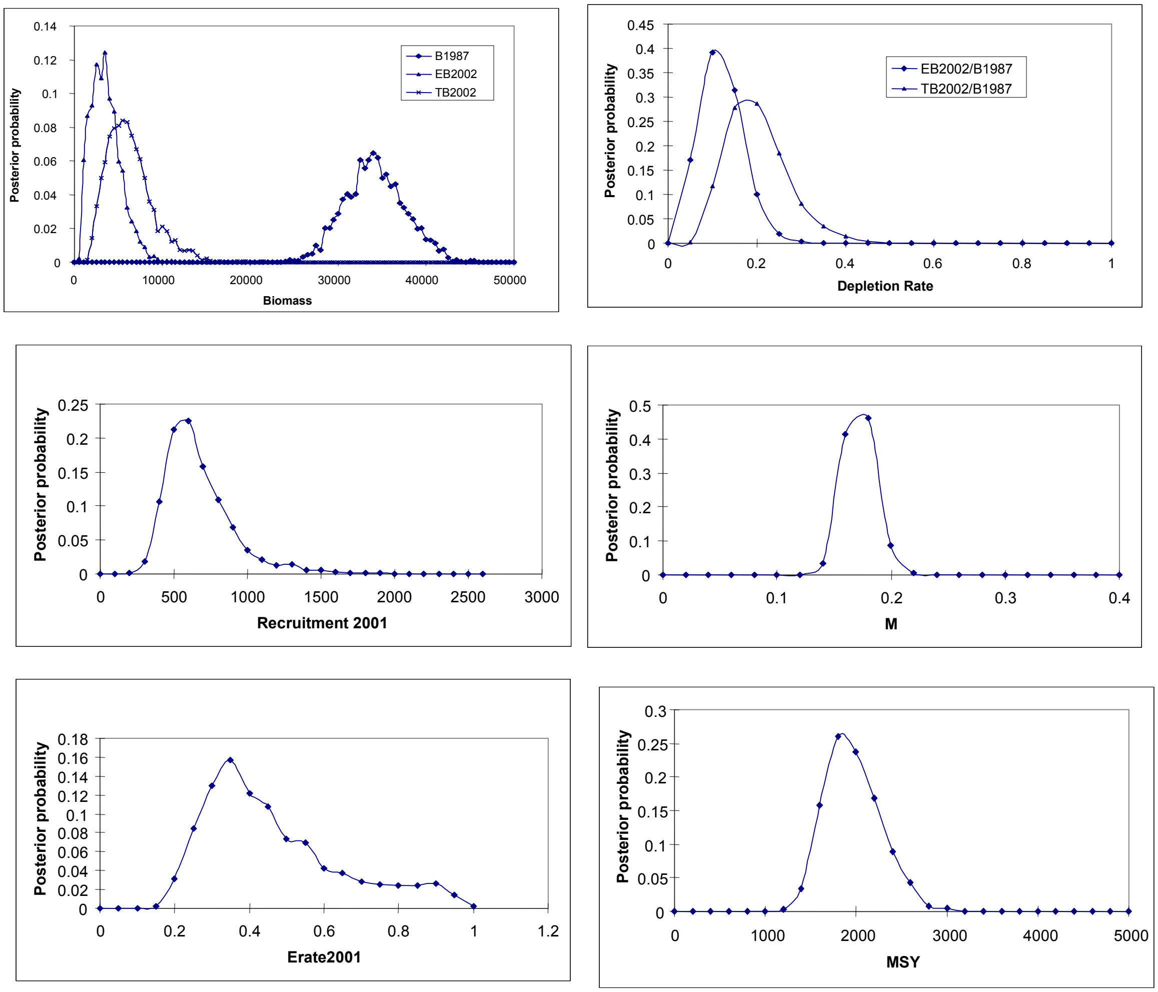


Figure 16. Plot of recruitment against its corresponding spawning stock biomass (SSB) for Management Zone 1. Numbers labeled are years when the recruits enter the fishery. Time lag between SSB and recruitment is assumed to be 3. The recruits are estimated using the reported landings (i.e. Data set 1).

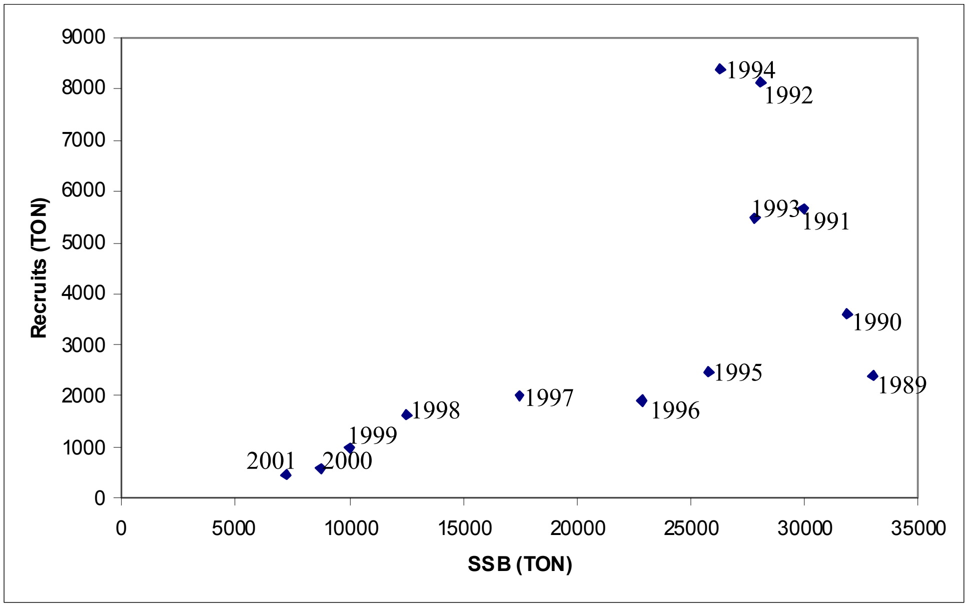


Figure 17. Total stock biomass, exploitable stock biomass, and recruits estimated by applying the proposed stock assessment model to data set 1A (i.e. landings adjusted from reported datafor underreporting) for Management Zone 1. Dashed lines are 5th and 95th percentiles of the Bayesian posterior estimates. The solid line is the median value of the Bayesian posterior estimates.

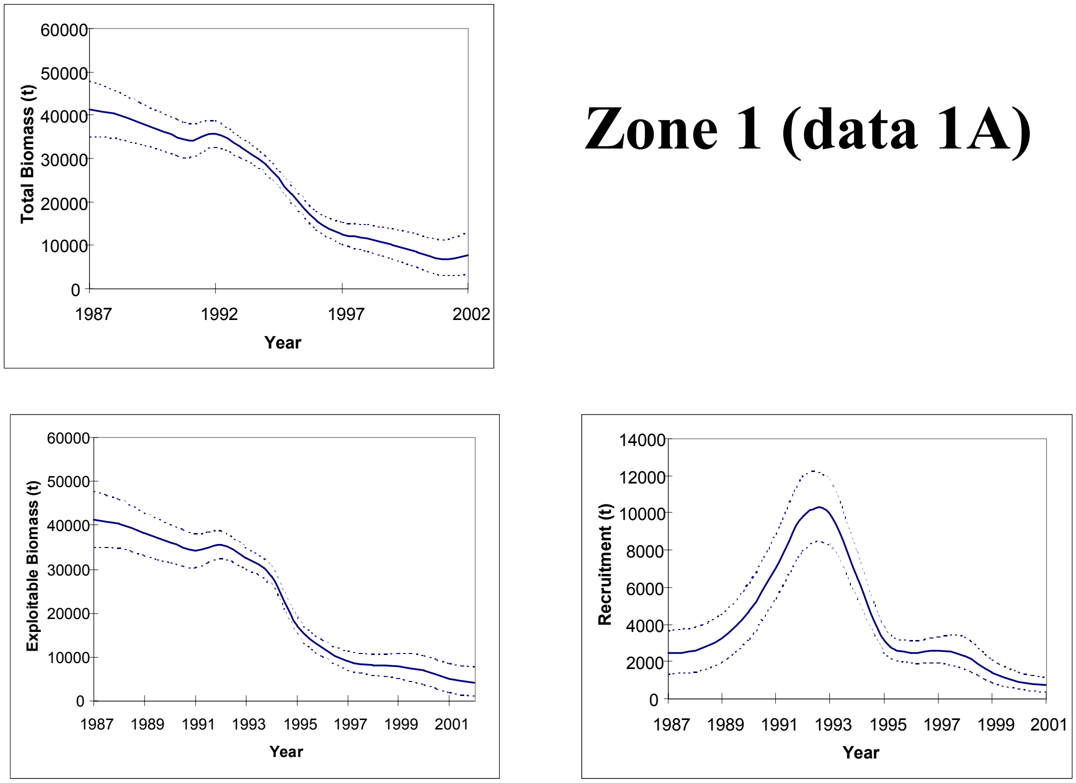


Figure 18. Posterior distributions of some key fishery parameters for Management Zone 1 using the adjusted landings (i.e. data set 1A). The parameters include biomass in 1987 (B1987; stock biomass in the beginning of the fishery); exploitable stock biomass in year 2002 which is the last year included in the assessment (EB2002); total biomass in 2002 (TB2002); depletion rate defined as a ratio of current stock biomass versus stock biomass in the beginning of the fishery (EB2002/B1987 for exploitable biomass and TB2002/B1987 for the total biomass); recruitment in 2001, natural mortality, exploitation rate in 2001 defined as the ratio of catch versus total biomass (Erate 2001), and maximum sustainable yield (MSY).

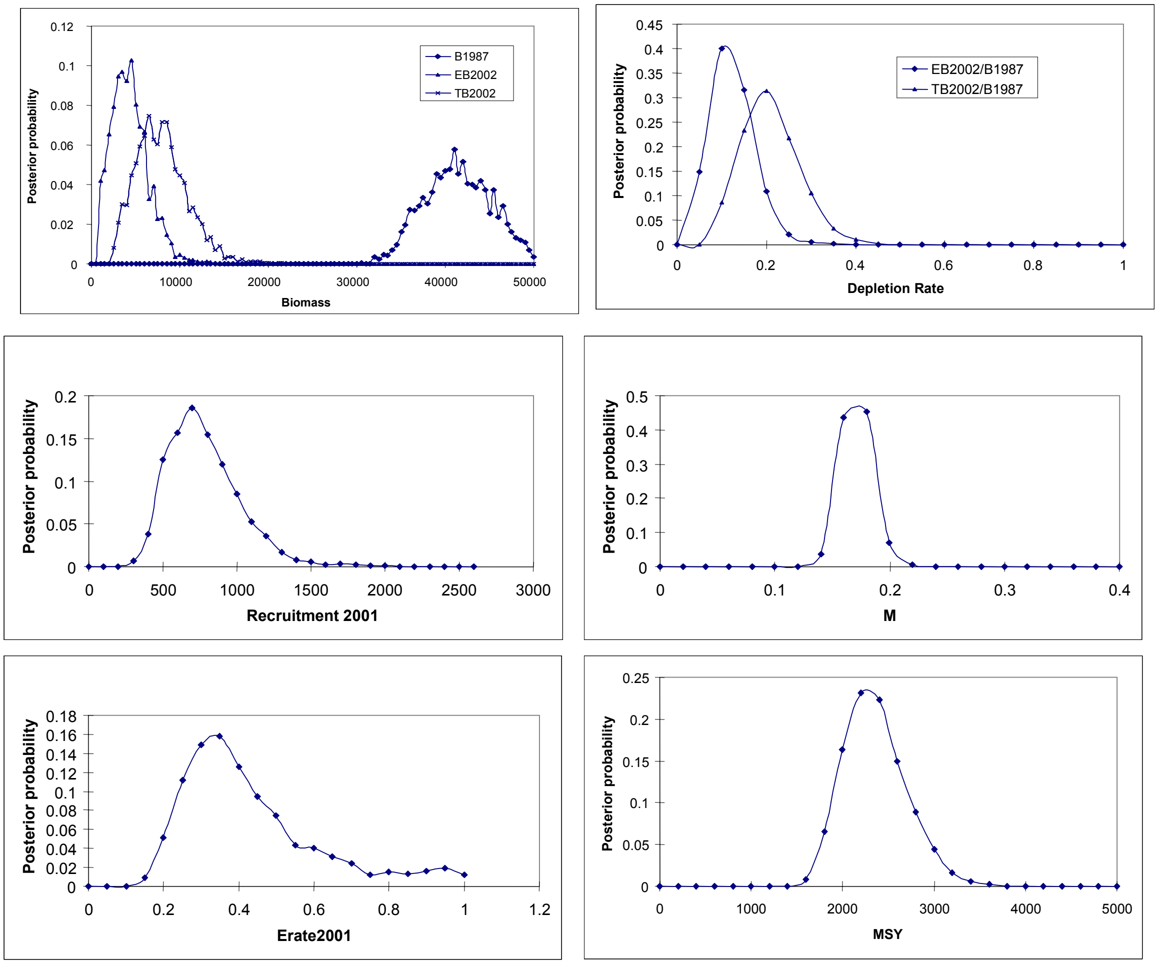


Figure 19. Plot of recruitment against its corresponding spawning stock biomass (SSB) for Management Zone 1. Numbers labeled are years when the recruits enter the fishery. Time lag between SSB and recruitment is assumed to be 3. The recruits are estimated using the adjusted landings (i.e. Data set 1A)

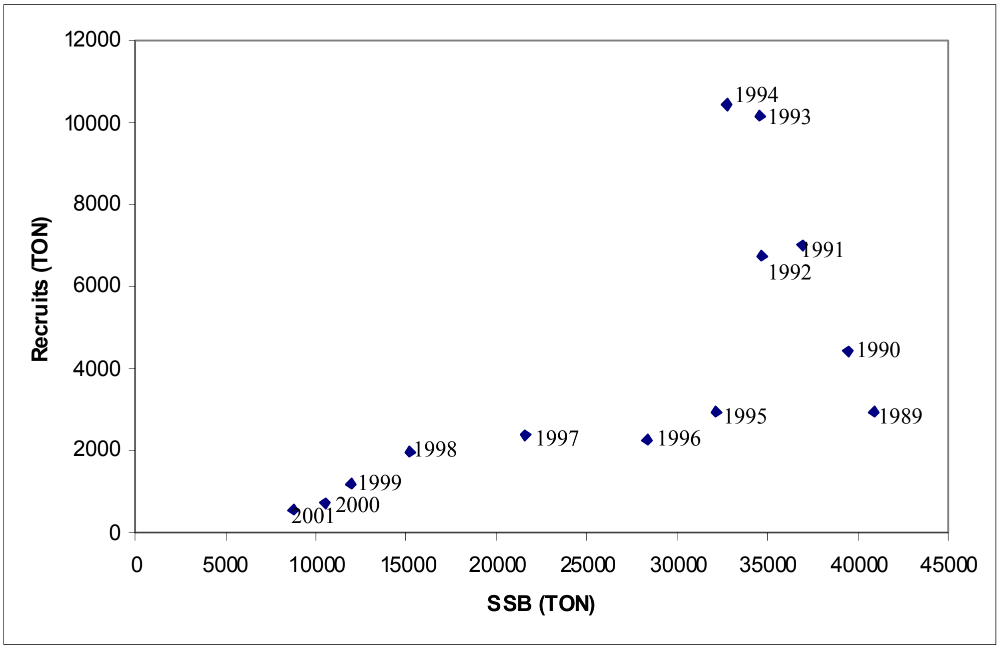


Figure 20. Total stock biomass, exploitable stock biomass, and recruits estimated by applying the proposed stock assessment model to data set 2 (i.e. reported landings) for Management Zone 2. Dashed lines are 5th and 95th percentiles of the Bayesian posterior estimates. The solid line is the median value of the Bayesian posterior estimates.

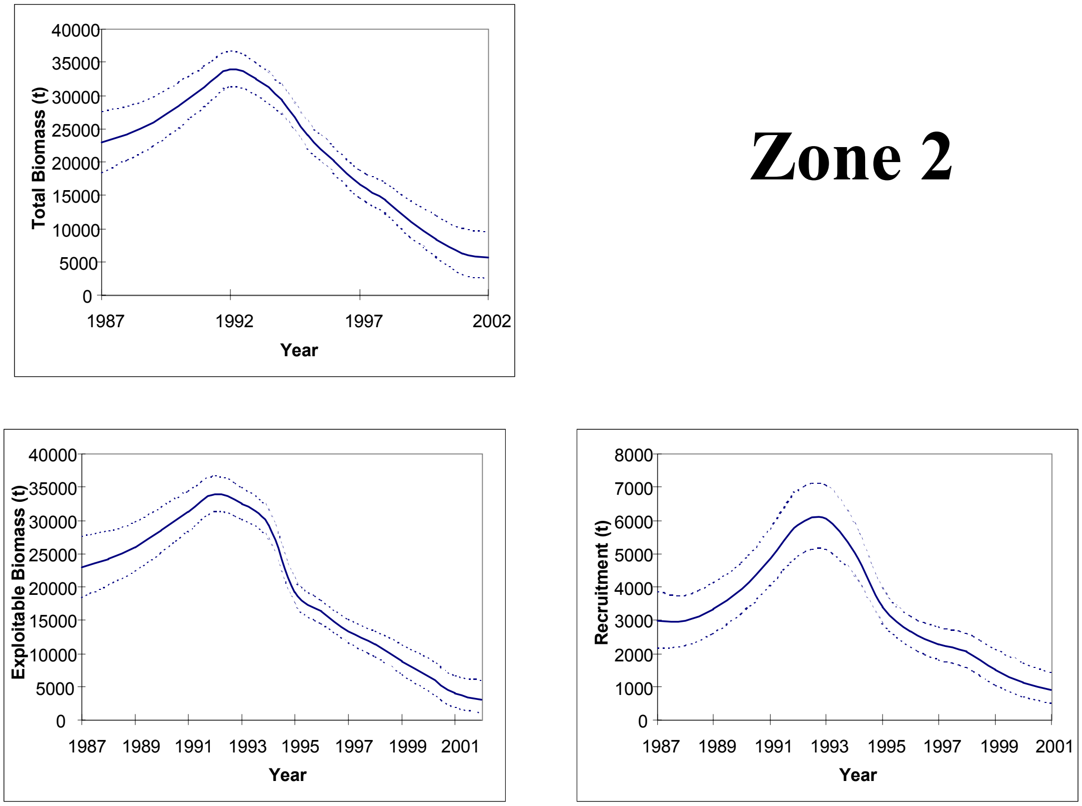


Figure 21. Posterior distributions of some key fishery parameters for Management Zone 2 using the reported landings. The parameters include biomass in 1987 (B1987; stock biomass in the beginning of the fishery); exploitable stock biomass in year 2002 which is the last year included in the assessment (EB2002); total biomass in 2002 (TB2002); depletion rate defined as a ratio of current stock biomass versus stock biomass in the beginning of the fishery (EB2002/B1987 for exploitable biomass and TB2002/B1987 for the total biomass); recruitment in 2001, natural mortality, exploitation rate in 2001 defined as the ratio of catch versus total biomass (Erate 2001), and maximum sustainable yield (MSY).

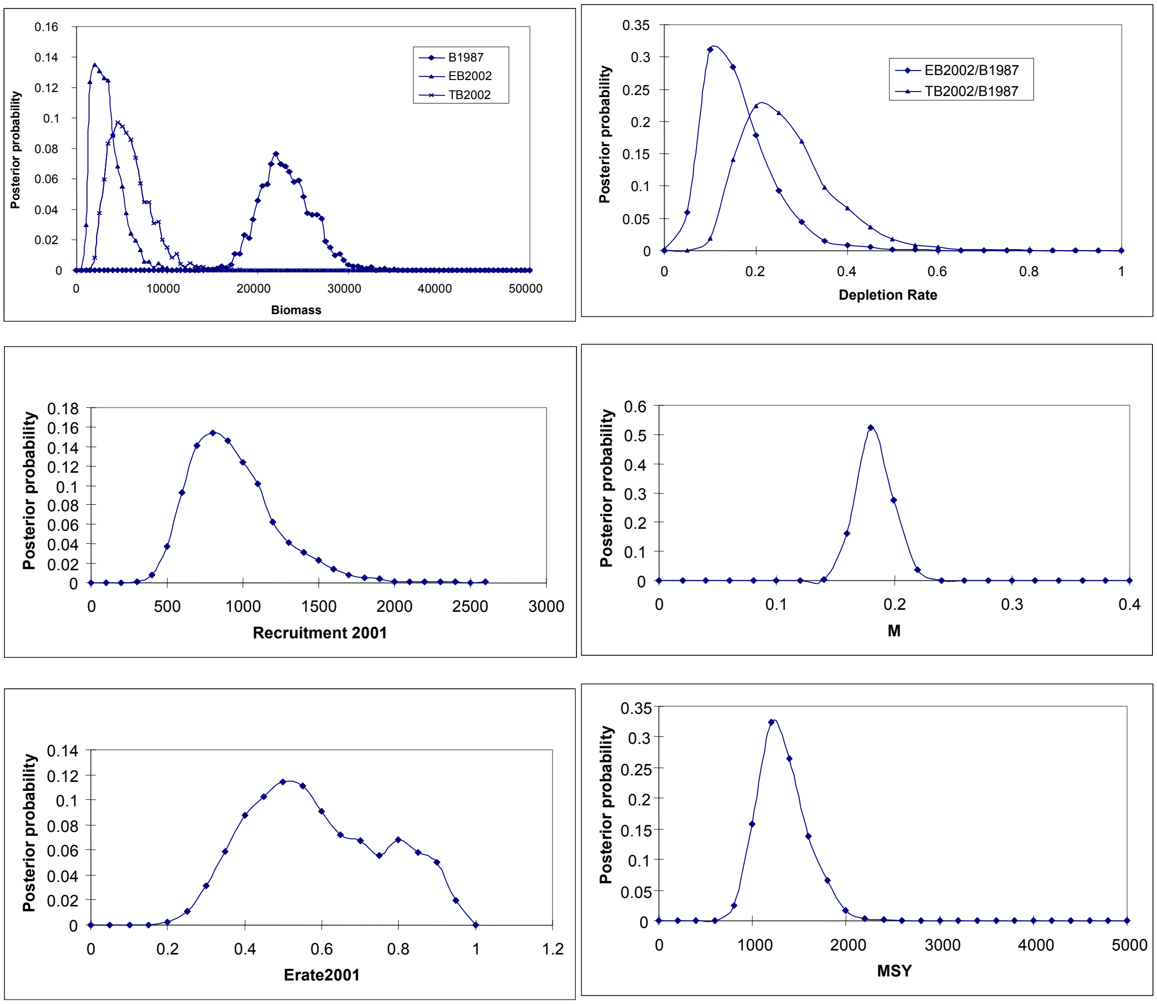


Figure 22. Plot of recruitment against its corresponding spawning stock biomass (SSB) for Management Zone 2. Numbers labeled are years when the recruits enter the fishery. Time lag between SSB and recruitment is assumed to be 3. The recruits are estimated using the reported landings (i.e. Data set 2).

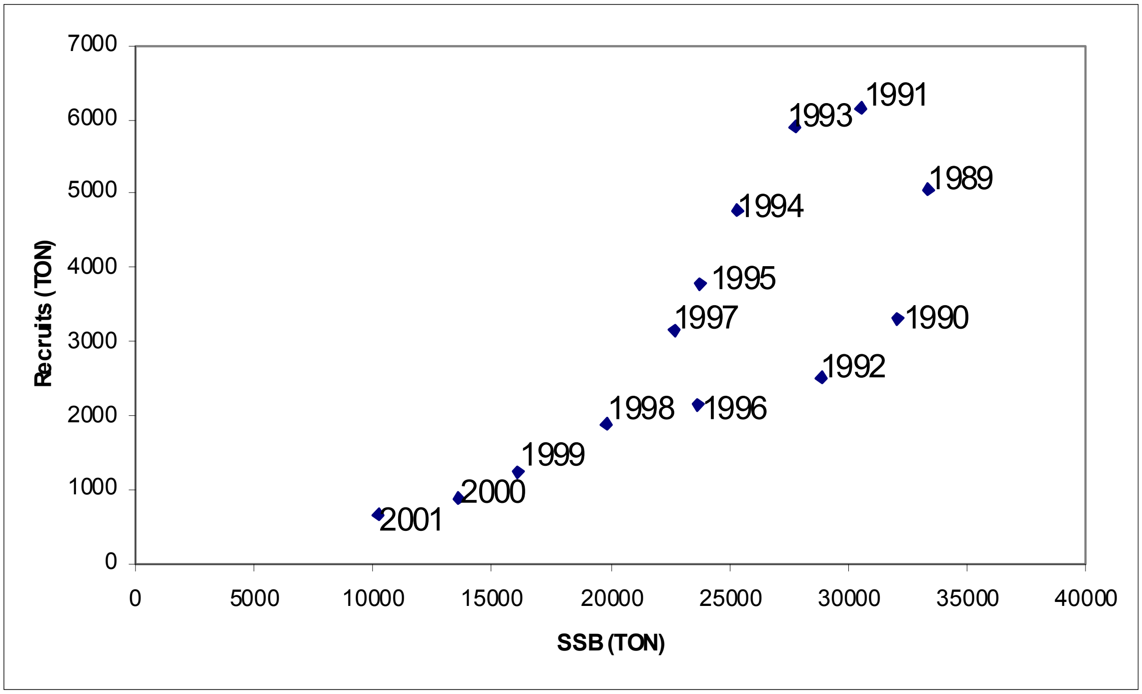


Figure 23. Total stock biomass, exploitable stock biomass, and recruits estimated by applying the proposed stock assessment model to data set 2A (i.e. landings adjusted from reported data to take account for underreporting) for Management Zone 2. Dashed lines are 5th and 95th percentiles of the Bayesian posterior estimates. The solid line is the median value of the Bayesian posterior estimates.

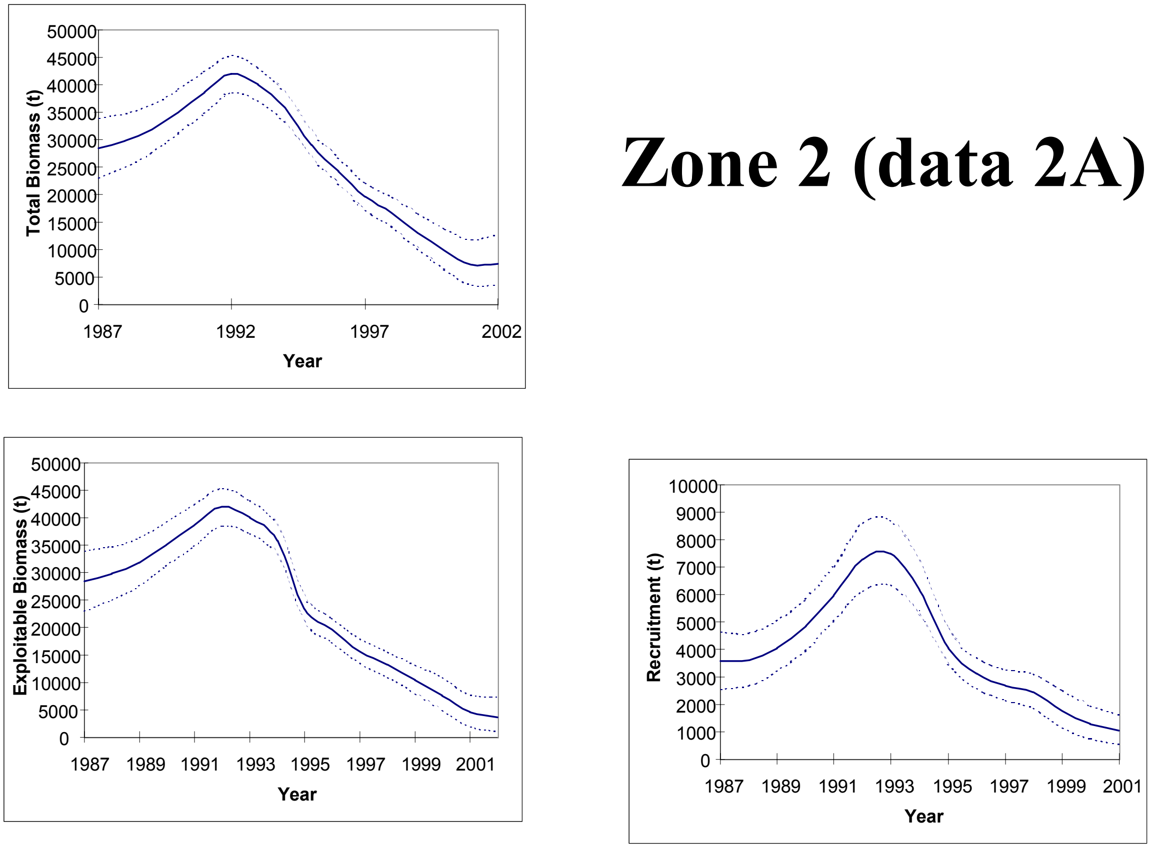


Figure 24. Posterior distributions of some key fishery parameters for Management Zone 2 using the adjusted landings. The parameters include biomass in 1987 (B1987; stock biomass in the beginning of the fishery); exploitable stock biomass in year 2002 which is the last year included in the assessment (EB2002); total biomass in 2002 (TB2002); depletion rate defined as a ratio of current stock biomass versus stock biomass in the beginning of the fishery (EB2002/B1987 for exploitable biomass and TB2002/B1987 for the total biomass); recruitment in 2001, natural mortality, exploitation rate in 2001 defined as the ratio of catch versus total biomass (Erate 2001), and maximum sustainable yield (MSY).

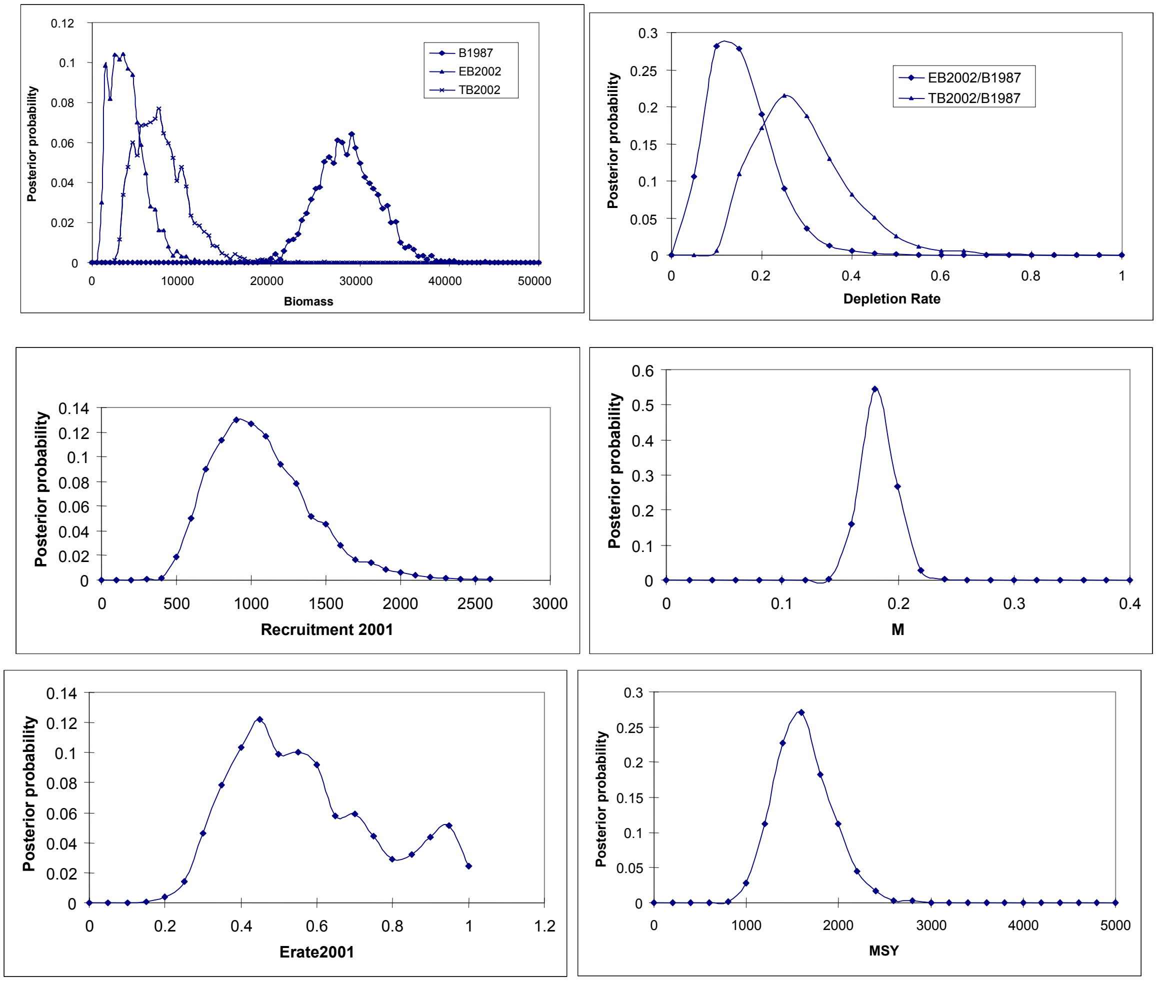


Figure 25. Plot of recruitment against its corresponding spawning stock biomass (SSB) for Management Zone 2. Numbers labeled are years when the recruits enter the fishery. Time lag between SSB and recruitment is assumed to be 3. The recruits are estimated using the adjusted landings (i.e. Data set 2A).

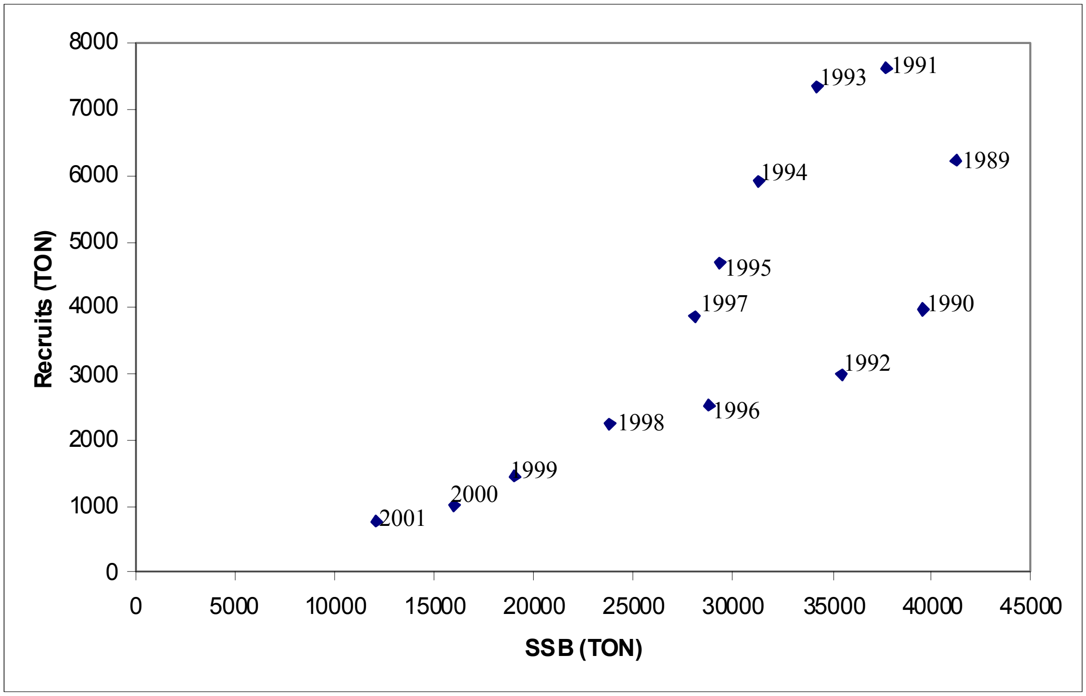


Figure 26. Size compositions of landings, and CPUEs observed in the fishery and predicted by the proposed assessment model.

## Observed and predicted for Zone 1

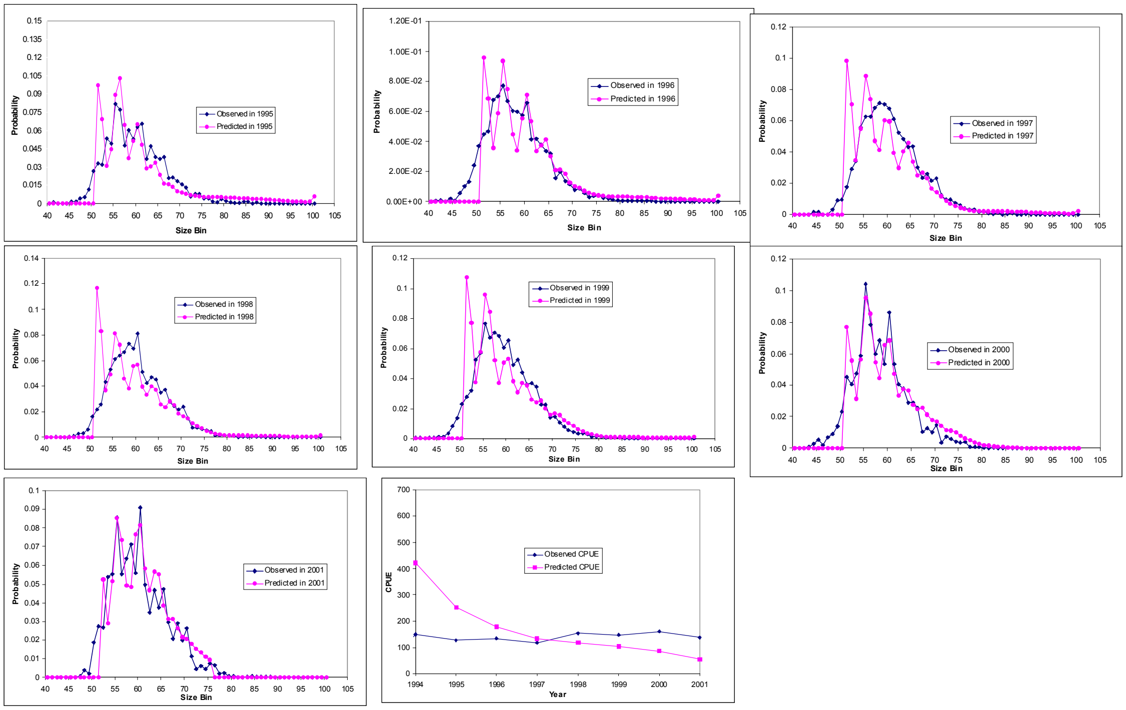


Figure 27. Size compositions of landings, and CPUEs observed in the fishery and predicted by the proposed assessment model.

## Observed and predicted for Zone 1(data A)

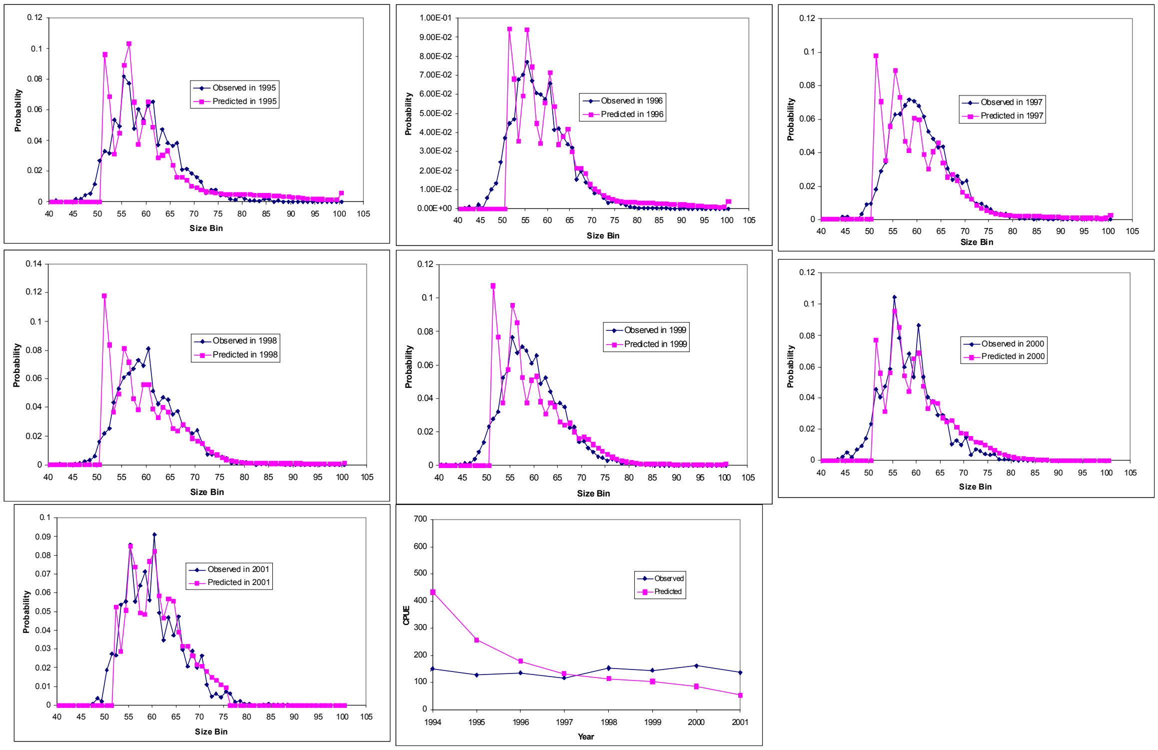
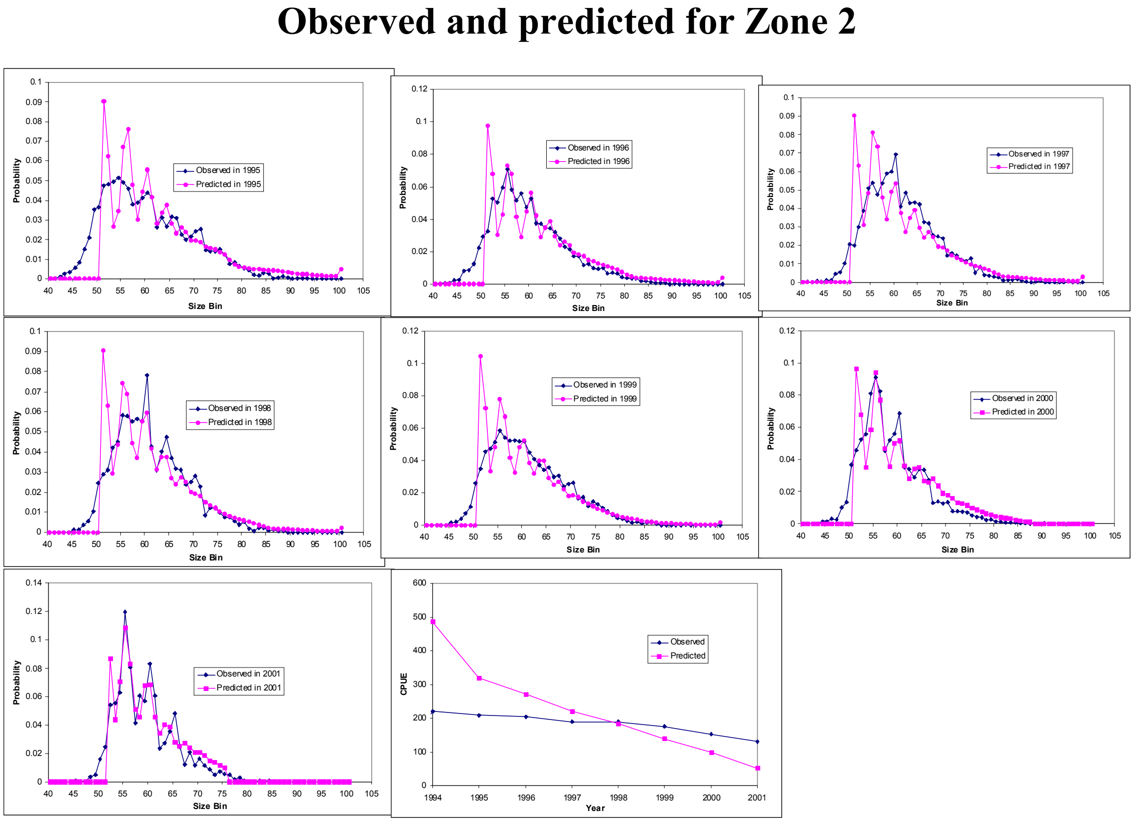


Figure 28. Size compositions of landings, and CPUEs observed in the fishery and predicted by the proposed assessment model.



**Observed and predicted for Zone 2**

Figure 29. Size compositions of landings, and CPUEs observed in the fishery and predicted by the proposed assessment model.

**Observed and predicted for Zone 2 (data A)**

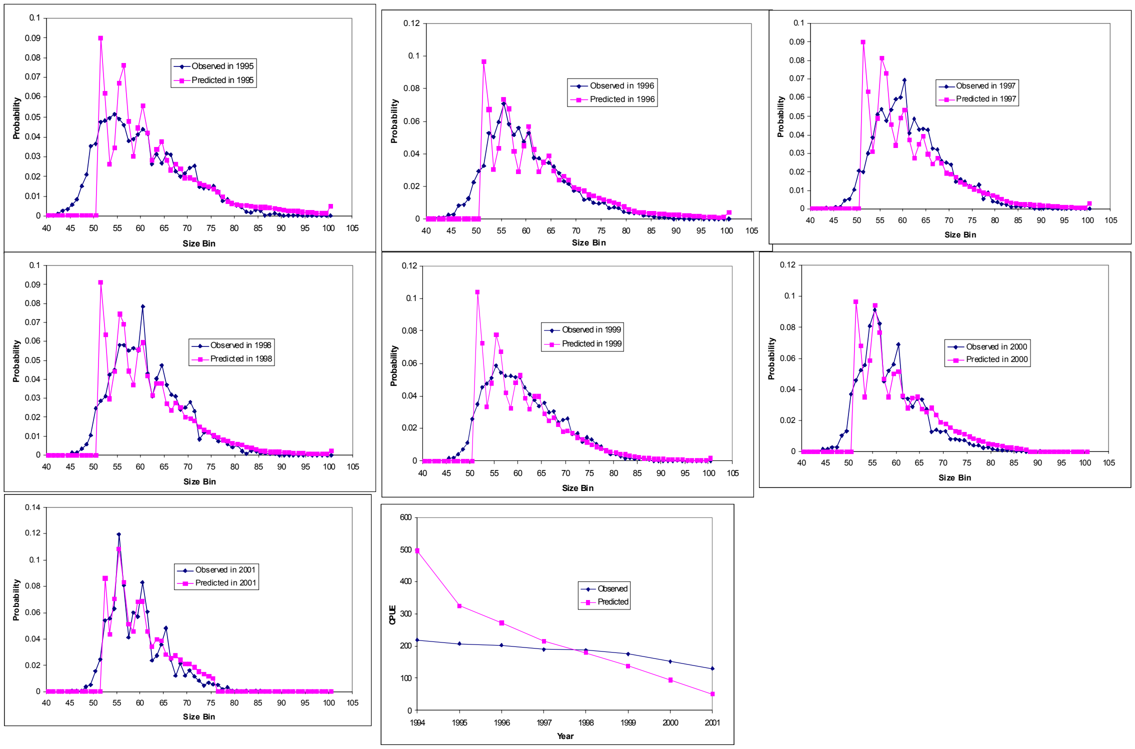
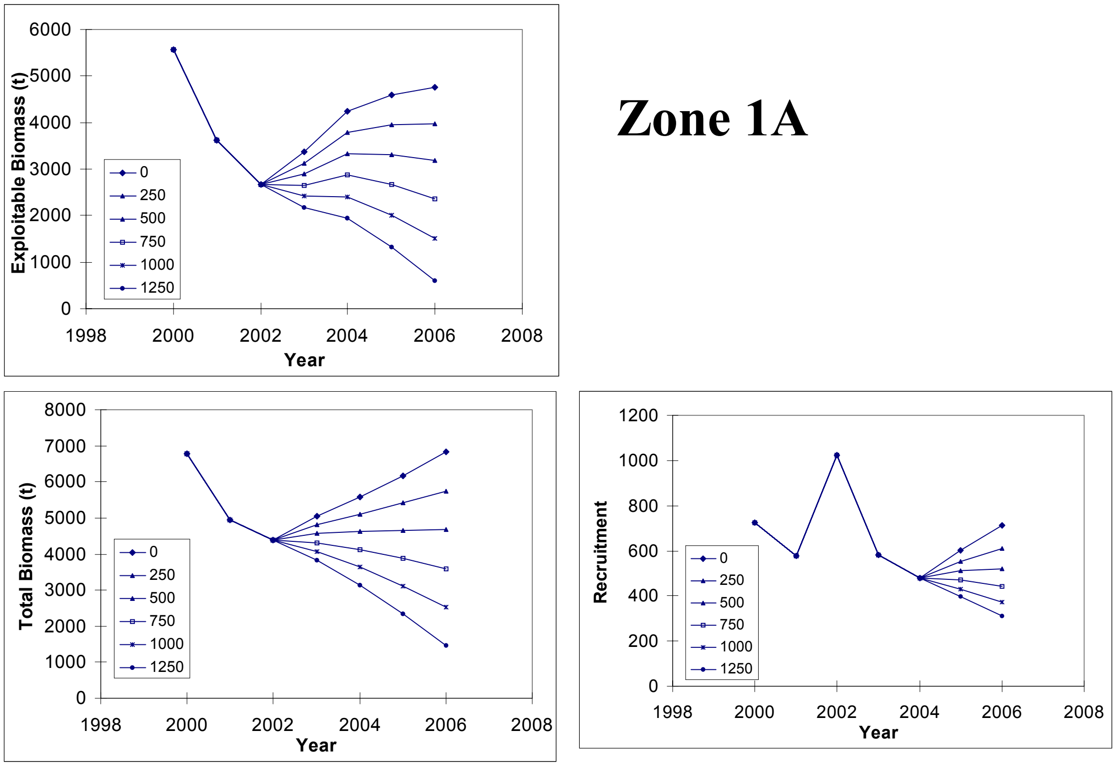


Figure 30. Exploitable stock biomass, total biomass and recruits projected under different levels of landings for 2003 to 2006 for Management Zone 1. The population model was derived from data with adjusted landings (i.e. Data set 1A).



**Zone 1A**

Figure 31. Exploitable stock biomass, total biomass and recruits projected under different levels of landings for 2003 to 2006 for Management Zone 2. The population model was derived from data with adjusted landings (i.e. Data set 2A).

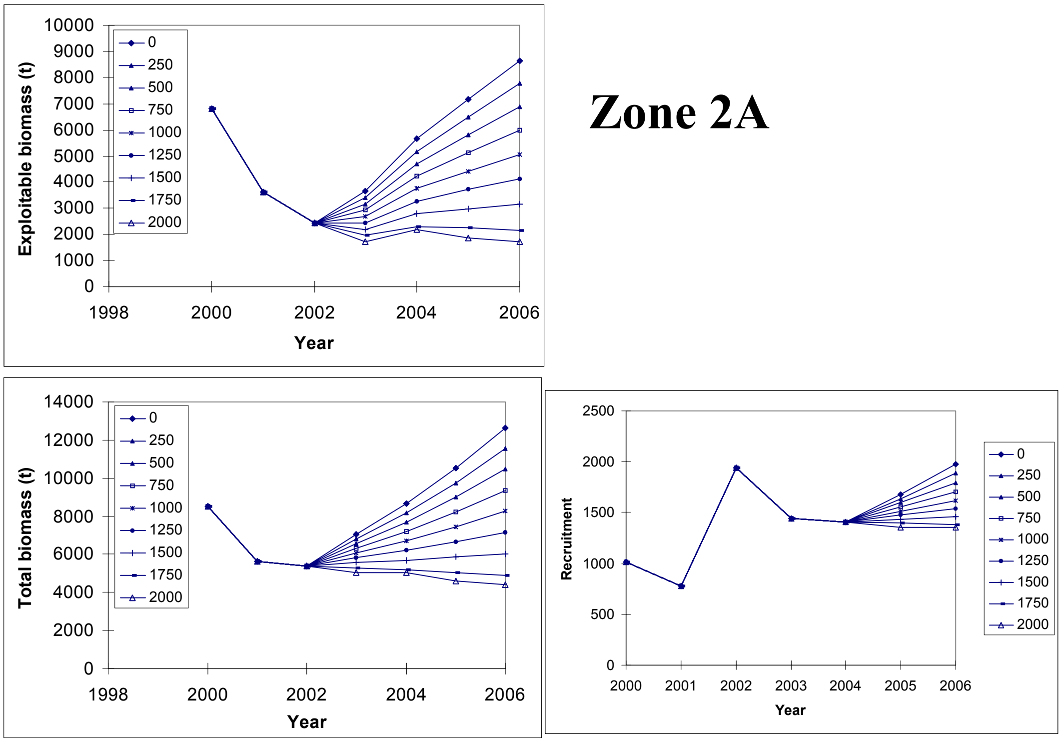


Figure 32. Cumulative probability distributions of total biomass, exploitable biomass and recruits in 2002 versus cumulative probability distributions of total biomass, exploitable biomass, recruits in 2006, respectively, projected with different levels of landings for Management Zone 1. The results are derived from data with adjusted landings (i.e. Data set 1A).

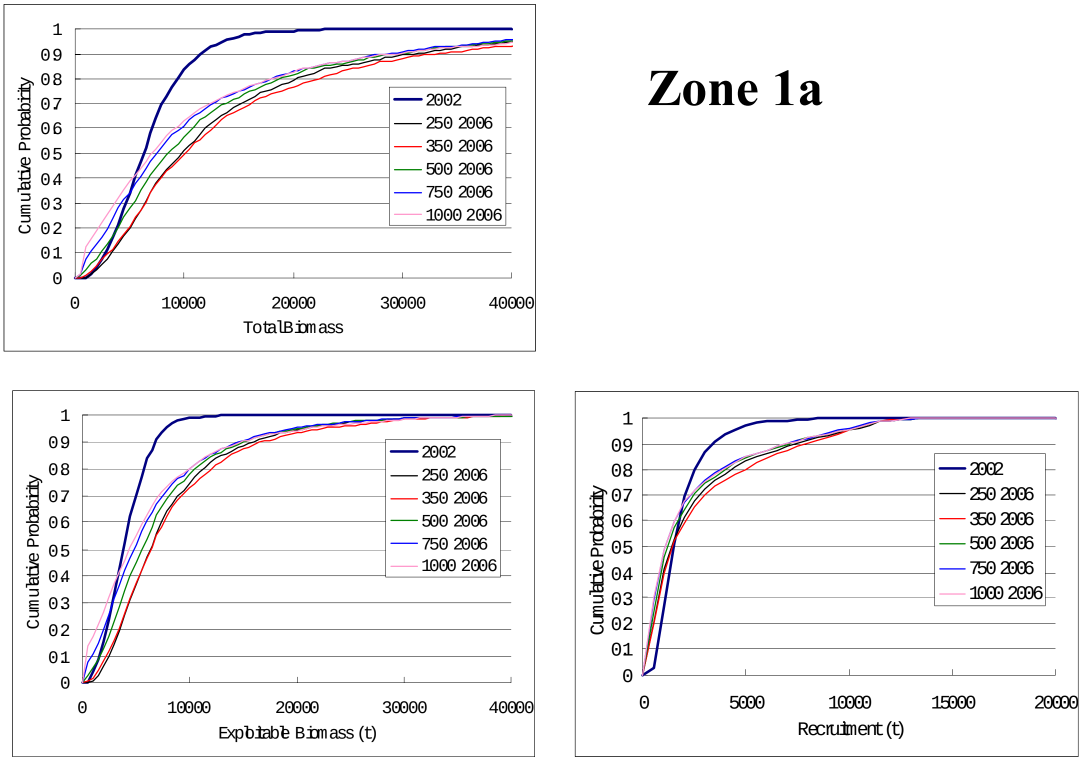
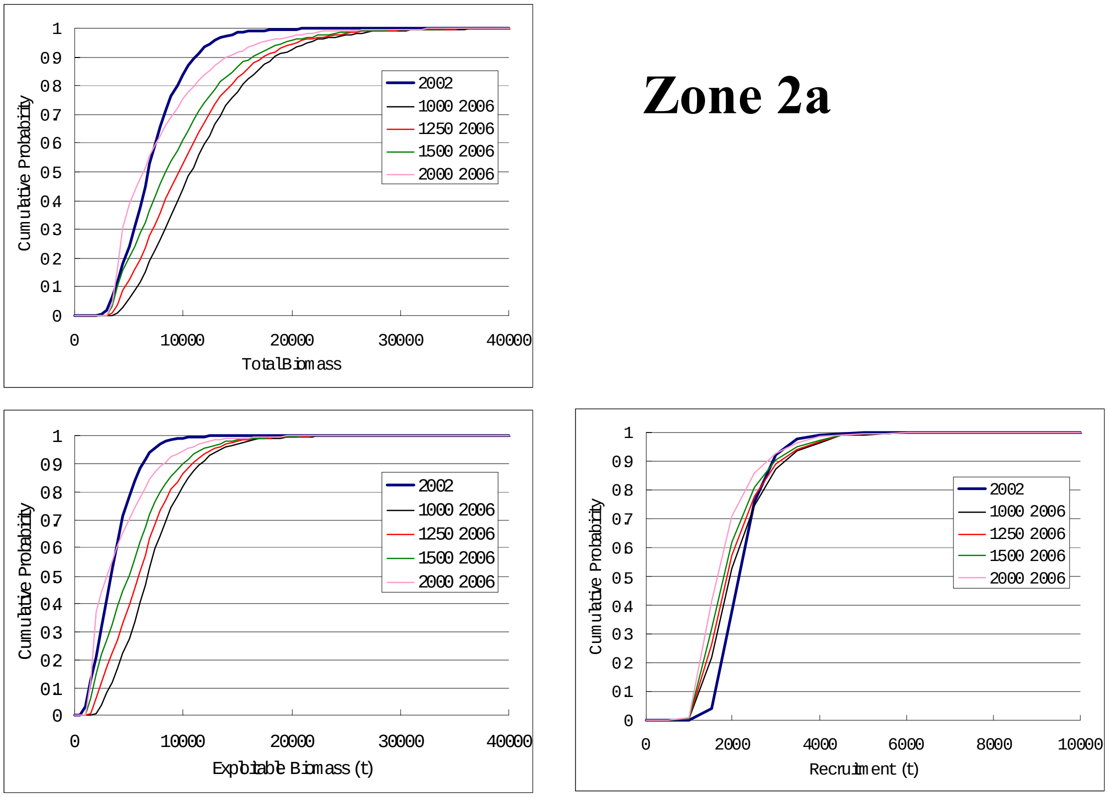


Figure 33. Cumulative probability distributions of total biomass, exploitable biomass and recruits in 2002 versus cumulative probability distributions of total biomass, exploitable biomass, recruits in 2006, respectively, projected with different levels of landings for Management Zone 2. The results are derived from data with adjusted landings (i.e. Data set 2A).



**Zone 2a**

## Appendix I: Development of sea urchin population dynamics models

### Bin of the size class

We set bin sizes between 40 mm and 100 mm, and the interval was set at 1mm.

Models developed to describe various life-history and fishery processes were grouped as population dynamics models. These models were used to simulate the sea urchin fishery with various output variables mimicking those outputs observed in the fishery. A group of observational models were developed to relate the output variables predicted by the population dynamics models and observed in the fishery. The differences between the predicted and observed output variables in the observational models were assumed to be random and follow certain distributions, which were used to formulate the likelihood functions needed in the Bayesian parameter estimation.

The population dynamics models include a recruitment model, a growth model, and a number-at-catch model. They are detailed below.

### Modeling recruitment

We assume that recruitment is independent of Spawning Stock Biomass. We estimate recruitment number in the first year ($R_0$), dispersion of recruitment in each year ($Eps_t$) and the ratio between one year's recruitment and next year's recruitment ($Rho$). Then in year $t$, recruitment is defined as

$$R_t = R_0 \exp(Rdev_t - 0.5\sigma_{Rdev}^{2}) \tag{1}$$

where $R_t$ is the recruitment for year t, $Rdev_t$ is the recruitment deviation from the mean value for year t, and $\sigma_{Rdev}$ is the standard deviation of the estimated recruitment deviations for all the years included in the assessment. $Rdev_t$ is defined as

$$Rdev_t = \sqrt{Rho}\,Rdev_{t-1} + \sqrt{1 - Rho}\,Eps_t\,. \tag{2}$$

### Modeling population dynamics

Each year the model calculates the total biomass, $B_t^{total}$, as

(3) $$B_t^{total} = \sum_k N_{k,t} w_k \ .$$

The exploitation rate, $U_t$, is calculated as

(4) $$U_t = \frac{C_t}{B_t^{total}}$$

where $C_t$ is the catch in year t observed in the fishery. The survival rate from fishing, $SV_{k,t}$, can be calculated as

(5) $$SV_{k,t} = 1 - U_t P_{k,t}$$

where $P_{k,t}$ is a switch that determines whether size-class k is within the legal sizes. Thus, the number of sea urchins in size class k in year t, $N_{k,t}$, can be calculated as

(6) $$N_t = SV_{t-1} N_{t-1}' G \ e^{-M}$$

We assume that the size distribution of recruitment coming into the population is proportional to the probability of the urchin in the first size class growing into other size classes. Thus, if we assume the recruitment is coming into the stock early in a fishing year, the number of sea urchins in the stock in year t, after including the recruitment of the year, becomes $N_t + R_t G_1$ .

**Model Prediction**

Using the above population dynamics models we can simulate a fishery. The following predictions are made from the simulated fishery:

(8) total biomass $B_t^{total} = \sum_k N_{k,t} w_k$

(8) legal-sized sea urchin biomass $B_t^{legal} = \sum_k P_{k,t} N_{k,t} w_k$

(9) catch per unit of effort in the fishery $I_t^{pred} = q_1 B_t^{legal}$ ,

where $q_1 = Average(I_t^{obs} / B_t^{legal})$

(10) stock abundance index $\mu_t^{pred} = q_2 B_t^{total}$

(10) size composition of the catch $Cp_{k,t}^{pred} = \dfrac{P_{k,t} S_k N_{k,t}^{pred}}{\sum_k P_{k,t} S_k N_{k,t}^{pred}}$

(11) size composition of the sea urchin stock $p_{k,t}^{pred} = \dfrac{N_{k,t}^{pred}}{\sum_k N_{k,t}^{pred}}$

**Observational models**

Various observational models were developed to relate fishery predictions made using the above population dynamic models and fishery data measured in the sea urchin fishery. They include observed and predicted catch per unit of effort described as

(11) $I_t^{obs} = I_t^{prei} \exp(\varepsilon_{I_t})$; and

observed and predicted size composition of the catch described as

(12) $Cp_{k,t}^{obs} = Cp_{k,t}^{pred} + \varepsilon_{Cp_{k,t}}$.

where $\varepsilon_{I_t}$ and $\varepsilon_{Cp_{k,t}}$ follow normal and multinominal distributions, respectively. The above two observational models are for data collected in the fishery. The data collected in the fishery-independent survey program are related to predicted survey data using the following two observational models:

(13) $\mu_t^{obs} = \mu_t^{pred} \exp(\varepsilon_{\mu_t})$ for survey abundance index; and

(14) $p_{k,t}^{obs} = p_{k,t}^{pred} + \varepsilon_{p_{k,t}}$ for survey size composition data.

The error terms $\varepsilon_{\mu_t}$ and $\varepsilon_{p_{k,t}}$ follow normal and multinominal distributions, respectively.

## Likelihood functions

Based on the distributional assumptions in the observational models, the following likelihood functions are developed.

(13a) $$p(I_t^{obs} \backslash I_t^{pred}) = \prod_i \prod_t \left[ \frac{1}{\sqrt{2\pi}\hat{\sigma}_{I_t^{obs}}} \exp\left\{ - \frac{\left(\ln(I_t^{obs}) - \ln(I_t^{pred})\right)^2}{2(\hat{\sigma}_{I_t^{obs}})^2} \right\} \right]$$

(13b) $$p(I_t^{obs} \backslash I_t^{pred}) = \prod_i \prod_t \left[ \frac{1}{\sqrt{2\pi}\hat{\sigma}_{I_t^{obs}}} \exp\left\{ - \frac{\left(\ln(I_t^{obs}) - \ln(I_t^{pred})\right)^2}{2(\hat{\sigma}_{I_t^{obs}})^2} \right\} + 0.01 \right]$$

(13c) $$p(I_t^{obs} \backslash I_t^{pred}) = \prod_i \prod_t \left[ \frac{1.329}{\sqrt{4\pi}} \left\{ 1 + - \frac{\left(\ln(I_t^{obs}) - \ln(I_t^{pred})\right)^2}{4(\hat{\sigma}_{I_t^{obs}})^2} \right\}^{-2.5} \right]$$

(14)

$$L(Cp_{k,t}^{obs}) =$$

$$\prod_t \prod_k \frac{1}{\sqrt{2\pi Cp_{k,t}^{obs}(2 - Cp_{k,t}^{obs}) + 0.1/\pi}} \exp\left[ \frac{-N_{k,t}(Cp_{k,t}^{obs} - Cp_{k,t}^{pred})^2}{2\left\{Cp_{k,t}^{obs}(1 - Cp_{k,t}^{obs}) + 0.1/\pi\right\}} + 0.01 \right]$$

## Prior distribution

distribution functions for priors

(15) $$f(Y) = -\frac{(\log(Y) - \log(\mu))^2}{2\sigma^2} + \log\left(\frac{1}{\sqrt{2\pi}\sigma}\right)$$

(16) $$f(Y) = \left[ \pi\lambda \left\{ 1 + \left( \frac{Y - \theta}{\lambda} \right)^2 \right\} \right]^{-1} \qquad (\theta = \mu\ ,\ \lambda = 0.675\sigma\ )$$

$Y \in R_0$, $M$ $Select50LF$ $h_{select}$ $Eps_t$ and $R_p$.

# Appendix II:
# Developing a model describing somatic growth for the Maine sea urchin

## II-1. Introduction

One of the key components of a size-structured population dynamics model is a growth transition matrix, which describes the probability of an organism growing from one size class to another size class in a given unit of time (Sullivan et al., 1990; Sullivan, 1992). In practice, two approaches can be used to incorporate a growth transition matrix into a stock assessment: one is to incorporate the growth transition matrix and simultaneously estimate matrix parameters with parameters that describe other biological processes in the fishery (Sullivan et al., 1990), and the other approach is to estimate the growth transition matrix independent of other stock assessment models (Chen et al., 2000). The former considers covariance among different processes by estimating all parameters simultaneously, but makes the analysis more complicated. The latter approach reduces the complexity of modeling, but does not consider the covariance of growth and other biological processes. Because size-structured models are often complicated and have many parameters to be estimated, the estimation of a growth transition matrix outside the main modeling process may be preferable (Chen et al., 2000). In either case, the quality of the growth transition matrix can greatly influence the quality of the stock assessment. It is thus essential to develop a growth transition matrix for Maine sea urchin stocks that can capture the variations in growth increments among individuals.

The information required in estimating a growth transition matrix includes the mean growth increment in a given unit of time and its associated variation for sea urchins of different sizes. Because growth rates of sea urchins vary with size, growth increments also vary with size, and this variation in growth with size is rarely constant. This has been implicit in the statements of model assumptions in many papers (e.g. Sullivan et al., 1990; Sullivan, 1992, Quinn and Deriso, 1999). However, because the variance for growth increments is difficult to estimate, it is often assumed constant for organisms of different sizes (Quinn and Deriso, 1999). Such an assumption of constant variation in growth increments is rather unrealistic and may introduce biases in estimating a growth transition matrix. Thus, for the Maine sea urchin we need to develop an approach that can explicitly consider non-constant variances for growth increments of sea urchins of different sizes.

Growth of the sea urchin along the Maine coast has not been studied extensively and the data are limited. The data we used for this study were from Vadas et al. (2002) who collected size-at-age data for sea urchins in two habitats (barren and kelp) from three areas along the coast of Maine.

## II-2. Methods and materials

Previous studies have indicated that many environmental variables might influence the growth of the sea urchin (Meidel and Scheibling, 1998; Russell, 1998). Sea urchins in favorable habitats feeding on preferred seaweeds grow faster than those feeding on non-preferred algae and mussels, and urchins on barren grounds grow slower. Even in the same habitat, different forms of growth were identified (Vadas, 1977). Previous studies divided the coast of Maine into three regions, Northeast, Center, and Southwest (Vadas et al., 1997). For each region, sea urchin samples were randomly taken from two habitats, barren and kelp. Size-at-age data were collected in 1997/98 for sea urchins in each habitat and area (Vadas and Beal, 1999). Detailed descriptions about the derivation of size-age information, justification for dividing the Maine coast, and selection of the habitats can be found in Vadas et al. (1997), Vadas and Beal (1999), and Vadas et al. (2002).

Vadas et al. (1997) modeled the size-at-age data using the von Bertalanffy growth function (VBGF) described as

$$L_t = L_\infty (1 - e^{-K(t-t_0)}), \tag{II-1}$$

where $L_t$ is size at age $t$, $L_\infty$ is defined as the mean asymptotic length the sea urchin may attain, $K$ is the Brody growth parameter, and $t_0$ is the hypothetical age of size 0 (Ricker, 1975). For each area and habitat, a VBGF was used to fit the size-at-age data. Three parameters in the VBGF (i.e. $L_\infty$, $K$, and $t_0$) and their standard errors were estimated using the nonlinear least squares method. These estimates were presented in Vadas and Beal (1999) and Vadas et al. (2002), and were made available to this study (Table II-1). Clearly there were large differences in the estimates of $L_\infty$ and K and their associated variations among different areas and habitats (Table II-1).

The $L_\infty$'s estimated for different areas and habitats ranged from 63.1 (Northeast region with barren habitat) to 95.2mm (Southeast region with Kelp habitat) (Table II-1) and tended to be smaller than some large individuals observed in the fishery (about 100mm, Vadas, 1977; Hunter, unpublished data). This likely resulted from relatively small sample sizes that covered relatively small areas, in a relatively short period, compared with the fishery catch, which targeted larger sized individuals. Excluding individuals observed in the fishery catch, but which were larger than the $L_\infty$'s estimated in Vadas and Beal (1999) and Vadas et al. (2002) from the calculation of the growth transition matrix may under-estimate the variability in sea urchin growth, thus introducing errors in stock assessment. Based on the data collected in the Maine sea urchin fishery (Hunter, unpublished data) and previous studies (Vadas, 1977), 100mm was considered a reasonable value for the average asymptotic size a sea urchin on the coast of Maine could attain ($L_\infty$). More extensive sampling needs to be done in the future to verify this estimate.

We might be able to derive an estimate of $L_\infty$ for the Maine sea urchin stock based on the examination of the data collected from the fishery and other studies (Ricker, 1975; Moreau, 1987; Chen et al., 1992). An estimate of $K$ for the whole Maine urchin stock is, however, more difficult because $K$ is an abstract rate describing how fast organisms approach the $L_\infty$ and there are no observations or background information to compare (Ricker, 1975; Moreau, 1987). We thus need to develop an approach to estimate $K$ for the Maine sea urchin stock that corresponds to the value we assumed for the $L_\infty$. Many studies have indicated that estimates of $K$ and $L_\infty$ tend to be highly and negatively correlated (e.g. Moreau, 1987; Chen and Harvey, 1994). Thus, a fish population or species with a large $L_\infty$ tends to have a low $K$ value, and vice versa (Gallucci and Quinn, 1979; Chen et al., 1992). This suggests a strong relationship between $L_\infty$ and $K$ estimates (Pauly, 1980; Stergiou, 1993). Such a relationship may be used to estimate $K$ for a given $L_\infty$ or to estimate $L_\infty$ for a given $K$. In this study we developed and used the following empirical approach to derive the $K$ for the given value of $L_\infty$ and their associated uncertainties in the development of a growth transition matrix: (1) conduct a regression analysis for $K$ and $L_\infty$ estimated for different areas and habitats along the coast of Maine (Table II-1); (2) calculate coefficients of variation ($CV$) for each $K$ and $L_\infty$ (Table II-1) as

$$\text{(II-2)} \qquad CV(K) = \frac{\text{standard error for K}}{K}, and\, CV(L_\infty) = \frac{\text{standard error for L}_\infty}{L_\infty},$$

and conduct a regression analysis of $CV(K)$ and $CV(L_\infty)$ estimates of different areas and habitats (data in Table II-1); (3) use 100 mm to approximate $L_\infty$ and use this $L_\infty$ to estimate $K$ from the regression analysis between $K$ and $L_\infty$; and (4) calculate the average $CV$ for $L_\infty$s of different areas and habitats and then use the average $CV(L_\infty)$ to estimate $CV(K)$ from the $CV(K)$-$CV(L_\infty)$ regression equation.

Because $K$ and $L_\infty$ were estimated for different areas and habitats and had different precisions, outliers might arise in the regression analyses. To avoid possible bias introduced by outliers, we used a reweighted least squares (RLS) method for the regression analyses (Chen et al., 1994). This involves conducting a robust least median of squares (LMS) analysis to identify outliers (Rousseeuw and Leroy, 1987) and justifying the identified outliers using background information, followed by a weighted LS analysis with justified outliers being weighted by 0 and other data having a weight of 1 (Chen et al., 1994). In the two regression analyses (i.e. steps 1 and 2), $L_\infty$ and $CV(L_\infty)$ were used as the independent variables while $K$ and $CV(K)$ were used as the dependent variables. The reason for this, instead of the other way around, is that $L_\infty$ is often estimated more reliably and with much smaller variations (Chen et al., 1992; also see Table II-1), while $K$ is often less reliably estimated (Moreau, 1987). One of the basic assumptions for a regression analysis is that the independent variable is error free. In practice, this assumption is often relaxed when the independent variable has a much smaller error than the dependent variable (McArdle, 1988). Whether the errors in the regression analyses follow a normal distribution determines if we can test the significance of the regression model and its parameters using common parametric tests ($F$- or $t$-test). It does not necessarily result in biases in the regression analysis (Sen and Srivastava 1990).

Given $K$ and $L_\infty$, the growth increment during a unit of time (i.e. year) can be calculated as

$$\text{(II-3)} \qquad \Delta L_n = (L_\infty - L_n)(1 - e^{-K}),$$

where $K$ and $L_\infty$ are the true values without errors, $n$ indexes size class, and $L_n$ is the middle point of the $n^{th}$ size class. With equation (III-3), we can develop two approaches to estimate the growth transition matrix. One approach is a Monte Carlo simulation. We can randomly sample $H$ sets of $K$ and $L_\infty$ values from their joint distributions (thus consider their covariance) and then use them in equation (II-3) to calculate *H* sets of $\Delta L$ for each size group. We can then derive the probability distribution for $\Delta L$ from these *H* sets of $\Delta L$ values for each size group. The Monte Carlo simulation approach is straightforward, but requires extensive calculations, in particular when there are a large number of size groups. It is also inconvenient to update the growth transition matrix when there are new growth data or large changes in growth due to changes in the environment. The second is an analytic approach that is not so straightforward, but is easy to update with new information and is less computationally intensive. Since it is likely that the growth transition matrix for the Maine sea urchin fishery will need to be updated because of possible changes in growth caused by changes in the sea urchin population size and its ecosystem, we used the second approach, which is described as follows.

Assuming the uncertainties associated with the VBGF parameters $L_\infty$ and $K$ are $\Delta L_\infty$ and $\Delta K$ respectively, where $\Delta L_\infty \in N(0, \sigma^2_{L_\infty})$ *and* $\Delta K \in N(0, \sigma^2_K)$, we have

(II-4) $$L_\infty = \overline{L}_\infty + \Delta L_\infty \quad \text{and} \quad K = \overline{K} + \Delta K$$

where $\overline{L}_\infty$ *and* $\overline{K}$ are the estimated parameters. Replacing the true values of $L_\infty$ and $K$ in equation (II-3) with equation (II-4) and using the approximation $e^{\Delta X} \approx 1 + \Delta X$ for small $\Delta X$, we have

(II-5)

$$\Delta L_n \approx (\overline{L}_\infty - L_n)(1 - e^{-\overline{K}}) + \left[ \Delta L_\infty (1 - e^{-\overline{K}}) - (\overline{L}_\infty - L_n)\Delta K e^{-\overline{K}} - \Delta L_\infty \Delta K e^{-\overline{K}} \right] = \overline{\Delta L}_n + \varepsilon_n$$

where

(II-6) $$\overline{\Delta L}_n = (\overline{L}_\infty - L_n)(1 - e^{-\overline{K}}) \quad \text{and}$$

(II-7) $$\varepsilon_n = \Delta L_\infty (1 - e^{-\overline{K}}) - (\overline{L}_\infty - L_n)\Delta K e^{-\overline{K}} - \Delta L_\infty \Delta K e^{-\overline{K}}$$

Thus, the expected (mean) value of $\Delta L_n$ is $\overline{\Delta L}_n$ and variance of $\Delta L_n$ can be estimated from equation (II-7) as

(II-8)

$$Var(\overline{\Delta L_n}) \approx \sigma^2_{L_\infty}(1-e^{-\bar{K}})^2 + (\bar{L}_\infty - L_n)^2 \sigma^2_K e^{-2\bar{K}} - 2COV(L_\infty, K)(1-e^{-\bar{K}})(\bar{L}_\infty - L_n)e^{-\bar{K}}$$

Items with the order of three and above for $\Delta L_\infty$ and $\Delta K$ are omitted in deriving equation (II-8) from equation (II-7). From equation (II-8), it is clear that the variance of the growth increment varies among different size classes.

From $\overline{\Delta L_n}$ estimated in equation (II-6), an expected average yearly growth increment was calculated for each size class. The variability for the average yearly growth increment was assumed to follow a normal distribution with a mean of $\overline{\Delta L_n}$ and variance of $Var(\overline{\Delta L_n})$ estimated from equation (II-8). This distribution was used to determine the vector of probabilities of growing from size class k to other size classes. If $d_{low}$ and $d_{up}$ are the lower and upper ends of size class *d*, the probability of a sea urchin growing from size class *n* to size class *d* can be computed as

(II-9) $$P_{n\rightarrow d} = \int_{d_{low}}^{d_{up}} f(x \mid \overline{\Delta L_n}, Var(\Delta L_n))\, dx,$$

where *x* is a random variable having a density probability distribution defined by $f(x \mid \overline{\Delta L_k}, Var(\overline{\Delta L_k}))$ with its expected value of $\overline{\Delta L_k}$ and variance of $Var(\overline{\Delta L_k})$ (Quinn and Deriso, 1999). In this study we assumed the *x* variable was a normal density distribution function with a mean of $\overline{\Delta L_k}$ defined by equation (II-6) and variance of $Var(\overline{\Delta L_k})$ defined by equation (III-8). The probability of a sea urchin growing from one size to another was estimated for all size classes to form the matrix. Negative growth increments were not permitted. The largest size class acts as a plus group, so sea urchins in this group have a probability of 1 of remaining in the group. The model contains 61 size classes, each with 1 mm interval width, ranging from 40 mm size (midpoint value for size class from 39.5- 40.5 mm) to 100 mm.

Because no negative growth was allowed, the summation of the probabilities of a sea urchin of size class *k* growing into all other size classes was smaller than 1 (because the normal distribution is symmetric). This problem was avoided by standardization which involved dividing the probability of an urchin in a given size class *n* growing into each size class by the summation of the probabilities of growing from a given size *n* to all the size classes. All calculations were done in MS-Excel©. A worksheet for estimating a growth transition matrix using the approach described above is available upon request.

## II-3. Results

The LMS analysis suggested that the logarithmic $K$- $L_\infty$ data for the barren habitat in the Southwest area was an outlier in the $K$- $L_\infty$ regression analysis (Fig. II-2). The estimated $K$ and $L_\infty$ values for the barren habitat in the Southwest had *CV*s over 120% and 24%, respectively, much larger than the estimates for other locations and habitats (Table II-1). This was the only site where the $K$ estimate was not significantly different from 0 (thus the VBGF was not significant). We thus concluded that this data point was an outlier due to the poor fit of the VBGF, and subsequently it was given a zero weight in the RLS analysis. The RLS regression equation for $K$ and $L_\infty$ was estimated as

(II-10) $Ln(K) = 8.653 - 2.3777 Ln(L_\infty), \qquad P = 0.0038, \; Adj.\, r^2 = 0.94$

The standard deviations for the intercept and slope were 1.2605 and 0.28923, respectively. The $P$ value for equation (II-10) indicates that the regression model is significant. The adj. $r^2$ is the coefficient of determination adjusted for the sample size, suggesting 94% of the variance in ln($K$) could be explained by the model.

The LMS analysis of the *CV*s of parameters $K$ and $L_\infty$ also suggested that the barren habitat in the Southwest area was an outlier because it had an exceptionally large *CV* for $K$ (Fig. II-3). We thus concluded this data point was an outlier and should be given a weight of zero in the RLS analysis. The RLS regression equation for the *CV*s of parameters $K$ and $L_\infty$ was estimated as

(II-11) $CV(K) = 0.189 + 1.5602\, CV(L_\infty), \qquad P = 0.034, \quad Adj.r^2 = 0.76$

The standard deviations for the intercept and slope were 0.0561 and 0.42319, respectively. The $P$ value suggested the regression model was significant ($P < 0.05$). The value of $r^2$ suggests 76% of the variance in $CV(K)$ could be explained by the model.

The average *CV* for $L_\infty$'s of different areas and habitats was 15%. The $L_\infty$ was assumed to have a value of 100 mm in this study as discussed previously. This gave the $L_\infty$ a standard error estimate of 15.0mm, making its 95% confidence intervals 70 mm to 130 mm. The *K* value was estimated to be 0.1006 using equation (II-10) and $L_\infty$ of 100 mm. Using equation (II-11) and the *CV* for $L_\infty$, the *CV* for *K* was estimated to be 42.3%, which yielded the value of 0.0426 for the standard error for *K*.

The annual expected growth increment decreased quickly with sea urchin size (Fig. II-4). The largest expected annual increment was 6 mm for the smallest size class (39.5–40.5 mm) included in the study. The variance for annual growth increments calculated using equation (II-8) was large for small sea urchins. It decreased initially with size, reaching the smallest value at the 59 mm size class (58.5-59.5mm), followed by a progressive increase with size (Fig. II-5). The expected annual growth increment for the largest size class included in this study had the highest variance, which was over eight times as high as the smallest variance (Fig. II-5).

The probability distribution of annual growth increment varied among size classes (Fig. II-6), reflecting the differences in variances associated with different size classes. The last size class was a plus class, with the probability of staying in the same size class being 1. Fig. II-6 clearly indicated that no negative growth was allowed.

## II-4. Discussion

Great variation in growth was observed in the Maine sea urchin stock (Vadas et al., 2002). Such a pattern of variation was reflected in estimating the VBGF parameters for different areas and habitats (Table II-1). Large standard errors were estimated for the VBGF parameters for sea urchins of the same area and habitat, and large differences occurred in the estimated VBGF parameters between different areas and habitats (Table II-1). The approach developed in this study considered observations made in both the fishery and scientific studies and provided a systematic way to incorporate the large variation in growth into the estimation of a growth transition matrix, and subsequently into the sea urchin stock assessment.

It should be noted that the algorithm developed for estimating the variance of growth increments is approximate, and violations of the assumptions used in deriving the algorithm may introduce errors in estimating a growth transition matrix. For example, large errors in estimating $K$ and $L_\infty$ will introduce errors in equation (II-5), which was derived assuming small errors for the two growth parameters. Non-normal distribution of $\Delta L$ with its mean defined by equation (II-6) and variance defined by equation (II-8) will also result in errors in developing a growth transition matrix. Other factors that may influence the quality of the estimated growth transition matrix include errors in estimating $CV$s for $K$ and $L_\infty$ (equations II-10 and II-11) and omitting high order items in deriving equation (II-8).

Unlike most studies in which the variance for the annual growth increment was assumed to be the same for all size classes (Quinn and Deriso, 1999), this study explicitly suggested that the variance for the annual growth increment changed with size (Fig. II-4). The differences in the variance were large between size classes, and changed nonlinearly with size. If a constant variance were used for all size classes, the variance in growth increment would be severely under-estimated for large and small animals. This could introduce large biases in a stock assessment.

Size-dependent variation might better describe the variation in annual growth increment. Fish in small size classes tend to grow fast, but their growth tends to be more susceptible to environmental variation than adult growth, often resulting in large variation among individuals (Summerfelt and Hall, 1987). Fish in large size classes (older fish) have to divert some energy to reproduction, but tend to have considerable variation in energy allocation strategies among individuals. Differences among adults in the ability to grow can also be considerable because of genetics, specific growth patterns during juvenile stages, and differences in energy allocation between growth and maturation during younger ages (Nikolskii, 1969). This may cause large variations in growth for large and old fish (Chen et al., 1988; Summerfelt and Hall, 1987). Compared with old and young ages, growth rates for medium sized and aged fish may be less varied (Nikolskii, 1969). This pattern can be reflected realistically in the variation estimated using the approach derived in this study.

Although the choice of $L_\infty$ was a bit arbitrary in this study, it reflects observations from both the fishery and scientific studies. The largest sea urchins observed in the different scientific studies tend to be smaller than 100 mm, as indicated by the estimated $L_\infty$ values for different areas and habitats (Fig. II-2). The inability to observe larger sea urchins in scientific studies may result from relatively small sample sizes, focused research areas, and large growth variations even in small spatial scales. The data collected from the fishery were more extensive and covered more areas. This, together with the tendency for taking large individuals in the fishery, may suggest that large individuals are more likely to appear in the fishery, rather than in scientific studies. Thus, it may be reasonable to set the expected value of $L_\infty$ at 100 mm. Also, this higher value corresponds more closely to the upper growth estimates for green sea urchins from the northeast Pacific (Vadas, 1977). The $CV$ was assumed to be 15% for $L_\infty$, resulting in the 95% confidence interval of $L_\infty$ being 70 mm to 130 mm. This range was believed to be a reasonable estimate for the maximum attainable length on the coast of Maine (Vadas, 1977).

The approach developed in this study can be readily used to incorporate the VBGF parameters estimated from different studies. This can be accomplished by re-running the regression analyses between $K$ and $L_\infty$ and between $CV$s for $K$ and $L_\infty$. With more information about the growth of sea urchins on the coast of Maine becoming available, the growth transition matrix can be easily updated to reflect the variation identified in newer studies. The flexibility and ability to easily update and incorporate new information makes this approach desirable to the Maine sea urchin fishery, which is currently undergoing large changes in its population size and has only limited growth data.

The value of 100 mm chosen for $L_\infty$ was rather arbitrary. However, because we considered the negative correlation between $K$ and $L_\infty$ in deriving the growth transition matrix, a small error in the $L_\infty$ estimate would not change the growth transition matrix greatly. In the future, however, we can conduct a systematic sampling of the stock across its geographical range and derive some forms of weighted average size with a composite variance that captures the range of sizes exhibited by the species. Such an approach would provide us with a better estimate of $L_\infty$.

The growth transition matrix developed in this study summarizes the growth patterns of sea urchins along the coast of Maine. It can be updated whenever new growth data become available. It can be readily incorporated into a size-structured stock assessment model to evaluate the status of sea urchin stock and to evaluate alternative management strategies for the Maine sea urchin fishery (Chen and Hunter, 2003).

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Table II-1. The average asymptotic size ($L_\infty$) and Broady growth coefficient ($K$) estimated for different areas and habitats along the coast of Maine in the study done by Vadas et al. (1997, 2002). Coefficient of variation ($CV$) was calculated using equation (II-2).

| Area | Habitat | Parameter | | Coefficient of variation ($CV$) | |
|---|---|---|---|---|---|
| | | $L_\infty$ | $K$ | $CV(L_\infty)$ | $CV(K)$ |
| Northeast | Barren | 63.1 | 0.1404 | 0.242 | 1.209 |
| Northeast | Kelp | 88.5 | 0.1263 | 0.224 | 0.543 |
| Center | Barren | 67.0 | 0.2315 | 0.084 | 0.354 |
| Center | Kelp | 63.4 | 0.3268 | 0.065 | 0.248 |
| Southeast | Barren | 80.1 | 0.1776 | 0.099 | 0.397 |
| Southeast | Kelp | 95.2 | 0.1181 | 0.128 | 0.338 |

Figure II-2.The regression analysis of logarithmic *K* and $L_\infty$ for different locations and habitats of Maine sea urchins.

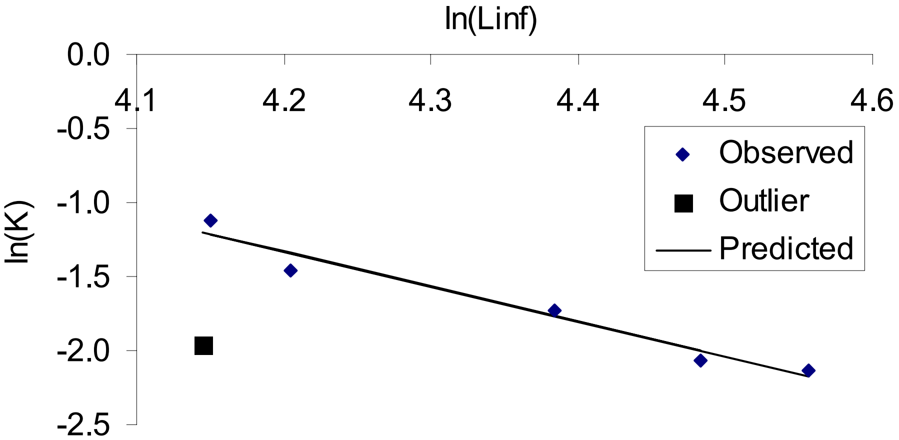


Figure II-3. The regression analysis of *CV*s for *K* and $L_\infty$ for different locations and habitats of Maine sea urchins.

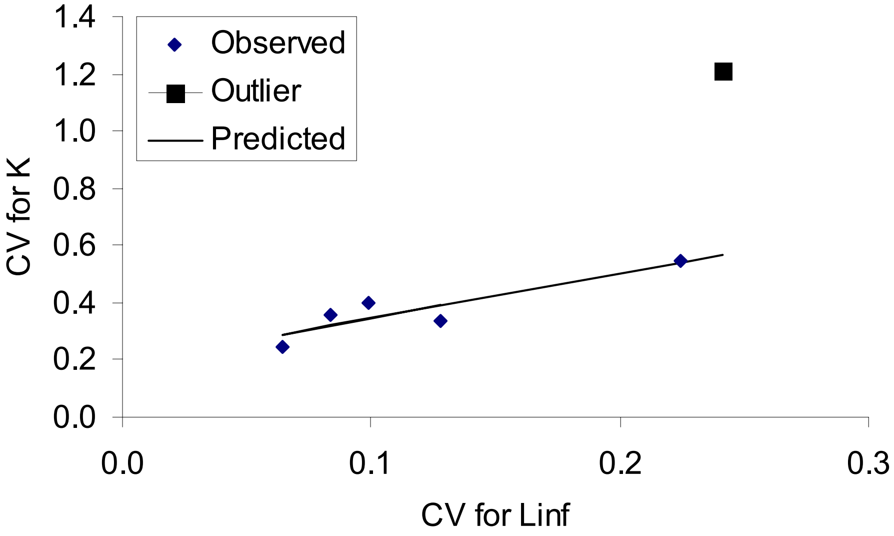


Figure II-4.The expected annual growth increment for Maine sea urchins of different size classes.

Figure II-5. The variances of growth increment estimated for different sea urchin size classes using equation (8).

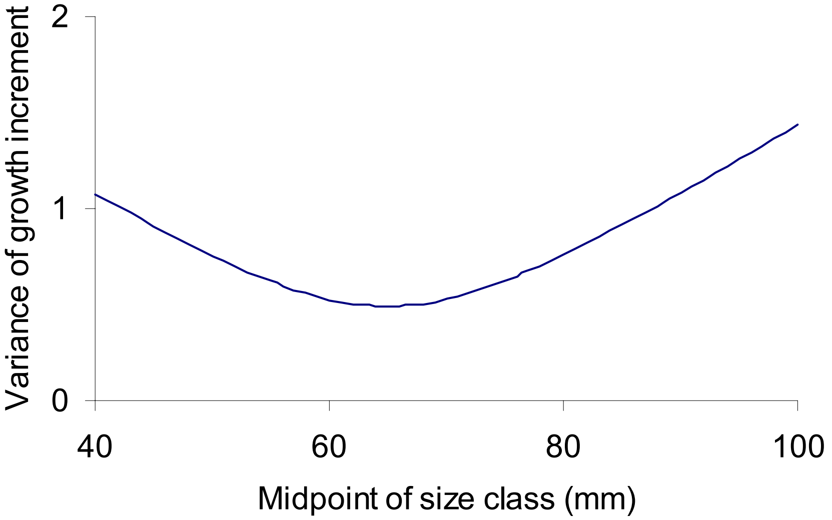
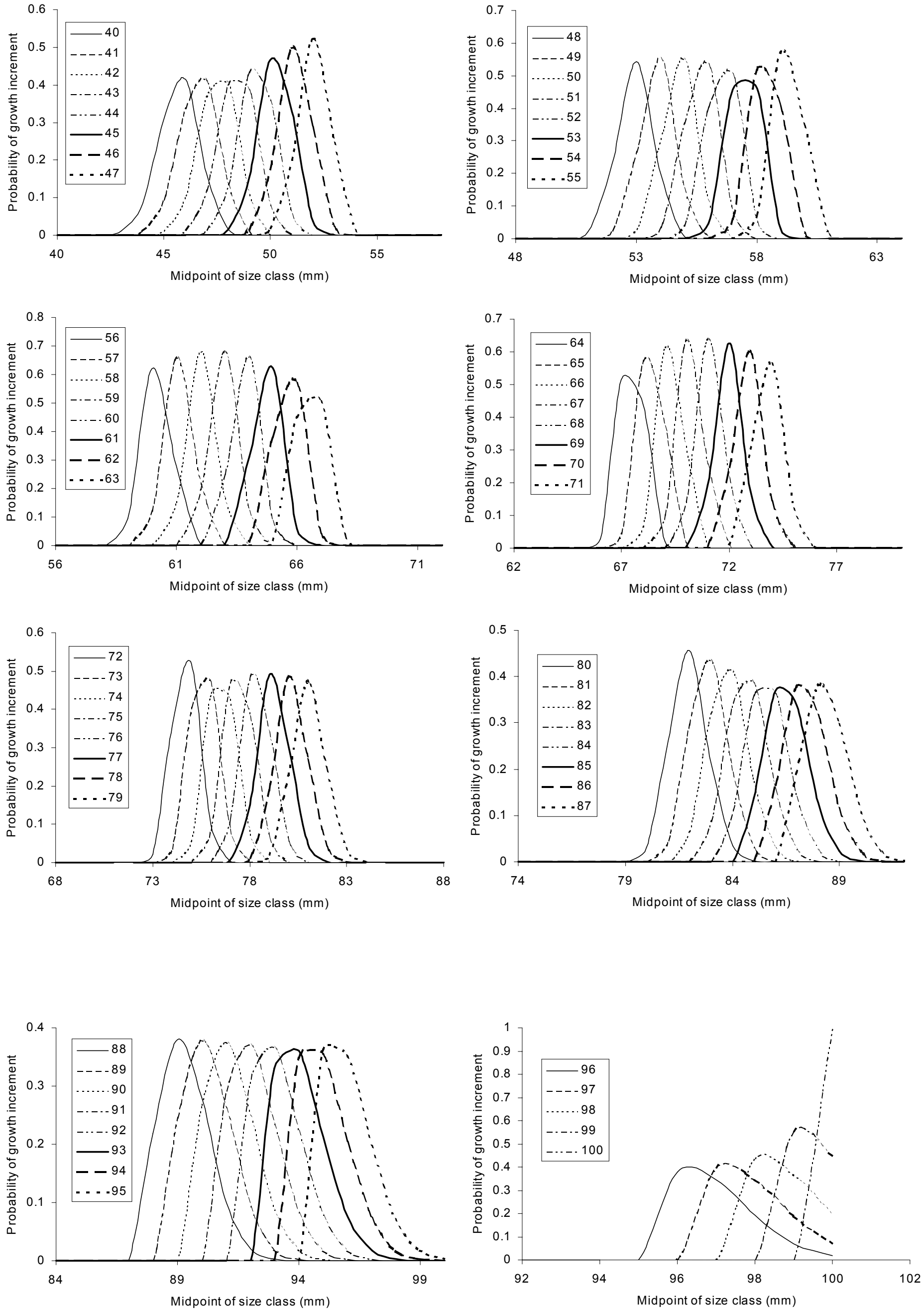


Figure II-6. Probabilities of sea urchins growing from one size class to others. Each probability distribution was labeled with the midpoint value of the current size class of the sea urchin.



# Appendix III

## Appendix III-1: Data set 1 used for Management Zone 1

```
#data for SeaUrchin for model
#this one is Zone 1 data
#serial number
53811
# debug
0
#init_int restart   normally zero
0
#likeswitch 1=normal 2=fattail
#use fattails
2
#priorswitch 1=lognormal 2= Cauchy
1
#FirstYear, LastYear, ProjectYear
      1987      2001            2006
#init_ivector LL1switch(1,6);        switches for the data
# 1 CPUE 2 IS 3 LF 4 LF2 5 tags
1 0 1 0 0 0
#LFweight LF2weight  LFminobs LF2minobs
1 1  40  40
# cols, L, firstbin (centre), binwidth


7  61   40.5  1.0


#year  TCC    CPUE          MLL    Surv   MaxLL  Tolerance
1987   1175   -1            -1     -1     -1     -1
1988   2727   -1            -1     -1     -1     -1
```

```
1989   4138   -1            -1     -1     -1     -1
1990   6583   -1            -1     -1     -1     -1
1991   6319   -1            -1     -1     -1     -1
1992   10583  -1            -1     -1     -1     -1
1993   8876   -1            -1     -1     -1     -1
1994   8255   150.00 -1     -1     -1     -1
1995   7253   126.00 50.8   -1     -1     0.1
1996   4805   133.67 50.8   -1     -1     0.1
1997   3138   116.67 50.8   -1     -1     0.1
1998   2765   153.20 50.8   -1     -1     0.1
1999   2385   145.73 50.8   -1     -1     0.1
2000   2148   161.07 50.8   -1     88.9   0.05
2001   1524   136.75 52.4   -1     76.2   0.05

#catch and MLS MxLS and sigmaProject for projections
   1500      52.4    76.2  0.60
# a and b for the length-weight power function

2.71E-09
2.544

# burn-in period


#SHOULD BE 50
50
# lag between spawning and rect
# SHOULD BE 3
3
# ERatemax and ERateweight for penalty
#SHOULD BE 0.8 and something big
0.70  1000
```

```
#maturity  mat50 mat95                     (*)dummy set all 1
91 105
#---------------------------------------------
#PRIORS
#---------------------------------------------


#phase lb      ub      type   mean   cv initial value
#type: 0 uniform, 1 normal, 2 lognormal                  (*)initial value


#Rcoff


1      5    50    0     20       1    15
#M
1   0.01  0.50    2  0.10     0.1  0.20
#Linf (commented out, not used in this assessment)
#2    100   250    0     0       0   150
#BrodyK (commented out, not used in this assessment)
#2   0.01  0.80    0     0       0  0.25
#Select50IS (commented out, not used in this assessment)
#2   70     125    0     0       0    95
#Select95IS   (commented out, not used in this assessment)
#2   70     125    0     0       0   110
#Select50LF
#-2   40     125    0     0       0   46
2   40     125    0     0       0   52
#Select95LF (commented out, not used in this assessment)
#-2   45     145    0     0       0   47
#2   45     145    0     0       0   53
#r (slope for the selectivity curve)
2   0.00001   2   2     0.1       0.1   0.5
```

```
#Eps
3   -2.3   2.3    1     0     0.4     0
#rho
#-3   0.00001 0.99  0     0       0 0.0001
1   0.00001 0.99  0     0       0 0.0001
#GrowthStddev (commented out, not used in this assessment)
#-1  -1       1    0     0       0     0
#GrowthCV(commented out, not used in this assessment)
#-1   0       1    0     0       0  0.39
#---------------------------------------
#init_number xxstdmin;
1
#init_number sigmaIS;
0.25
#init_number sigmaCPUE;
0.50
#nLFs
7
# LFs  (shed)
#      Sqrt(N)mm 40  41     42     43     44     45     46     47
       48     49     50     51     52     53     54     55     56
       57     58     59     60     61     62     63     64     65
       66     67     68     69     70     71     72     73     74
       75     76     77     78     79     80     81     82     83
       84     85     86     87     88     89     90     91     92
       93     94     95     96     97     98     99     100
1995   94.2   0      258    0      0      0      438    405    1104
       1349   2946   6726   8312   8032   13443  12433  20675  19501
       12075  15275  13437  15827  16517  9293   11935  9635   9277
       9610   5283   5409   4622   3997   3312   1471   2023   1939
       1077   1009   394    328    924    489    224    198    75
       397    414    0      217    14     51     33     0      0
       33     0      0      0      0      0      0      33
```

```
1996   124.6  30     158    457    0      1152   154    3072   5424
       7138   13022  19935  24086  25272  36443  37851  41499  36003
       32572  32266  30880  35346  22239  22547  20366  18141  17291
       8294   10510  7288   6158   4282   4588   2999   1613   2063
       2221   1366   1136   614    380    167    175    168    225
       125    132    150    42     42     0      94     0      0      0
       0      0      0      0      0      0      0
1997   126.2  0      0      0      0      729    719    78     19
       1618   4481   4714   8865   14440  17040  27877  31321  31403
       34058  35772  35334  33860  30613  26276  24035  21630  21834
       15188  11849  12964  10814  11550  6116   4737   4698   3674
       3009   2003   1609   1499   818    1009   481    227    583    0
       261    300    43     0      116    0      0      0      0      0
       0      0      0      0      0      0
1998   135.6  0      0      206    0      0      297    548    1533
       2004   3696   9835   13158  15458  26169  32027  36962  38671
       40387  44167  41935  48998  30957  25573  28384  27291  21293
       22536  16841  14714  13189  14397  8982   4384   4446   3810
       3223   2727   955    889    805    1138   669    90     142
       352    363    152    141    0      0      133    44     0      0
       0      0      0      0      0      0      0
1999   119.0  159    249    0      107    130    550    468    1533
       3576   6153   10313  12245  14244  23419  25446  34100  30053
       31565  30555  27139  29223  21845  23347  19666  16201  16554
       15497  10076  10117  6234   6440   4623   3514   2408   1915
       1308   1587   1268   554    546    507    194    431    217
       189    52     0      52     42     0      0      0      0      0
       0      0      0      0      0      0      0
2000   103.5  0      0      0      266    1035   2105   732    2822
       3639   5635   9326   18178  16236  19019  23596  41943  31561
       24124  27453  21412  34661  21460  16269  15224  11583  11686
       10290  4130   5155   4047   5953   1403   2923   2404   1637
       1405   1558   254    322    272    136    65     166    0      0
```

```
        89      74      0       0       0       0       0       0       0       0
        0       0       0       0       0       0
2001    87.2    0       0       0       0       0       0       0       141
        974     529     4762    6995    6827    13701   14133   21859   14137
        16229   18242   14292   23217   12627   8866    11900   9538    12082
        7583    5256    7390    5120    6697    2848    1158    1573    1108
        1850    1615    457     557     170     192     25      0       78
        192     64      100     86      74      0       0       0       0       0
        0       0       0       0       0       0       0
#
#nLF2s
1
#LF2            (*)Dummy Data
#       Sqrt(N)mm 40    41      42      43      44      45      46      47
        48      49      50      51      52      53      54      55      56
        57      58      59      60      61      62      63      64      65
        66      67      68      69      70      71      72      73      74
        75      76      77      78      79      80      81      82      83
        84      85      86      87      88      89      90      91      92
        93      94      95      96      97      98      99      100
1995    94.2    0       258     0       0       0       438     405     1104
        1349    2946    6726    8312    8032    13443   12433   20675   19501
        12075   15275   13437   15827   16517   9293    11935   9635    9277
        9610    5283    5409    4622    3997    3312    1471    2023    1939
        1077    1009    394     328     924     489     224     198     75
        397     414     0       217     14      51      33      0       0
        33      0       0       0       0       0       0       33



#test
53811
```

## Appendix III-2: Data set 1A used for Management Zone 1

```
#data for SeaUrchin for model
#this one is Zone 1 data
#serial number
53811
# debug
0
#init_int restart   normally zero
0
#likeswitch 1=normal 2=fattail
#use fattails
2
#priorswitch 1=lognormal 2= Cauchy
1
#FirstYear, LastYear, ProjectYear
      1987      2001            2006
#init_ivector LL1switch(1,6);        switches for the data
# 1 CPUE 2 IS 3 LF 4 LF2 5 tags
1 0 1 0 0 0
#LFweight LF2weight  LFminobs LF2minobs
1 1  40  40
# cols, L, firstbin (centre), binwidth


7  61   40.5  1.0


#year  TCC    CPUE          MLL    Surv   MaxLL  Tolerance
1987   1468   -1            -1     -1     -1     -1
1988   3409   -1            -1     -1     -1     -1
1989   5173   -1            -1     -1     -1     -1
1990   7779   -1            -1     -1     -1     -1
```

```
1991   7899   -1            -1     -1     -1     -1
1992   13228  -1            -1     -1     -1     -1
1993   11095  -1            -1     -1     -1     -1
1994   10289  150.00        -1     -1     -1     -1
1995   9066   126.00        50.8   -1     -1     0.1
1996   6006   133.67        50.8   -1     -1     0.1
1997   3766   116.67        50.8   -1     -1     0.1
1998   3180   153.20        50.8   -1     -1     0.1
1999   2862   145.73        50.8   -1     -1     0.1
2000   2523   161.07        50.8   -1     88.9   0.05
2001   1676   136.75        52.4   -1     76.2   0.05

#catch and MLS MxLS and sigmaProject for projections
   1500      52.4    76.2  0.60
# a and b for the length-weight power function

2.71E-09
2.544

# burn-in period


#SHOULD BE 50
50
# lag between spawning and rect
# SHOULD BE 3
3
# ERatemax and ERateweight for penalty
#SHOULD BE 0.8 and something big
0.70  1000

#maturity  mat50 mat95                     (*)dummy set all 1
91 105
```

```
#----------------------------------------------
#PRIORS
#----------------------------------------------


#phase lb     ub     type   mean   cv initial value
#type: 0 uniform, 1 normal, 2 lognormal                 (*)initial value


#Rcoff


1      5    50    0     20       1    15
#M
1   0.01  0.50    2  0.10     0.1  0.20
#Linf (commented out, not used in this assessment)
#2    100   250    0     0       0   150
#BrodyK (commented out, not used in this assessment)
#2   0.01  0.80    0     0       0  0.25
#Select50IS (commented out, not used in this assessment)
#2   70     125    0     0       0    95
#Select95IS   (commented out, not used in this assessment)
#2   70     125    0     0       0   110
#Select50LF
#-2   40     125    0     0       0   46
2   40     125    0     0       0   52
#Select95LF (commented out, not used in this assessment)
#-2   45     145    0     0       0   47
#2   45     145    0     0       0   53
#r (slope for the selectivity curve)
2   0.00001   2   2     0.1       0.1   0.5
#Eps
3   -2.3   2.3    1     0     0.4     0
```

```
#rho
#-3   0.00001 0.99  0      0        0 0.0001
1   0.00001 0.99  0     0       0 0.0001
#GrowthStddev (commented out, not used in this assessment)
#-1  -1       1    0     0       0     0
#GrowthCV(commented out, not used in this assessment)
#-1   0       1    0     0       0  0.39
#--------------------------------------
#init_number xxstdmin;
1
#init_number sigmaIS;
0.25
#init_number sigmaCPUE;
0.50
#nLFs
7
# LFs  (shed)
#      Sqrt(N)mm 40  41     42     43     44     45     46     47
       48     49     50     51     52     53     54     55     56
       57     58     59     60     61     62     63     64     65
       66     67     68     69     70     71     72     73     74
       75     76     77     78     79     80     81     82     83
       84     85     86     87     88     89     90     91     92
       93     94     95     96     97     98     99     100
1995   94.2   0      258    0      0      0      438    405    1104
       1349   2946   6726   8312   8032   13443  12433  20675  19501
       12075  15275  13437  15827  16517  9293   11935  9635   9277
       9610   5283   5409   4622   3997   3312   1471   2023   1939
       1077   1009   394    328    924    489    224    198    75
       397    414    0      217    14     51     33     0      0
       33     0      0      0      0      0      0      33
1996   124.6  30     158    457    0      1152   154    3072   5424
       7138   13022  19935  24086  25272  36443  37851  41499  36003
```

```
        32572   32266   30880   35346   22239   22547   20366   18141   17291
        8294    10510   7288    6158    4282    4588    2999    1613    2063
        2221    1366    1136    614     380     167     175     168     225
        125     132     150     42      42      0       94      0       0       0
        0       0       0       0       0       0       0
1997    126.2   0       0       0       0       729     719     78      19
        1618    4481    4714    8865    14440   17040   27877   31321   31403
        34058   35772   35334   33860   30613   26276   24035   21630   21834
        15188   11849   12964   10814   11550   6116    4737    4698    3674
        3009    2003    1609    1499    818     1009    481     227     583     0
        261     300     43      0       116     0       0       0       0       0
        0       0       0       0       0       0
1998    135.6   0       0       206     0       0       297     548     1533
        2004    3696    9835    13158   15458   26169   32027   36962   38671
        40387   44167   41935   48998   30957   25573   28384   27291   21293
        22536   16841   14714   13189   14397   8982    4384    4446    3810
        3223    2727    955     889     805     1138    669     90      142
        352     363     152     141     0       0       133     44      0       0
        0       0       0       0       0       0       0
1999    119.0   159     249     0       107     130     550     468     1533
        3576    6153    10313   12245   14244   23419   25446   34100   30053
        31565   30555   27139   29223   21845   23347   19666   16201   16554
        15497   10076   10117   6234    6440    4623    3514    2408    1915
        1308    1587    1268    554     546     507     194     431     217
        189     52      0       52      42      0       0       0       0       0
        0       0       0       0       0       0       0
2000    103.5   0       0       0       266     1035    2105    732     2822
        3639    5635    9326    18178   16236   19019   23596   41943   31561
        24124   27453   21412   34661   21460   16269   15224   11583   11686
        10290   4130    5155    4047    5953    1403    2923    2404    1637
        1405    1558    254     322     272     136     65      166     0       0
        89      74      0       0       0       0       0       0       0       0
        0       0       0       0       0       0
```

```
2001    87.2    0       0       0       0       0       0       0       141
        974     529     4762    6995    6827    13701   14133   21859   14137
        16229   18242   14292   23217   12627   8866    11900   9538    12082
        7583    5256    7390    5120    6697    2848    1158    1573    1108
        1850    1615    457     557     170     192     25      0       78
        192     64      100     86      74      0       0       0       0       0
        0       0       0       0       0       0       0
#
#nLF2s
1
#LF2            (*)Dummy Data
#       Sqrt(N) mm 40   41      42      43      44      45      46      47
        48      49      50      51      52      53      54      55      56
        57      58      59      60      61      62      63      64      65
        66      67      68      69      70      71      72      73      74
        75      76      77      78      79      80      81      82      83
        84      85      86      87      88      89      90      91      92
        93      94      95      96      97      98      99      100
1995    94.2    0       258     0       0       0       438     405     1104
        1349    2946    6726    8312    8032    13443   12433   20675   19501
        12075   15275   13437   15827   16517   9293    11935   9635    9277
        9610    5283    5409    4622    3997    3312    1471    2023    1939
        1077    1009    394     328     924     489     224     198     75
        397     414     0       217     14      51      33      0       0
        33      0       0       0       0       0       0       33



#test
53811
```

## Appendix III-3: Data set 2 used for Management Zone 2

```
#data for SeaUrchin for model
#this one is Zone 2 data
#serial number
53811
# debug
0
#init_int restart   normally zero
0
#likeswitch 1=normal 2=fattail
#use fattails
2
#priorswitch 1=lognormal 2= Cauchy
#use Cauchy
1
#FirstYear, LastYear, ProjectYear
      1987      2001            2006
#init_ivector LL1switch(1,6);       switches for the data
# 1 CPUE 2 IS 3 LF 4 LF2 5 tags
1 0 1 0 0 0
#LFweight LF2weight  LFminobs LF2minobs
1 1  40  40
# cols, L, firstbin (centre), binwidth


7  61   40.5  1.0



#year  TCC    CPUE          MLL    Surv   MaxLL  Tolerance
1987   674    -1            -1     -1     -1     -1
1988   666    -1            -1     -1     -1     -1
```

```
1989   628    -1            -1     -1     -1     -1
1990   1355   -1            -1     -1     -1     -1
1991   2619   -1            -1     -1     -1     -1
1992   7239   -1            -1     -1     -1     -1
1993   8283   -1            -1     -1     -1     -1
1994   8590   219.67 -1     -1     -1     -1
1995   6474   208.00 50.8   -1     -1     0.1
1996   6016   203.52 50.8   -1     -1     0.1
1997   4550   188.50 50.8   -1     -1     0.1
1998   4811   187.86 50.8   -1     -1     0.1
1999   3991   175.36 50.8   -1     -1     0.1
2000   3213   151.67 50.8   -1     88.9   0.05
2001   2037   130.20 52.4   -1     76.2   0.05

#catch and MLS MxLS and sigmaProject for projections
   2000      52.4    76.2  0.60
# a and b for the length-weight power function
1.74E-09
2.655
# burn-in period


#SHOULD BE 50
50
# lag between spawning and rect
# SHOULD BE 3
3
# ERatemax and ERateweight for penalty
#SHOULD BE 0.8 and something big
0.70  1000

#maturity  mat50 mat95                     (*)dummy set all 1
91 105
```

```
#---------------------------------------------
#PRIORS
#---------------------------------------------


#phase lb     ub     type   mean    cv initial value
#type: 0 uniform, 1 normal, 2 lognormal                  (*)initial value


#Rcoff


1      5    50    0     20       1    15
#M
1   0.01  0.50    2  0.10     0.1  0.20
#Linf (commented out, not used in this assessment)
#2    100   250    0     0       0   150
#BrodyK(commented out, not used in this assessment)
#2   0.01  0.80    0     0       0  0.25
#Select50IS (commented out, not used in this assessment)
#2   70     125    0     0       0    95
#Select95IS   (commented out, not used in this assessment)
#2   70     125    0     0       0   110
#Select50LF
#-2   40     125    0     0       0   46
2   40     125    0     0       0   52
#Select95LF (commented out, not used in this assessment)
#-2   45     145    0     0       0   47
#2   45     145    0     0       0   53
#r (slope of selectivity curve)
2   0.00001   2   2     0.1       0.1   0.5
#Eps
3   -2.3   2.3    1     0     0.4     0
```

```
#rho
#-3   0.00001 0.99  0     0       0 0.0001
1   0.00001 0.99  0     0       0 0.0001
#GrowthStddev
#-1  -1       1    0     0       0     0
#GrowthCV
#-1   0       1    0     0       0  0.39
#---------------------------------------
#init_number xxstdmin;
1
#init_number sigmaIS;
0.25
#init_number sigmaCPUE;
0.50
#nLFs
7
# LFs  (shed)
#      Sqrt(N)mm 40  41     42     43     44     45     46     47
       48     49     50     51     52     53     54     55     56
       57     58     59     60     61     62     63     64     65
       66     67     68     69     70     71     72     73     74
       75     76     77     78     79     80     81     82     83
       84     85     86     87     88     89     90     91     92
       93     94     95     96     97     98     99     100
1995   116.0  123    129    510    1321   1724   2809   4245   7541
       10556  17774  18313  23842  24273  24826  25837  24719  23115
       19040  19567  20660  22123  20831  13162  15642  13381  15900
       15477  11434  10036  10897  12235  12698  7277   7086   6979
       7490   6198   3765   4179   3306   2673   2189   970    847
       1476   1381   170    347    675    410    0      169    169
       169    55     67     0      0      0      0      0
1996   164.9  276    300    668    1035   2555   3169   9151   9738
       14122  24678  32950  36295  58823  56257  66413  78981  65250
```

```
        57444  62628  52678  58927  41858  41542  38744  38217  35872
        31416  25626  24091  19335  19118  13019  13894  10945  10522
        11153  7273   7888   7217   4812   4455   3873   3944   2210
        2014   1397   859    1059   784    201    464    201    156    0
        349    0      0      0      0      0      0
1997    146.3  0      355    101    442    245    881    831    4043
        4750   9022   17980  17282  25954  33464  44101  46614  41273
        46355  51191  52168  60217  35552  41996  37260  37581  36800
        28318  27676  22168  21487  20758  12543  13701  12727  10764
        10029  11253  4494   7367   3385   3088   2402   2128   905
        1232   1122   1346   898    275    49     256    610    57
        25     0      0      131    180    0      0      0
1998    151.2  0      0      0      0      96     1299   1268   3116
        4974   9374   21992  25681  27737  37767  40311  51933  51692
        49243  50399  49271  69914  38374  27699  35957  42289  33043
        28345  27798  21306  22374  25008  20548  7466   10778  10740
        8775   6692   6713   5108   3534   4679   1641   522    1991
        1905   860    1027   604    694    136    74     89     0      0
        0      263    61     67     74     0      94
1999    139.7  0      0      0      0      145    1106   1473   2978
        5411   8313   19145  26001  33754  35220  38104  43547  40258
        38797  39044  38436  38409  33576  30426  27741  25232  26634
        22222  22751  17785  18814  19556  12171  12711  8811   10775
        9728   7816   6498   4544   3109   2889   2063   1218   1351
        859    1250   1313   575    133    126    78     0      0
        161    0      0      0      0      0      43     0
2000    113.8  0      0      0      0      717    855    1442   1279
        5031   6442   17919  22312  25578  27062  39341  44338  40152
        22033  25395  27255  33528  17030  16505  14105  16465  16278
        13191  6268   6784   6175   6487   3892   3799   3693   3511
        2591   2023   1851   1182   1396   844    555    375    347
        354    182    149    0      0      43     202    0      0      0
        0      0      0      0      0      0      0
```

```
2001    103.2   0       0       0       0       0       278     224     243
        1434    1928    5985    9284    20501   20986   23803   45274   30590
        15636   22873   21597   31427   23020   8944    10387   13459   18269
        9324    4623    8019    4480    6174    4374    3245    1822    2680
        2094    1936    738     1230    320     234     76      379     87
        351     198     0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0
#\
#nLF2s
1
#LF2            (*)Dummy Data
#       Sqrt(N)mm 40    41      42      43      44      45      46      47
        48      49      50      51      52      53      54      55      56
        57      58      59      60      61      62      63      64      65
        66      67      68      69      70      71      72      73      74
        75      76      77      78      79      80      81      82      83
        84      85      86      87      88      89      90      91      92
        93      94      95      96      97      98      99      100
1995    116.0   123     129     510     1321    1724    2809    4245    7541
        10556   17774   18313   23842   24273   24826   25837   24719   23115
        19040   19567   20660   22123   20831   13162   15642   13381   15900
        15477   11434   10036   10897   12235   12698   7277    7086    6979
        7490    6198    3765    4179    3306    2673    2189    970     847
        1476    1381    170     347     675     410     0       169     169
        169     55      67      0       0       0       0       0



#test
53811
```

## Appendix III-4: Data set 2A used for Management Zone 2

```
#data for SeaUrchin for model
#this one is Zone 2 data
#serial number
53811
# debug
0
#init_int restart   normally zero
0
#likeswitch 1=normal 2=fattail
#use fattails
2
#priorswitch 1=lognormal 2= Cauchy
#use Cauchy
1
#FirstYear, LastYear, ProjectYear
      1987      2001            2006
#init_ivector LL1switch(1,6);        switches for the data
# 1 CPUE 2 IS 3 LF 4 LF2 5 tags
1 0 1 0 0 0
#LFweight LF2weight  LFminobs LF2minobs
1 1  40  40
# cols, L, firstbin (centre), binwidth


7  61   40.5  1.0



#year  TCC    CPUE          MLL    Surv   MaxLL  Tolerance
1987   842    -1            -1     -1     -1     -1
```

```
1988   832    -1            -1     -1     -1     -1
1989   785    -1            -1     -1     -1     -1
1990   1602   -1            -1     -1     -1     -1
1991   3274   -1            -1     -1     -1     -1
1992   9048   -1            -1     -1     -1     -1
1993   10354  -1            -1     -1     -1     -1
1994   10707  219.67 -1     -1     -1     -1
1995   8093   208.00 50.8   -1     -1     0.1
1996   7520   203.52 50.8   -1     -1     0.1
1997   5459   188.50 50.8   -1     -1     0.1
1998   5533   187.86 50.8   -1     -1     0.1
1999   4789   175.36 50.8   -1     -1     0.1
2000   3775   151.67 50.8   -1     88.9   0.05
2001   2241   130.20 52.4   -1     76.2   0.05

#catch and MLS MxLS and sigmaProject for projections
   2000      52.4    76.2  0.60
# a and b for the length-weight power function
1.74E-09
2.655
# burn-in period

#SHOULD BE 50
50
# lag between spawning and rect
# SHOULD BE 3
3
# ERatemax and ERateweight for penalty
#SHOULD BE 0.8 and something big
0.70  1000

#maturity  mat50 mat95                    (*)dummy set all 1
91 105
```

```
#---------------------------------------------
#PRIORS
#---------------------------------------------


#phase lb     ub     type   mean   cv initial value
#type: 0 uniform, 1 normal, 2 lognormal                  (*)initial value


#Rcoff


1      5    50    0     20       1    15
#M
1   0.01  0.50    2  0.10     0.1  0.20
#Linf (commented out, not used in this assessment)
#2    100   250    0     0       0   150
#BrodyK(commented out, not used in this assessment)
#2   0.01  0.80    0     0       0    0.25
#Select50IS (commented out, not used in this assessment)
#2   70     125    0     0       0    95
#Select95IS   (commented out, not used in this assessment)
#2   70     125    0     0       0   110
#Select50LF
#-2   40     125    0     0       0   46
2    40    125    0     0       0   52
#Select95LF (commented out, not used in this assessment)
#-2   45     145    0     0       0   47
#2   45     145    0     0       0   53
#r (slope of selectivity curve)
2   0.00001   2   2     0.1       0.1   0.5
#Eps
3   -2.3   2.3    1     0     0.4     0
```

```
#rho
#-3   0.00001 0.99  0     0       0 0.0001
1   0.00001 0.99  0     0       0 0.0001
#GrowthStddev
#-1  -1       1    0     0       0     0
#GrowthCV
#-1   0       1    0     0       0  0.39
#---------------------------------------
#init_number xxstdmin;
1
#init_number sigmaIS;
0.25
#init_number sigmaCPUE;
0.50
#nLFs
7
# LFs  (shed)
#      Sqrt(N)mm 40  41     42     43     44     45     46     47
       48     49     50     51     52     53     54     55     56
       57     58     59     60     61     62     63     64     65
       66     67     68     69     70     71     72     73     74
       75     76     77     78     79     80     81     82     83
       84     85     86     87     88     89     90     91     92
       93     94     95     96     97     98     99     100
1995   116.0  123    129    510    1321   1724   2809   4245   7541
       10556  17774  18313  23842  24273  24826  25837  24719  23115
       19040  19567  20660  22123  20831  13162  15642  13381  15900
       15477  11434  10036  10897  12235  12698  7277   7086   6979
       7490   6198   3765   4179   3306   2673   2189   970    847
       1476   1381   170    347    675    410    0      169    169
       169    55     67     0      0      0      0      0
1996   164.9  276    300    668    1035   2555   3169   9151   9738
       14122  24678  32950  36295  58823  56257  66413  78981  65250
```

```
        57444   62628   52678   58927   41858   41542   38744   38217   35872
        31416   25626   24091   19335   19118   13019   13894   10945   10522
        11153   7273    7888    7217    4812    4455    3873    3944    2210
        2014    1397    859     1059    784     201     464     201     156     0
        349     0       0       0       0       0       0
1997    146.3   0       355     101     442     245     881     831     4043
        4750    9022    17980   17282   25954   33464   44101   46614   41273
        46355   51191   52168   60217   35552   41996   37260   37581   36800
        28318   27676   22168   21487   20758   12543   13701   12727   10764
        10029   11253   4494    7367    3385    3088    2402    2128    905
        1232    1122    1346    898     275     49      256     610     57
        25      0       0       131     180     0       0       0
1998    151.2   0       0       0       0       96      1299    1268    3116
        4974    9374    21992   25681   27737   37767   40311   51933   51692
        49243   50399   49271   69914   38374   27699   35957   42289   33043
        28345   27798   21306   22374   25008   20548   7466    10778   10740
        8775    6692    6713    5108    3534    4679    1641    522     1991
        1905    860     1027    604     694     136     74      89      0       0
        0       263     61      67      74      0       94
1999    139.7   0       0       0       0       145     1106    1473    2978
        5411    8313    19145   26001   33754   35220   38104   43547   40258
        38797   39044   38436   38409   33576   30426   27741   25232   26634
        22222   22751   17785   18814   19556   12171   12711   8811    10775
        9728    7816    6498    4544    3109    2889    2063    1218    1351
        859     1250    1313    575     133     126     78      0       0
        161     0       0       0       0       0       43      0
2000    113.8   0       0       0       0       717     855     1442    1279
        5031    6442    17919   22312   25578   27062   39341   44338   40152
        22033   25395   27255   33528   17030   16505   14105   16465   16278
        13191   6268    6784    6175    6487    3892    3799    3693    3511
        2591    2023    1851    1182    1396    844     555     375     347
        354     182     149     0       0       43      202     0       0       0
        0       0       0       0       0       0       0
```

```
2001   103.2  0      0      0      0      0      278    224    243
       1434   1928   5985   9284   20501  20986  23803  45274  30590
       15636  22873  21597  31427  23020  8944   10387  13459  18269
       9324   4623   8019   4480   6174   4374   3245   1822   2680
       2094   1936   738    1230   320    234    76     379    87
       351    198    0      0      0      0      0      0      0      0
       0      0      0      0      0      0      0
#\
#nLF2s
1
#LF2          (*)Dummy Data
#      Sqrt(N)mm 40  41     42     43     44     45     46     47
       48     49     50     51     52     53     54     55     56
       57     58     59     60     61     62     63     64     65
       66     67     68     69     70     71     72     73     74
       75     76     77     78     79     80     81     82     83
       84     85     86     87     88     89     90     91     92
       93     94     95     96     97     98     99     100
1995   116.0  123    129    510    1321   1724   2809   4245   7541
       10556  17774  18313  23842  24273  24826  25837  24719  23115
       19040  19567  20660  22123  20831  13162  15642  13381  15900
       15477  11434  10036  10897  12235  12698  7277   7086   6979
       7490   6198   3765   4179   3306   2673   2189   970    847
       1476   1381   170    347    675    410    0      169    169
       169    55     67     0      0      0      0      0



#test
53811
```