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**An age-structured stock reduction analysis (SRA) model for Gulf of Mexico red snapper that accounts for uncertainty over the ages of density-dependent natural mortality**

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**Executive Summary**

The stock reduction analysis does the following.

1. The method starts the population at projected unfished conditions (based on data derived from historical documents dating back to 1872) and projects the population to the present time taking into account the fishery removals from the population.

2. The model uses a stock-recruit function that can incorporate density dependence in survival rates for the juvenile phases of the fish's life history. Density dependence can be specified to occur just before the shrimp trawl bycatch of age-0 fish, just after the first six months after emergence (called age-1), or just after the first 18 months following shrimp trawl bycatch of age 1 fish (called age-2).

3. The model requires life history parameter inputs such as mass at age, fecundity at age, steepness in the stock-recruit function and natural mortality rate at age which are provided by NMFS and agreed to by SEDAR participants

4. The model requires fishery inputs such as observed bycatch, landings for recreational and commercial fisheries, out of season discards for recreational and commercial fisheries, selectivity at age for each of the different fisheries modelled, including the selectivity of discarded fish, relative to the landed fish. Selectivity at age for shrimp trawl bycatch has been computed separately for the years before 1999 and then after 1999 to take into account the introduction of bycatch reduction devices late in 1998. These are provided by NMFS and agreed to by SEDAR participants.

5. The model can be fitted to relative abundance indices by estimating average unfished recruitment ($R_0$) and the constants of proportionality (i.e., factors that scale model predicted abundance to each abundance index) for each index of abundance. The model finds the best fit of the predicted abundance trends to the observed abundance trends. Catch-age estimates of stock-recruit deviates can also be included to account for variation in cohort strength. The model can also be constrained to fit recent estimates of fishing mortality rates obtained from other analyses (e.g., ASAP, CATCHEM).

6. Density-dependent survival rate implies that the average survival rate of individuals of a given age group in a population depends on the abundance of conspecifics of that age group; higher abundance will tend to lower the survival rate for example due to increased exposure to predation when the availability of hiding spots is limited. When density dependent survival rate is specified to occur at either age-one or two years the model calculates density independent survival of eggs to age-0 just at settlement and applies the density-independent rates of natural mortality for each age that have been previously specified in the data workshop. The model uses the initial slope of the stock recruit function under the age-0 density dependent scenario to obtain the number of age-0 fish in models with density dependence at either age-1 or 2 years. This permits the model to account for shrimp bycatch removals, directed fishery bycatch and natural mortality regardless of the age at which density dependence is assumed to occur.

7. Once a value for $R_0$ is obtained, the model can be projected from unfished conditions in 1872 to the present and then from the present into the future to evaluate the potential consequences of alternative fishery management options.

<u>The general advantages of the stock reduction analysis are as follows</u>:

1. The model runs very fast (a few seconds to do an estimation and projection) and permits a “gaming” approach in which a large variety of model assumptions and input settings can be efficiently evaluated. This is facilitated because the model has on-screen graphics to show the

fit of the model to the abundance indices and the results of model projections. This permits quick learning about the sensitivity of assessment model results to different input assumptions.

2. The model permits an evaluation of the plausibility of stock-recruit parameter estimates obtained in catch-age analyses of the last few decades in over a century of exploitation of this fish stock. Specifically, the appropriateness of specific catch-age estimated $R_0$ and steepness values can be evaluated based on the criteria that subsequent model outputs should be consistent with the historical record. For example, if the modelled stock hardly depletes at all with these inputs, this model prediction is inconsistent with the high values of fishing mortality rate implied in the catch-age data and this provides reason to question the credibility of the catch-age stock-recruit parameter estimates and assumptions.

3. The model permits an evaluation of the credibility of alternative assumptions about where in the life history density dependence occurs. The model can be fitted to indices of abundance and catch-age fishing mortality rate estimates under the different assumptions about the ages of density dependence. The goodness of fits of the model to the data under the different assumptions about the age of density dependence can be assessed.

4. Because this model runs very fast, it would permit simulation testing of the accuracy of the model or extension so that it could be applied in Bayesian probabilistic calculations to take into account parameter uncertainty. These extensions may be implemented at some later date to test the accuracy of the estimation and provide measures of the uncertainty in estimated quantities.

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5. The model computes an Akaike Information Criterion (AIC) to permit evaluations of the goodness of fit of the different model assumptions to the data and model selection, taking into account differences in the numbers of parameters estimated.

6. The model computes MSY reference points to permit evaluations of stock status and future states of the stock under different management methods with respect to MSY reference points.

7. The program is written in Visual Basic and can be easily learned and modified by those who know VB.

<u>Some of the limitations of SRA analysis are as follows</u>:

1. The model currently does not permit computation of probability intervals or confidence intervals of modelled quantities which should normally be done for any stock assessment method to allow inspection of the statistical uncertainty in parameter estimates. This capability will be included in the near future. Providing confidence intervals will not change the point estimates much at all but will provide indications of the relative amount of uncertainty in them given the fit of the model to the available data.

2. The model depends upon outputs from catch-age analyses for selectivity functions and stock-recruit function deviates. This could increase potential biases in model outputs in some runs when settings (e.g., natural mortality rate at age and steepness) different from the catch-age analysis are applied. Such biases could be reduced by updating the SRA analysis to estimate stock-recruit deviates and fishery selectivity parameters and by fitting the SRA model to additional age-structured datasets.

3. The SRA models mortality as a discrete process in the year rather than as a continuous process and could introduce some biases. Although mortality rates occur as continuous

processes over time, it is computationally more efficient to model them as discrete processes that occur at a specific point within each year. Previous modelling work, however, demonstrates that under most conditions, representing mortality rate as events at discrete points in time produces similar results as the full continuous case.

4. It is most likely that density dependence in survival rate occurs over a range of ages rather than at one single age. To increase computational efficiency and maintain a simple approach to keeping track of mortality rates from fishing, density independent natural mortality rates, fishing mortality rates and shrimp trawl bycatch, the density dependence in survival rate is modelled to occur at a single age, rather than as a continuous process and this could introduce bias in estimates of abundance and abundance trends. The direction and magnitude of the bias introduced by the simplifying assumption is not immediately obvious. However, the basic effects on the stock assessment of assuming different mean ages over which density dependence occurs can still be readily evaluated with the current model.

5. The SRA does not compute SPR reference points (due to lack of time to implement these).

6. The model assumes stationarity in most parameters over time. For example, it assumes that the fisheries' catchabilities, the carrying capacity and selectivity functions for the commercial and recreational fisheries have remained constant over time. However, the introduction of additional offshore oil and gas platforms could mean that the stock has become more resilient to exploitation if carrying capacity is increased– or it may mean that it is more susceptible because it aggregates snapper making them easy to find for even novice fishermen. The assumption of stationarity in the SRA model could thus lead to underestimates of the recent potentially higher values for carrying capacity and MSY (average unfished recruitment) or underestimates of potential recent increases in catchability. These assumptions could be modified however to evaluate the sensitivity of model results to such alternative hypotheses.

7. The SRA model assumes that the inputted catches are known without error, when in fact there may be pronounced observation error in some of the catch time series such as the bycatch time series and earlier parts of the commercial and recreational catch time series.

<u>Key results</u>

1. Under density dependence at age 0, and using the 1999 ASAP settings (most recent past stock assessment settings) for steepness (h), average unfished recruitment ($R_0$) natural mortality rates, and stock-recruit deviates, the SRA model was run from 1872 to the present. This was done to evaluate the plausibility of stock-recruit parameter estimates obtained in the 1999 stock assessment and others presented at SEDAR when the stock assessments fitted to shorter time series. According to the SRA model, it was not possible to obtain values for fishing mortality rates as high as those from current and past ASAP or VPA. If h is set at 0.95 and $R_0$ is set at 245 million (obtained from the 1999 stock assessment), then the computed fishing mortality rates were very low (e.g., 0.002 $yr^{-1}$ for the average F for age 3 for years 1987-1998 ($F_{3,\ 87\text{-}89}$)) compared to about 0.47 $yr^{-1}$ in the 2005 ASAP assessment. In this case, the estimate of spawner potential in 2004 ($Eggs_{04}/Eggs_{unfished}$) turned out to be implausible, i.e., at 110% of unfished conditions. This value resulted because the ASAP stock-recruit residuals for the 1990s were strongly positive and the fishery removals were insufficient to appreciably reduce the stock at the $R_0$ of 245 million fish and steepness of 0.95. The main conclusion that can be drawn is that stock-recruit parameter estimates obtained by fitting a model to data obtained at the end of a time series of exploitation such as has been done in the 1999 and 2004 ASAP

assessments, can produce stock-recruit parameter estimates that are inconsistent with the longer historical time series and possibly highly biased.

2. The sensitivity of stock assessment model output to differing assumptions about the age at which density dependent survival rate occurs was evaluated. With density dependence set at age 0 years, as in the 1999 and 2004 ASAP assessment, and when $R_0$ and constants of proportionality for abundance indices were estimated and the model was fitted to the relative abundance indices, it was not possible to find parameters values that achieved estimates of depletion and fishing mortality rates as high as the values found in the 1999 and 2004 ASAP and 2004 VPA assessments. For example, under a variety of conditions, and different sets of abundance indices used, the estimates of $Eggs_{04}/Eggs_{unfished}$ were between 33% and 89% and $F_{3,\ 87\text{-}89}$ were between 0.004 and 0.04 $yr^{-1}$. Thus, the SRA model results indicate that 1999 ASAP settings for density dependence at age 0 and average unfished recruitment (both the low and high values assumed) are inconsistent with the historical record of catch removals -- and that the 1999 ASAP results which are based on the assumptions that density dependence occurs at age 0 and that recruitment was either near to unfished conditions in 1971 or near to unfished conditions in the mid to late 1970s should not be applied to provide management advice.

3. With density dependence set at either age 1 or age 2 years (both are equally plausible given current knowledge) rather than age 0, it became possible to obtain estimates of current stock status similar to those obtained in the ASAP and VPA assessments of the recent catch-age data. This provides empirical support in favour of the hypothesis that density dependence occurs at age 1 or 2 years rather than at age 0. Estimates of $Eggs_{04}/Eggs_{unfished}$ ranged between 8% and 37% and $F_{3,87\text{-}89}$ ranged between 0.09 and 0.18 $yr^{-1}$. The MSY values estimated under these more plausible settings were far lower than those under density dependence at age 0, and indicate that the current TAC may be higher than the MSY.

4. Under projections with density dependence at age 1 or age 2 years, the projected recovery time was highly sensitive to the TAC but relatively insensitive to different future values for shrimp trawl bycatch (STBC) removals. For example, under the scenarios and constant TAC policies evaluated (ranging between 0 and 9 million pounds per year), future annual STBC from zero to 25 million age 0 to 2 year fish changed stock recovery rates relatively little.

5. The projections changed very little when minimum size limits were removed in the recreational and commercial fisheries. This was partly because the low capture induced mortality rates for fish released by the recreational sector permitted the majority of these fish to survive and contribute the annual catch at later ages and larger sizes. The average age of fish discarded in the recreational fishery was one year (as opposed to two years for the commercial fishery), and a far larger number of fish are discarded in the recreational fishery. In contrast, if all of the discarded recreational fish are retained, then due to the small size of recreational discards, the number of fish killed before the TAC is met can be nearly as high or higher than when discarding is permitted. Thus, the high survival rate of fish discarded from the recreational fishery and the larger numbers of small fish required to make up the TAC reduced considerably the potential positive effects of eliminating the minimum size limits in both the commercial and recreational fisheries.

6. Under the scenarios (which) considered, stock recovery to $B_{MSY}$ before 2032 could only be achieved only by reducing the TAC. TACs between about 2.5 and 4.5 mp permitted recovery to $B_{msy}$ before 2032. Failure to reduce the TAC by about half resulted in projected stock collapse within the next 10 years.

## Introduction

In this paper, I present an age-structured population dynamics model of Gulf of Mexico *Lutjanus campechanus* and apply it in a stock reduction analysis (SRA) from unfished conditions circa 1872. Stock reduction stock assessment models have been applied in the last few decades in many different instances including stock assessments of South African pelagic fishes, New Zealand groundfish, North Pacific groundfish, Namibian groundfish, to name a few. The model presented in this paper (termed "SRA model") has been constructed to evaluate the plausibility of stock-recruit model parameters and assumptions by taking into account catch removals from the population from unfished conditions. This SRA is also applied to help identify modelling assumptions and those parameters where uncertainty is consequential and to indicate the implications of key alternative hypotheses for stock status and appropriate management methods to help achieve stock rebuilding.

One key uncertainty is over where density dependence in survival rates occurs in the fish's life history. This has been a topic of debate since before the 1999 stock assessment and a few papers were presented at this assessment that further address the issue (Gazey 2004; Powers and Brookes 2004). In this paper the assumption of density dependence at the beginning of age 0 year as in the 1999 assessment is one alternative considered. The paper presents one alternative in which Beverton-Holt recruitment is applied at the beginning of age 1 and the beginning of age 2 year.

There are several simplifying approximations utilized in the current form of the SRA model that will impact the model's results and make them different from those obtained in the ASAP, VPA and CATCHEM assessments. While the details of the results might be different from the ASAP, VPA and CATCHEM assessments, the age structured model applied still captures many of the key features of the population dynamics, fishery and bycatch and is applied as an alternative stock assessment approach.

This paper also presents results using contrasting methods to compute MSY-related reference points for fish stocks with large amounts of bycatch of juveniles, and different values for the rate of natural mortality at age for age 0 and age 1 year fish.

## Methods and Data Inputs

The equations for the age-structured population dynamics model are presented in Appendix 1. The model is age structured with a plus group at 15 years. The simulation model is set up to allow the plus group to be easily changed to younger or older ages. The Beverton-Holt stock-recruit function employed models recruitment at the beginning of either age 0, 1 or 2 years. In the former case, age 0 recruits are predicted from the total number of eggs spawned, assuming a sex ratio of 50% females at age. In age 1 case, age 1 recruits are predicted from the total number of fish at the end of age 0. In age 2 case, age 2 recruits are predicted from the total number of fish at the end of age 1. The fish killed by commercial fishing were modelled using the catch biomass data for the commercial fleets aggregated into single annual values. Recreational fishing mortality and shrimp trawl bycatch mortality were modelled separately using recreational catch data and annual shrimp trawl bycatch estimates provided at the August SEDAR workshop (Table 1).

Unlike the ASAP assessment, this model projected the population from the year 1872, the first year that records of commercial catches are available. Records of recreational catch values begin in 1900. Records Shrimp trawl bycatch of juvenile red snapper begin in 1948 when the brown shrimp fishery began and the values in unreported years before 1972 were filled using estimates of shrimp fishing effort prior to 1972 and an approximation of catch of juvenile red snapper per unit shrimp trawl effort in 1972-1974 (Tables 1 and 2). Using a time series of filled shrimp trawl bycatch and commercial catch values from before 1971 will help to test whether the recent fishing mortality rate values estimated under catch-age methods can be achieved under the values for steepness and average unfished recruitment ($R_0$) estimated from the same methods. For example, if only very low fishing mortality rates result even when the full historic catch series have been modelled, this may imply that either the value for steepness or $R_0$ applied or both may be too large. Catch from recreational and commercial fisheries and estimated shrimp trawl bycatch and commercial and recreational discard mortality rates are listed in Table 1.

Fishery selectivity at age vectors for the retained catch were modelled to be stationary over time (Table 3). The selectivity at age vectors used in the SRA model were approximated by using approximations of partial fishing mortality rate (*F*) values at age for the recreational, shrimp trawl bycatch and the aggregated commercial fleets. To compute selectivity at age for the commercial landed catch, out of season commercial discard, recreational catch, shrimp trawl bycatch and recreational and commercial discards, the total fishing mortality rate at age estimates for 1984-2003 from the base case ASAP run were utilized (F-at-age and catch and discard-at-age matrices provided by Steve Turner in November 2004). An approximation of fishing mortality rate at age from each catch component was obtained by multiplying the total fishing mortality rate at age in each year by the catch component divided by the total catch at age from all of the different sources of fishing mortality. The commercial landed catch and out of season discards at age were aggregated to produce a single selectivity function for these two sources of fishing mortality, due to similarities in relative catch at age between landings and out of season commercial discards. The average fishing mortality rate at age for each source of fishing mortality was computed from the years 1984 to 2003. This was done for the commercial catches, recreational landings, in-season and out of season recreational discards, and in-season and out-of season commercial discards and shrimp by catch. The average fishing mortality rate at age estimates for each source of fishing mortality were divided by the maximum average fishing mortality rate at age to produce the selectivity at age functions used in the SRA model (Table 3). However, a separate selectivity at age function was computed for shrimp trawl bycatch for periods up to 1997 and 1998 and after to take into account changes in selectivity in shrimp trawl bycatch due to the introduction of red snapper bycatch reduction devices in 1998.

A linked selectivity at age function for one set of MSY reference point computations was obtained by taking the average of the total fishing mortality rate at age from 2001-2003 and dividing by the maximum fishing mortality at age for fish recruited to the directed fishery. The discards in the recreational and commercial fisheries are modelled to have begun in 1988 and 1985, respectively. Discards only started to register in the years for each of these fisheries, after the first size-based regulations were imposed in 1984. The selectivity functions for in-season discards in the recreational and commercial fisheries were computed by computing the average fishing mortality rates at age from these two sources of mortality from years 1988 to 2003, and 1985 to 2003, respectively and then dividing by the maximum average fishing mortality rate at age from the landed catch in years from 1984-2003. The values for weight and fecundity at age and fraction mature at age are also listed in Table 3.

Due to time limitations, the model was not fitted to catch-age data. However, the lognormal recruitment residuals from the ASAP assessment for the years 1962 to 2003 were utilized in the SRA model to take into account the recent estimates of variations in cohort strength (Table 4). The SRA model was fitted to relative abundance indices developed for the August 2004 assessment (and have been updated slightly since) and a normal likelihood function with a standard deviation of 0.05 $yr^{-1}$ was applied to constrain the average SRA fishing mortality rate at age 3 years old for years 1987-1989 to be close to that estimated in the ASAP stock assessment (approximately 0.3 $yr^{-1}$).

To compute maximum sustainable yield (MSY) and MSY-related reference points, the 1999 assessment utilized a linked selectivity function that incorporated all sources of estimated fishing and discard mortality from the years 1995-1997 (Schirripa and Legault 1999) (Table 3). While this appears to be reasonable, the computation of MSY is not straightforward. It is argued here that if it is unavoidable shrimp trawl bycatch, then this bycatch mortality rate should not be made to be directly linked to the targeted fishing mortality rates, as it was in the 1999 MSY calculation. This linking of the directed fishery and shrimp trawl selectivity functions for MSY calculation ignores the relationships between shrimp trawl fishing effort and shrimp yield and economics. To recognize the shrimp trawl and red snapper fisheries as separate fisheries, the red snapper MSY calculation could instead utilize a bycatch fishing mortality rate that is cognizant of these various considerations regarding the value of F that is imposed by shrimp trawl bycatch. It is argued here that the shrimp trawl bycatch mortality rates at age should be fixed at values deemed to be plausible under near future conditions (e.g., in the stock-rebuilding horizon), rather than deterministically linked to the directed fishery mortality rates. This could be taken to be the average value for estimated fishing mortality rates from shrimp trawl bycatch with the average taken from the most recent few years, e.g., from 2001-2003. $F_{MSY}$ could then be found by adjusting the fishing mortality rate on the recruited population but keeping the shrimp trawl bycatch fishing mortality rates constant at the values deemed to be most plausible for the next several years. If discards for the recreational and commercial fisheries are a function of recreational and commercial fishing effort, then only the recreational and commercial discards in the computation of MSY should be made to be directly linked to the fishing mortality rate targeted on the recruited population.

A variety of measures of abundance are computed to allow inspection of how different aspects of the population have responded to exploitation. These include calculations of total mature stock biomass at MSY, unfished conditions, and in each year. Similarly, total egg abundance, and total abundance that's been recruited to the fishery and vulnerable to exploitation are also computed at MSY, unfished conditions and in each year.

Moreover, the selectivity pattern utilized for MSY computation should be the selectivity deemed most plausible for the stock rebuilding horizon and thus could be taken from the average of the estimated selectivities in the last few years.

The MSY calculations in this paper can thus utilize either a linked selectivity function like the one used in Schirripa and Legault (1999) or alternative selectivity functions that for example represent a constant shrimp trawl bycatch fishing mortality rate on juvenile snapper (set separately for age 0 and age 1 fish) and the selectivity at age of the directed fisheries, also taking into account bycatch from the directed fisheries (Table 3).

The SRA model can be run with a fixed set of parameter value inputs or fitted to one or more relative abundance time series based on maximum likelihood and a lognormal likelihood function of the data (Appendix 1). The time series of relative abundance to which the model is fitted are listed in Table 5. These include the SEAMAP index of age 1 fish abundance (1972-2003), the shrimp trawl fishery nominal red snapper index (1967-1979), the Gulf-wide MRFSS recreational index, the video index (1992-2002), and the larval bongo net index (1986-2002). The model was also fitted to estimates of the average fishing mortality rate for age 3 fish for the years 1987-1989 from the ASAP base case stock assessment run. This was done to constrain the SRA model to be consistent with the fishing mortality rates indicated by catch-age analysis.

The SRA model can be projected into the future to evaluate the potential consequences of alternative fisheries management policies for Gulf of Mexico red snapper under a variety of plausible alternative scenarios for population dynamics and shrimp trawl bycatch. These include alternative TAC policy options for the directed fishery and alternative assumptions about the future shrimp trawl bycatch of age 0-2 red snapper. The SRA model permits the evaluation of the potential consequences of the elimination of minimum size limits in which all fish captures are counted against the TAC (Appendix 1).

The modelling work undertaken in this paper explores the implications for assessment of stock status and rebuilding potential of some alternative methods to compute MSY. The implications of different values for Beverton-Holt steepness, $M_0$ and $M_1$ are also explored. Furthermore, the SRA is run assuming density dependence at either age 0, age 1 or age 2 years. Future policy options including different TACs, settings for shrimp trawl bycatch, and elimination of minimum size limits in the recreational and commercial fisheries are explored under plausible alternative assumptions for settings for the red snapper population dynamics model.

In the next section, I evaluate the following questions

1. Are the 1999 assessment settings and estimates consistent with the historical record?

2. How do MSY reference points vary when different methods for calculating MSY are used?

3. How do assessment results vary when different sets of indices are used?

4. How do assessment results vary when different values for $M_0$, and $M_1$ are inputted?

5. How do assessment results vary when steepness is varied?

6. How do assessment results vary when the age of density dependence is varied?

7. How do the assessment results vary when the early shrimp trawl bycatch values in years prior to 1973 are reduced by a factor of 0.25 to take into account possible positive bias in the 8.5 multiplier that was applied to shrimp trawl bycatch estimates for years prior to those in which shrimp trawl bycatch data are available and possible positive bias in the all time high estimate in 1972.

8. What are the potential consequences of alternative TAC and other management approaches under different scenarios for the age of density dependence and future scenarios for shrimp trawl bycatch?

In all the instances where an estimation was done, the AIC model goodness of fit statistic was calculated. AIC is computed from:

AIC = –2Log(likelihood) + 2(number of estimated parameters)

The number of estimated parameters in the SRA modelling reported in this paper includes $R_0$ and a constant of proportionality for each relative abundance index to which the model is fitted. The model with the smallest AIC is typically judged to be best overall.

## Results and Discussion

1. Are the 1999 assessment settings and estimates consistent with the historical record?

Running the SRA model from 1872 to the present using the estimates of historic catches, the 1999 parameter values for steepness (h), average unfished recruitment ($R_0$) and natural mortality rate values used in (Schirripa and Legault 1999), gives estimates of recent stock status starkly different from those in Schirripa and Legault (1999). With density dependence set at the beginning of age 0, a steepness of 0.95, an unfished average recruitment ($R_0$) of 245 million, and values of $M_0$ and $M_1$ of 0.5 and 0.3 $y^{r-1}$ as in Schirripa and Legault (1999), then the computed current spawning stock potential (egg abundance in 2004 / unfished egg abundance) is not depleted (e.g., $Eggs_{04}/Eggs_{unfished}$ = 110% and $Eggs_{04}$ / $Eggs_{msy}$ = 319% (Table 6, Figure 1). Values larger than unfished conditions are due to the high values for $R_0$, and steepness, low catch removals relative to these, and the series of high positive values for stock-recruit function residuals during the 1990s. The average fishing mortality rate for age 3 fish for years 1987-1989 ($F_{3,\ 87\text{-}89}$) is about 0.002 $yr^{-1}$, much lower than the values of about 0.3 $yr^{-1}$ in the ASAP results (Table 6). When the stock-recruit residuals are set at 0, $Eggs_{04}/Eggs_{unfished}$ was about 70%, still far too high and $F_{3,\ 87\text{-}89}$ was still 0.002 $yr^{-1}$, still far too low (Table 6). Using the lower $R_0$ value from Schirripa and Legault (1999) of 163 million provided stock status estimates also far less depleted than indicated in Schirripa and Legault (1999) (Table 6).

The ratio of model-predicted recruits in 1972 to estimated unfished recruits ($R_{72}/R_0$) was 3.0. The model predicted recruits incorporated the ASAP stock- recruit residuals for years from 1962-2003 and the value for 1972 is the maximum in the time series (3.0 times the predicted). The reason for $R_{72}/R_0$ being equal to the recruitment residual is mainly because of the high steepness which indicates that with stock size of 20% of unfished conditions, recruitment can be expected to be 95% of unfished recruitment. In the 1999 stock assessment, the estimated value for $R_{72}$ which was the highest in the time series was taken as an approximation for $R_0$. However, if steepness is assumed to be very high, my results indicate that this may lead to positive bias in the presumed value for $R_0$. When high steepness is presumed and when SSB is believed to be relatively undepleted, the best approximation of $R_0$ if estimated recruitments are to be utilized to approximate $R_0$ is the average of estimated recruitments values, not a recruitment that's about three times the average. Using a very high recruitment estimate as a proxy for $R_0$ in a stock assessment when high steepness (e.g., 0.95) is assumed may thus give a positively biased estimate of $R_0$.

These results demonstrate that when the time series of catches and shrimp trawl bycatch since 1872 are applied, the settings and estimates obtained in the 1999 stock assessment do not appear to be consistent with the historical record of fishery removals and current understanding of the status of the stock. Other settings for model assumptions and input values are evaluated further below, to find ones that may be more consistent with the historical record.

2. How do MSY reference points vary when different methods for calculating MSY are used?

In most but not all calculations using the SRA model, the estimates of MSY reference points are sensitive to the manner in which MSY is computed, as has been found in other works (Gazey 2004; Powers and Brookes 2004). At first, results using settings as close as possible to the 1999 assessment are reported. These settings include density dependence at age 0 and the 1999 base case value for $R_0$ (245 million fish), values for $M_0$ and $M_1$ of 0.5 and 0.3 $yr^{-1}$, steepness of 0.95, and a linked selectivity function based on the most recent fishing mortality at age matrix from ASAP. The value obtained for $F_{MSY}$ (0.117 $yr^{-1}$) is similar to that obtained in Schirripa and Legault (1999) (0.118 $yr^{-1}$) (Table 6). However, the value for MSY was considerably higher than the 1999 value (202 million pounds versus 108 million) and the total stock biomass at MSY, $totB_{MSY}$, was somewhat higher than that obtained in Schirripa and Legault (1999) (4580 million pounds as opposed to 3930 million pounds). The average unfished total stock biomass ($totB_0$) was 13,089 million pounds. One reason for the differences between these results and the 1999 results is the update in the linked selectivity function, which gives a considerably lower relative vulnerability of age 0 and 1 fish to capture in shrimp trawls than in the 1999 assessment.

When MSY calculations were done with fishing mortality rates from shrimp trawl bycatch unlinked to the targeted fishing mortality rate, considerable differences resulted (Table 6). This was done by applying the average fishing mortality rate on age 1 fish from the ASAP assessment of 0.68 $yr^{-1}$, and the shrimp trawl selectivity function also estimated from ASAP output. Keeping $R_0$ at 245 million, and the other parameter settings as above, the MSY dropped to 74 million pounds, $F_{MSY}$ increased to 0.136, $totB_{MSY}$ dropped to 1169 million pounds, $Eggs_{msy}$/ $Eggs_{unfished}$ dropped to 0.087 and $Eggs_{04}$/$Eggs_{msy}$ increased to 12.5 due to the lowering of the value for $Eggs_{msy}$ under the unlinked selectivity option. Thus, when the shrimp trawl bycatch mortality rates become unlinked to the directed fishery mortality rates and fixed at the estimates for recent estimates for the MSY calculation, the maximum yield obtainable drops considerably, and so does the stock size at which maximum sustainable yield can be obtained.

For an indication of the amount of MSY yield traded off as a result of bycatch in the shrimp trawl fishery, the shrimp trawl bycatch mortality rates were set to zero using the unlinked selectivity function and other parameter settings above. The MSY increased from 74 million pounds to 294 million pounds and $Eggs_{msy}$ / $Eggs_{Unfished}$ increased from 0.087 to 0.30. Under the density dependence at age 0 scenario, this indicates a very large trade-off in red snapper yield as a result of shrimp trawl bycatch and is also found in Gazey (2004).

3. How do assessment results vary when different sets of indices are used?

For comparability with the above results, the first estimation was done using steepness fixed at 0.95, and the settings for $M_0$ and $M_1$ as above and the linked selectivity function. The model was fitted to the indices showing increases, i.e., the MRFSS, video, and larval bongo data and constrained to fit the average of ASAP values for the directed fishing mortality rate in 1987-1989. In this estimation, $Eggs_{04}$/$Eggs_{unfished}$ dropped to a low in the early 1980s, just above the $Eggs_{msy}$ / $Eggs_{unfished}$ reference point of 0.34 and since then has rebounded to 0.885 (Figure 2). The MLE of $R_0$ in this scenario is 144 million and the associated estimate of MSY dropped to 143 million pounds. The estimated fishing mortality, $F_{3,\,87\text{-}89}$, from recreational and commercial fishing is 0.004 $yr^{-1}$. AIC = 1,196,419 (Table 6). Using the base case settings for steepness, natural mortality rates, and $R_0$, the stock assessment, results were identical when the model was fitted to different sets of indices. This is because the model is constrained to fit the average fishing mortality rate for age 3 in years 1987-1989 and does so at the expense of leaving a relatively poor goodness of fit to the relative abundance indices. Thus, the only thing that varied when the model was fitted to the different indices was the AIC. However, this is not comparable when the same model is fitted to different datasets. But overall, the upward bending indices provided the best fits of the SRA model to the data under density dependence at age 0.

When the model is fitted to the indices, the MSY under the linked selectivity option with the shrimp bycatch mortality rate ($F_{1,\,MSY}$) set at 0.68 $yr^{-1}$ on age 1 year, is 44 million pounds (Table 6). The increased to 173 mp when $F_{1,\,MSY}$ was set to 0.

4. How do assessment results vary when different values for $M_0$, and $M_1$ are inputted?

Only higher values for the rate of natural mortality at age 0 and age 1 were applied, since it was concluded in the August SEDAR workshop that the values of 0.5 and 0.3 $yr^{-1}$ were the lowest plausible values and other options to consider included only higher values. All other inputs and assumptions were held the same as in the "base case" 1999 run applied above. When values for $M_0$ and $M_1$ were set at $M_0 = 1$, $M_1 = 0.6\ yr^{-1}$, the estimates of $R_0$ increased from 144 million to 201 million fish, and the estimates of $F_{3,\ 87\text{-}89}$ from recreational and commercial fishing also increased from about 0.004 to 0.007 $yr^{-1}$. The estimate of depletion also was lower with $Eggs_{04}/Eggs_{unfished}$ dropping to 0.837. The estimated MSY dropped to 74 million pounds but the $Eggs_{msy}$ / $Eggs_{unfished}$ reference point remained at 0.34.

When $M_0$ and $M_1$ were increased to $M_0 = 2$, $M_1 = 1\ yr^{-1}$, (keeping steepness at 0.95) $Eggs_{04}/Eggs_{unfished}$ dropped to 0.73, still far above the values estimated in the ASAP assessment. $F_{3,\ 87\text{-}89}$ increased to 0.019 $yr^{-1}$, still far below the values estimated in the ASAP stock assessment (AIC = 5.60 E04) (Table 6).

5. How do assessment results vary when steepness is varied?

When steepness was set at the low value of 0.81, but keeping other settings at the 1999 "base case", the estimate of $R_0$ increased slightly from 144 million fish to 150 million fish and the estimated $F_{MSY}$ decreased to 0.101, MSY decreased to 113 million pounds, $Eggs_{msy}$ / $Eggs_{unfished}$ increased to 0.357 and $Eggs_{04}$/ $Eggs_{unfished}$ decreased to 0.846 (Table 6). Thus, under the 1999 ASAP settings, estimates of MSY reference points and stock status of red snapper are relatively insensitive to the value for steepness applied. When steepness was lowered to 0.81 and $M_0$ and $M_1$ were set at the highest values (2 and 1 $yr^{-1}$), the estimate for $R_0$ increased to 382 million. The estimate for $Eggs_{04}/Eggs_{unfished}$ dropped to 0.68 but MSY dropped considerably to 32 mp. The estimate for $F_{3,\ 87\text{-}89}$ remained very low at 0.017 $yr^{-1}$. The AIC was not as low as in the setting with steepness at 0.95 (AIC = 1.46 E06.); this is mainly because the values for $F_{3,\ 87\text{-}89}$ were higher under the run with $M_0 = 2$, $M_1 = 1\ yr^{-1}$ and steepness = 0.95. It thus appears that under the assumption of density dependence at age 0, it is not possible to obtain SRA results that are similar to the ones obtained by ASAP assessments using data from 1962 to the present.

6. How do assessment results vary when the age of density dependence is varied?

Results assuming density dependence at age 2 were markedly different than those obtained assuming density dependence at age 0 (Table 7). In a "comparability run", steepness was set at 0.95, $M_0$, and $M_1$, at 0.5, and 0.3 $yr^{-1}$, the selectivity for MSY was linked. The main difference is now that rather than seeing a sustained rebound in the stock following the 1970s, the stock shows a progressive decline, especially over the last decade. The model thus did not fit well the upward bending indices. The estimate of unfished age 0 abundance was 366 million. The $F_{MSY}$ estimate in this run was higher (e.g., 0.188) and the MSY reference points were considerably lower (e.g., $totB_{unfished}$ = 266 mp and $totB_{MSY}$ = 86 mp). The estimate of $Eggs_{msy}/Eggs_{unfished}$ did not change much (under the linked selectivity assumption) with the estimate at 0.32. The estimate of $Eggs_{04}/Eggs_{unfished}$ was far lower at 0.108. MSY was much lower at 5.9 million pounds. Estimates of fishing mortality rates resulting from directed fishing were much larger (e.g., $F_{3,\ 87\text{-}89} = 0.176$). The estimate of the ratio of $R_{72}$ / $R_0$ was still very high, i.e., at 1.48, still indicating that the use of the high recruitment observation in 1972, $R_{72}$, would still lead to an overestimate of $R_0$.

The lowest AIC from the runs with density dependence at age 0 and upbending indices came from the run with steepness set at 0.95 and $M_0 = 2$, $M_1 = 1\ yr^{-1}$ and STBC for early years multiplied by 0.25. The AIC was 1.10 E04 (Table 6). The AIC with the change from recruitment at age 0 to age 2 years and also using the upbending indices is far lower (AIC=526) (Table 7). The was because of the much better fit of the model to the ASAP fishing mortality rate estimates and resulted even though density dependence at age 2 provided a poorer fit to the down bending indices (Figure 3).

When the recruit residuals from the ASAP analysis were set to zero, similar levels of depletion from unfished conditions were found (Table 7). However, the maximum steepness that could be fitted was 0.94. Also, the fraction of age 0 abundance in 1972 to age 0 abundance in 1872 dropped from 1.5 to

0.531, indicating that at the 2004 level of SSB, even with very high steepness, the recruitment could be expected to be considerably lower than that under unfished conditions.

Again, when the model was fitted to different abundance indices, the estimates did not change, only the AIC changed. The model fitted the down bending indices (Age 1 sea map CPUE and shrimp trawl cpue) better than the upbending indices (MRFSS, larval bongo and video). Though an AIC is not perfectly comparable when the same model is fitted to different data, the AIC obtained with the down-bending indices was still lower at 437 (Table 7). AIC with all indices was 701. From now on, when density dependence is other than at age 0, these down bending indices will be used as the "base case" indices.

When $M_0 = 1$, $M_1 = 0.6$ $yr^{-1}$ were applied, the maximum value for steepness that could result in a successful fit of the model to the data was 0.92. The estimate of $Eggs_{msy}/Eggs_{unfished}$ changed very little and was 0.325. The MSY was 6.0 million pounds. The estimate of $Eggs_{04}/Eggs_{unfished}$ was still low at 0.154 and the estimate of $F_{3,\,87\text{-}89}$ was 0.157 $yr^{-1}$. The AIC obtained increased to from 437 to 568 (Table 7). On this basis, it would appear then that the option with lower estimates of natural mortality provide a better fit of the model to the data and ASAP fishing mortality rate estimates. However, these intermediate values for $M_0$ and $M_1$ will still be retained further SRA model runs since they were agreed at the August SEDAR workshop to be at least as plausible as the lower values used in the 1999 assessment.

When steepness was set at 0.81, keeping $M_0 = 1$, $M_1 = 0.6$ $yr^{-1}$, $Eggs_{04}/Eggs_{unfished}$ was not as low, at 0.366 or right at $E_{msy}$, ($Eggs_{msy}/Eggs_{unfished} = 0.37$) under the linked selectivity function. However, $F_{3,\,87\text{-}89}$ was lower at 0.085 $yr^{-1}$ and the AIC increased substantially to 2.23E03 (Table 7). Thus, the model fits the data better with higher estimates of steepness.

To evaluate the effects of unlinking the shrimp trawl selectivity in the MSY calculations under density dependence at age 2, the following run was done. At steepness of 0.95, unlinking the selectivity and setting the F at age 1 for STBC to 0.68 $yr^{-1}$ reduced the MSY from 5.9 mp to 5.1 mp (Table 7). The percentage reduction in MSY here is much less than when density dependence was at age 0 (Table 6). Under the unlinked MSY option and with STBC mortality rate at age 0 and 1, set to 0, the MSY was the same under the linked and unlinked selectivity options, i.e., at 5.9 million pounds (Table 7). This is because under the linked selectivity option, the total fishing mortality rate on age 0 and 1 fish was relatively small and at the highest steepness values, low fishing mortality rates before density dependence have practically no impact on recruitment and MSY. In other words, under density dependence at age 2, recruitment of fish to age to 2 years under linked selectivity is practically the same as under a 0 F for these ages. The next calculations were done with slightly lower steepness (0.92) and higher values for M for age 0 and 1, i.e., $M_0 = 1$, $M_1 = 0.6$ $yr^{-1}$. With the shrimp trawl bycatch selectivity unlinked to the directed fishery selectivity in the MSY calculation and $F_1$ set at 0.68 $yr^{-1}$, the MSY reference points obtained were still modified much less than was the case with density dependence at age 0. $Eggs_{msy}$ / $Eggs_{unfished}$ dropped slightly to 0.311. MSY dropped to 4.9 million pounds (Table 7). $F_{msy}$ dropped to 0.12 $yr^{-1}$. When $F_1$ was set to zero in the MSY calculation, the MSY increased from 6.0 mp (under linked selectivity) to 6.1 mp (unlinked selectivity) (Table 7). This slight increase in MSY under $F_1 = 0$ over the linked case is mainly a result of the decreased steepness.

Thus, under density dependence set at age 2 years, the MSY and MSY reference points were much less sensitive to whether the MSY was computed using linked or unlinked selectivity than was the case with density dependence set at age 0 (Table 7). This indicates that under density dependence at ages older than 0 years, there is far less of a trade-off in the yield of the red snapper fishery as a result of shrimp trawl bycatch. For reasons stated above, the MSY calculations in subsequent analyses will be based on the use of an unlinked selectivity function.

With density dependence at age 2 years, with $M_0$ and $M_1$ to 2 and 1 $yr^{-1}$, the maximum steepness that could be incorporated was 0.88. The $Eggs_{msy}$ / $Eggs_{Unfished}$ = 0.32. $Eggs_{fin}$ / $Eggs_{Unfished}$ = 0.13, MSY was 4.3 million pounds. $F_{3,\,87\text{-}89}$ was 0.161 $yr^{-1}$ and AIC was 523 (Table 7).

With density dependence set at age 1 year, steepness set at 0.95, and $M_0$ and $M_1$ set at 1 and 0.6 $yr^{-1}$, the stock assessment results are mostly similar to the instance with density dependence at age 2 years. The stock still declines considerably to the current year and does not rebound as it is shown to do with density dependence at age 0. The estimates for $Eggs_{msy}$ / $Eggs_{Unfished}$ was 0.15, $Eggs_{04}$ / $Eggs_{unfished}$ was 0.15. The estimate of MSY was lower at 3.3 million pounds. $F_{3, 87-89}$ was still close to the ASAP estimate at 0.141 $yr^{-1}$. However, the fit to the data was not quite as good, with the AIC at 667 (Table 7). Setting the shrimp trawl bycatch mortality rate to 0 $yr^{-1}$ in the MSY calculations more than doubled the MSY from 3.3 mp to 7.5 mp. However, this is still a much smaller trade-off in MSY than under the model in which density dependence occurs at age 0 years (Table 7).

Lowering the values for $M_0$ and $M_1$ to 0.5 and 0.3 $yr^{-1}$, provided a poorer fit to the data with the AIC increasing to 1.19 E03. $Eggs_{msy}$ / $Eggs_{Unfished}$ was 0.15. $Eggs_{04}$ / $Eggs_{Unfished}$ increased to 0.23. The MSY increased slightly to 4.1 million pounds (Table 7). $F_{3,87-89}$ dropped to 0.11 $yr^{-1}$.

Increasing the values for $M_0$ and $M_1$ to 2 and 1 $yr^{-1}$, the maximum steepness that could be fitted was 0.93. This provided an improved fit to the data with the AIC decreasing to 449. $Eggs_{msy}$ / $Eggs_{Unfished}$ was 0.16 (Table 7) (Figure 4). $Eggs_{04}$ / $Eggs_{Unfished}$ decreased to 0.092. The MSY decreased slightly to 2.78 million pounds. $F_{3,87-89}$ dropped to 0.167 $yr^{-1}$.

Lower values for steepness at density dependence at age 1, gave poorer fits to the data (Table 7). However, when the stock-recruit function residuals were set to zero, the maximum steepness that could be fitted was 0.90. This gave the lowest estimate of $Eggs_{04}$ / $Eggs_{Unfished}$ of 0.075.

7. How do the assessment results vary when the early shrimp trawl bycatch values are reduced by a factor of 0.25?

Estimates of shrimp trawl bycatch appear to be very large before 1973 compared to 1973 and after. Yet, estimates of shrimp trawl effort before 1973 indicate a gradual build up of shrimp trawl effort from 1948 until about 1980 (Table 2). The very high values for shrimp trawl bycatch prior to 1972 had been obtained by applying a multiplier of about 8.5 which was based on data analyses a few decades ago that suggested that recruitment prior to 1972 was about 8.5 times higher than that in the mid-1970s. In contrast, runs from the CATCHEM assessment model suggest that the shrimp trawl bycatch estimates for years before 1973 could be considerably over-estimated since if such large bycatch values were to have been taken then recreational catches in the 1970s would have to have been many times higher to reduce the stock to levels to those supported by catch-age data in the 1980s. To evaluate the sensitivity of results to potential positive bias in estimates of shrimp trawl bycatch for earlier years, shrimp trawl bycatch values were multiplied by 0.25 for years prior to 1973. In the first run, density dependence was set at age 0, steepness set at 0.95 and using the low values for $M_0$ and $M_1$, and unlinked selectivity was applied. The estimate of $R_0$ dropped considerably from about 144 million to 69 million (Table 6). The MSY also dropped by about half from 44 to 21 million. $Eggs_{04}$ / $Eggs_{Unfished}$ dropped from 10.2 to 5.37, still too high and $F_{3,87-89}$ increased to only 0.01 $yr^{-1}$. Lowering steepness to 0.81 and keeping the same high values for M, and then multiplying the earlier early shrimp trawl bycatch (STBC) values by 0.25 also failed to deplete the stock to levels obtained in ASAP and VPA (Table 6). Using steepness of 0.95 and the highest values for M for ages 0 and 1, and multiplying the STBC series by 0.25 produced slightly more depleted results, e.g., a slightly higher estimate of $F_{3, 87-89}$ of 0.04 $yr^{-1}$ (Table 6). However, this estimate is still much lower than values obtained in ASAP and VPA. Thus, it appears that under density dependence at age 0, modifying the early shrimp trawl bycatch values in combination with other permutations of model settings cannot produce SRA results at all close to those in the ASAP and VPA assessments.

When the earlier shrimp trawl bycatch series was multiplied by 0.25 and density dependence was set at either age 1 or 2 years, the estimates of $R_0$ decreased slightly and other estimated quantities changed relatively little (Table 7).

8. What are the potential consequences of alternative TAC and other management approaches under different scenarios for the age of density dependence and future scenarios for shrimp trawl bycatch?

Based on the above analyses, it was not possible under density dependence at age 0 to identify parameter inputs that could result in stock status and fishing mortality rate estimates at all close to the

ASAP and VPA estimates. Furthermore, the AIC's for all of the density dependence runs under density dependence at age 0 were far higher under the density dependence at age 1 or 2. For these reasons, projections were conducted only using density dependence at age 1 and age 2.

Of the runs with density dependence at either age 1 or 2 years, several resulted in stock status estimates similar to those in the ASAP, CATCHEM and VPA assessments (Table 7).

To limit the set of plausible scenarios for the projections, relatively few shrimp trawl bycatch scenarios and TAC options are considered.

The first set of projections was computed under density dependence at age 2 years, steepness at 0.95 and $M_0$ and $M_1$ of 0.5 and 0.3 $yr^{-1}$. When the TAC and shrimp trawl bycatch are set at zero, it takes until 2014 for the stock to exceed the $B_{MSY}$ reference point (Fig. 5). With STBC set at 15 million, this takes until 2015. With STBC set at 20 million this takes until 2016. With STBC set at 25 million this takes until 2018. The stock crashes in the next five years if STBC is set at 30 million. With STBC set at 15 million, TACs larger than about 1 million pounds failed to result in recovery by the year 2020 (Figure 6). A one million pound TAC permitted recovery by the year 2017. Removing the minimum size limit had no effect on the recovery.

The second set of projections are done under density dependence at age 1 years, steepness at 0.93 and $M_0$ and $M_1$ of 2 and 1 $yr^{-1}$. When the TAC and shrimp trawl bycatch are set at zero, it takes until 2011 for the stock to exceed the $B_{MSY}$ reference point (Fig. 7). With STBC set at 30 million it takes until 2012 for this to occur. With STBC set at 15 million, TACs larger than about 2 million pounds failed to result in recovery by the year 2020 (Figure 6). A two million pound TAC permitted recovery by the year 2017. With a two million pound TAC and the minimum size limit removed in both the commercial and recreational fisheries, the stock recovered a little faster, i.e., in 2016 rather than 2017. Under a 2.5 million pound TAC the stock recovered in 2028, without the size limit, the stock recovered in 2025.

In the third set of projections, the shrimp trawl bycatch was set to 15 million and for each of the stock assessment settings in Table 7 the constant TAC was found that permitted stock recovery to $B_{msy}$ before 2020 and then before 2032. In all of the runs that had better fits to the ASAP fishing mortality rate estimate (grey shaded cells in Table 7), constant TACs between 1.5 and 4 million pounds permitted recovery to $B_{msy}$ before the year 2020. TACS between 2.5 and 4.5 million pounds permitted recover by 2032. Better fits were considered to have AIC values of 857 or lower. The stock-recruit deviate time series from ASAP, particularly the large negative stock-recruit deviate in 2003 was influential in determining the rate of stock recovery. For example, under density dependence at age 2, steepness of 0.95 and rates of natural mortality of 0.5 and 0.3 $yr^{-1}$ for $M_0$ and $M_1$, a constant TAC of 1.5 million pounds achieved stock recovery before 2020. However, when the deviates were set to zero under the same settings, and the model was refitted to the data, then a TAC of 3.5 million pounds achieved stock recovery to $B_{msy}$ before 2020.

**Conclusions**

Applying the SRA in this paper, density dependence at age 0 and the "most likely" 1999 steepness and $R_0$ values, it was not possible to obtain estimates of stock status at all close to those obtained in the 1999 assessment. Under density dependence at age 0 and estimating $R_0$ under a variety of settings for *M* and steepness, it was also not possible to obtain estimates of stock status estimates consistent with those provided by the 1999 and 2004 ASAP and 2004 VPA applications. The amount of depletion from unfished stock sizes is negligible if a steepness of 0.95 and value for $R_0$ of 163 or 245 million are applied in SRA. Under the assumption of density dependence at age 0, the stock showed a strong decline in the 1970s and then a strong rebound in the late 1980s to the present. Under density dependence at age 0, none of the combinations of parameter inputs evaluated permitted the stock to survive through the low point in the 1980s and also to result in the high fishing mortality rates and moderately low stock sizes in the 1990s to the present that are seen in the ASAP and VPA analyses.

Changes in input values for $M_0$, $M_1$, steepness, and the manner in which MSY is calculated can produce different estimates of stock status and biological reference points. Under density dependence at age 0 and 1 years, unlinking the MSY selectivity function to the shrimp trawl fishery increased estimates of $F_{MSY}$, decreased $Eggs_{MSY}$ and MSY, and increased $Eggs_{04}/Eggs_{MSY}$. In contrast, under density dependence at age 2 years, unlinking the selectivity function from the shrimp trawl bycatch had a much smaller effect on the SRA model outputs. This is because under density dependence at age 2 years and the relatively high values for steepness considered, removals from ages 0 and 1 year classes have much less impact. The presumed relative abundance of these age groups is much higher with density dependence at age 2 years and abundance of age 1 fish needs to be substantially reduced before recruitment to age 2 would be affected. Decreasing steepness increased the estimate of $R_0$, and $Eggs_{MSY}$ and decreased $F_{MSY}$ and $Eggs_{04}/Eggs_{MSY}$. Increasing values for $M_0$ and $M_1$ decreased the estimate of $Eggs_{04}/Eggs_{MSY}$ and MSY and increased the estimates of directed fishery fishing mortality rates. When the shrimp trawl bycatch values were reduced to a quarter of the values supplied, the estimated fishing mortality rates in the last few decades were far too low. The same was the case when the stock-recruit function ASAP residuals were set to 0. It was only by increasing the age of density dependence to age 1 or 2 years, that it was possible to obtain estimates of recent fishing mortality rates and stock depletion levels similar to those in the ASAP and CATCHEM analyses.

The estimates of MSY were much lower than when density dependence was set at age 0, ranging between about 3 and 10 million pounds compared to between about 20 and 170 mp under density dependence at age 0. With density dependence at age 0, the depletion currently presumed is attributable mainly to the extraordinarily large shrimp trawl bycatch values in the 1960s and early 1970s which have since decreased markedly. The population would have to have extremely high productivity to survive these shrimp trawl bycatch removals and hence very high MSY values. In contrast, under density dependence at age 1 and 2 years, the presumed depletion has been relatively insensitive to the shrimp trawl bycatch removals and has instead resulted mainly from directed fishery removals. If the currently high values for fishing mortality rates (larger than $F_{MSY}$ values) and decline below $B_{msy}$ are a result of the directed fishery removals, then the MSY of the stock must be very low and likely less than the average directed fishery removals which have been about 9 million pounds on average. Hence, the estimates of MSY under density dependence at age 1 and 2 years are much smaller than those under density dependence at age 0.

The computations of MSY under density dependence at age 1 and 2 years were done assuming selectivity functions and fishing mortality rates on age 1 year fish based on ASAP output that assumes density dependence at age 0. Thus, the selectivity functions and age 1 year fishing mortality rates applied in the SRA model may overestimate the vulnerability and fishing mortality rates of age classes 0 and 1 years when the SRA models density dependence at age 1 and 2 years. This over estimation of vulnerability and fishing mortality rate on age 1 fish in the MSY calculations may also give negatively biased estimates of MSY in the SRA. Further work is required to obtain less biased methods to compute selectivity functions for SRA's that assume density dependence at age 1 or 2 years.

Density dependent survival rate during age 0 up to age 2 or more years during the settlement phase of the life history of red snapper is plausible because at higher fish density, higher rates of natural mortality are likely to occur e.g. due to predation because of there being limited reef habitat that serves as a refuge from predation.

Under density dependence at age 1 and age 2, the stock recovery was highly sensitive to the TAC imposed and relatively insensitive to future shrimp trawl bycatch values between about 0 and 25 million fish. Under the scenarios considered, it appears that stock recovery to $B_{MSY}$ can be achieved only by reducing the TAC considerably below the current one of 9 million pounds to between 2.5 and 4.5 million pounds to achieve recovery to $B_{msy}$ by 2032. Implementing a removal of the minimum size limit had little effect on stock recovery. This is presumably because a much larger number of fish was required to fill the TAC when the size limit was removed and the high survival rate presumed for recreational released fish allowed released fish to survive and contribute to the spawning stock or catch at larger sizes after being released.

In summary, this paper demonstrates that the application of density dependence at ages 1 and 2 years in SRA provide estimates of MSY reference points and stock status substantially different from the 1999 stock assessment assumption of density dependence at age 0 at the settlement stage. The empirical results of this paper support the notion that stock-recruit functions with recruitment at age 1 or 2 years are more plausible than density dependence at age 0 (upon settlement). In contrast, to density dependence at age 0, density dependence at age 1 or 2 years imply that the recent continued depletion of the stock has resulted largely from the directed fishery removals and that stock recovery cannot be achieved by relying primarily on decreases in shrimp trawling effort and bycatch or elimination of the minimum size limit. Instead, the SRA suggests that unless the TAC is reduced considerably in the immediate future, stock decline will continue and that the only way to ensure stock recovery is for the TAC to be reduced substantially.

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Table 1. Catch inputs and assumed discard mortality rates. Commercial and recreational catches are in thousands of pounds. Shrimp trawl bycatch is in 10's of millions of red snapper. NA means value not available. See text for methods used to interpolate and extrapolate missing values for the commercial and recreational catches. STBC refers to shrimp trawl bycatch.

| Year | Commercial catch | Recreational catch | STBC base case | STBC adjust pre-73 by 0.25 | STBC CATCHEM values for pre-1981 | Commercial discard mortality rate | Recreational discard mortality rate | Out of season commercial discard |
|---|---|---|---|---|---|---|---|---|
| 1872 | 521.326 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1873 | 781.989 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1874 | 1172.984 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1875 | 1433.647 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1876 | 1694.31 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1877 | 1433.647 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1878 | 1303.315 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1879 | 1433.647 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1880 | 2715.675 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1881 | 2854.324 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1882 | 2993.967 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1883 | 3144.174 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1884 | 3294.387 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1885 | 3443.615 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1886 | 3595.817 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1887 | 3626.896 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1888 | 3490.309 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1889 | 3752.758 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1890 | 4434.858 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1891 | 4091.814 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1892 | 4303.559 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1893 | 4444.201 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1894 | 4552.494 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1895 | 4459.129 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1896 | 4508.501 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1897 | 4478.894 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1898 | 5157.05 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1899 | 5869.201 | 0 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1900 | 6564.117 | 0.26952 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1901 | 7047.401 | 0.285059 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1902 | 7409.609 | 0.301074 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1903 | 6781.925 | 0.317568 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1904 | 6298.457 | 0.334604 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1905 | 5696.968 | 0.352118 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1906 | 5108.617 | 0.370125 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1907 | 4534.709 | 0.388692 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1908 | 4099.024 | 0.407786 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1909 | 3523.797 | 0.427473 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1910 | 2974.81 | 0.447735 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1911 | 2982.992 | 0.399523 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1912 | 2991.313 | 0.357994 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1913 | 2999.553 | 0.322604 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1914 | 3006.18 | 0.292992 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1915 | 3011.956 | 0.268812 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1916 | 3015.89 | 0.2499 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1917 | 2948.21 | 0.236089 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1918 | 2951.858 | 0.22725 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1919 | 3190.313 | 0.223366 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1920 | 3437.882 | 0.224501 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1921 | 3695.656 | 0.291396 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1922 | 3960.971 | 0.383277 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1923 | 4228.192 | 0.50826 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1924 | 4124.565 | 0.676039 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1925 | 4112.79 | 0.898598 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1926 | 3999.859 | 1.189977 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1927 | 4443.486 | 1.566571 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1928 | 3871.058 | 2.047458 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1929 | 4075.893 | 2.654413 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1930 | 2787.054 | 3.412029 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1931 | 2592.575 | 3.830926 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1932 | 2827.342 | 4.286513 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1933 | 2631.984 | 4.780584 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1934 | 2429.603 | 5.314785 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1935 | 3086.155 | 5.890943 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1936 | 3645.371 | 6.510704 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1937 | 3405.014 | 7.17583 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1938 | 4115.701 | 7.887999 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1939 | 4587.17 | 8.648841 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1940 | 3312.824 | 9.460118 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1941 | 3009.683 | 12.80659 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1942 | 2362.992 | 17.09721 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1943 | 1817.662 | 22.53226 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1944 | 1949.72 | 29.34076 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1945 | 1608.946 | 37.78298 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1946 | 2643.203 | 48.15252 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1947 | 2910.375 | 60.77911 | 0 | 0 | 0 | 0.73 | 0.275 | 0 |
| 1948 | 3194.103 | 76.03112 | 0.848977 | 0.212244 | 0.513357 | 0.73 | 0.275 | 0 |
| 1949 | 3978.195 | 94.31869 | 1.371668 | 0.342917 | 0.823328 | 0.73 | 0.275 | 0 |
| 1950 | 3169.166 | 116.0969 | 2.101978 | 0.525494 | 1.025344 | 0.73 | 0.275 | 0 |
| 1951 | 3494.457 | 140.0057 | 2.509344 | 0.627336 | 1.097415 | 0.73 | 0.275 | 0 |
| 1952 | 3899.216 | 168.017 | 2.962421 | 0.740605 | 1.265628 | 0.73 | 0.275 | 0 |
| 1953 | 3385.062 | 200.7233 | 3.006498 | 0.751625 | 1.254692 | 0.73 | 0.275 | 0 |
| 1954 | 3249.173 | 238.7917 | 3.928899 | 0.982225 | 1.649842 | 0.73 | 0.275 | 0 |
| 1955 | 3598.691 | 282.9713 | 3.698833 | 0.924708 | 1.478893 | 0.73 | 0.275 | 0 |
| 1956 | 4538.285 | 334.1022 | 4.768158 | 1.192039 | 1.911448 | 0.73 | 0.275 | 0 |
| 1957 | 4275.408 | 393.1257 | 5.672795 | 1.418199 | 2.354845 | 0.73 | 0.275 | 0 |
| 1958 | 7081.977 | 461.095 | 7.729918 | 1.93248 | 3.360843 | 0.73 | 0.275 | 0 |
| 1959 | 6839.453 | 539.1876 | 8.296415 | 2.074104 | 3.575774 | 0.73 | 0.275 | 0 |
| 1960 | 7418.007 | 628.719 | 6.667896 | 1.666974 | 3.03336 | 0.73 | 0.275 | 0 |
| 1961 | 7753.223 | 657.8243 | 6.554651 | 1.638663 | 2.86183 | 0.73 | 0.275 | 0 |
| 1962 | 7744.313 | 691.7879 | 6.407322 | 1.601831 | 2.851886 | 0.73 | 0.275 | 0 |
| 1963 | 6687.119 | 731.3563 | 7.384845 | 1.846211 | 3.248485 | 0.73 | 0.275 | 0 |
| 1964 | 6909.092 | 777.3437 | 8.181641 | 2.04541 | 3.519331 | 0.73 | 0.275 | 0 |
| 1965 | 7064.299 | 830.634 | 8.159014 | 2.039753 | 3.504336 | 0.73 | 0.275 | 0 |
| 1966 | 5894.394 | 892.1801 | 8.897167 | 2.224292 | 3.86276 | 0.73 | 0.275 | 0 |
| 1967 | 6852.379 | 963.0053 | 9.172676 | 2.293169 | 4.067254 | 0.73 | 0.275 | 0 |
| 1968 | 7467.295 | 1044.202 | 8.871226 | 2.217807 | 3.951218 | 0.73 | 0.275 | 0 |
| 1969 | 6364.226 | 1136.933 | 10.83247 | 2.708118 | 4.80047 | 0.73 | 0.275 | 0 |
| 1970 | 6683.695 | 1242.43 | 10.59877 | 2.649693 | 4.661589 | 0.73 | 0.275 | 0 |
| 1971 | 7286.014 | 1427.285 | 10.23141 | 2.557853 | 4.46417 | 0.73 | 0.275 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1972 | 6927.454 | 1634.927 | 14.86188 | 3.715469 | 7.960005 | 0.73 | 0.275 | 0 |
| 1973 | 7277.02 | 1867.848 | 2.212646 | 2.212646 | 5.154248 | 0.73 | 0.275 | 0 |
| 1974 | 7873.31 | 2128.847 | 2.467823 | 2.467823 | 5.911594 | 0.73 | 0.275 | 0 |
| 1975 | 7209.204 | 1725.772 | 1.129401 | 1.129401 | 4.415558 | 0.73 | 0.275 | 0 |
| 1976 | 6349.176 | 1853.885 | 4.63033 | 4.63033 | 7.279272 | 0.73 | 0.275 | 0 |
| 1977 | 4931.373 | 2159.033 | 2.286835 | 2.286835 | 6.534598 | 0.73 | 0.275 | 0 |
| 1978 | 4502.738 | 2777.838 | 1.318508 | 1.318508 | 6.94679 | 0.73 | 0.275 | 0 |
| 1979 | 4329.963 | 3112.92 | 4.269384 | 4.269384 | 8.271261 | 0.73 | 0.275 | 0 |
| 1980 | 4368.303 | 4128.421 | 4.545789 | 4.545789 | 8.72997 | 0.73 | 0.275 | 0 |
| 1981 | 5277.517 | 4056.056 | 9.479662 | 9.479662 | 9.479662 | 0.73 | 0.275 | 0 |
| 1982 | 5998.928 | 3935.952 | 3.147868 | 3.147868 | 3.147868 | 0.73 | 0.275 | 0 |
| 1983 | 6476.349 | 6328.521 | 2.020572 | 2.020572 | 2.020572 | 0.73 | 0.275 | 0 |
| 1984 | 5669.45 | 3088.47 | 1.870269 | 1.870269 | 1.870269 | 0.77 | 0.275 | 0 |
| 1985 | 4189.092 | 2987.607 | 1.835249 | 1.835249 | 1.835249 | 0.77 | 0.275 | 0 |
| 1986 | 3700.486 | 2607.934 | 0.980124 | 0.980124 | 0.980124 | 0.77 | 0.275 | 0 |
| 1987 | 3068.614 | 2066.605 | 2.069539 | 2.069539 | 2.069539 | 0.77 | 0.275 | 0 |
| 1988 | 3960.064 | 2507.67 | 1.566913 | 1.566913 | 1.566913 | 0.77 | 0.275 | 0 |
| 1989 | 3098.797 | 2282.757 | 2.060401 | 2.060401 | 2.060401 | 0.77 | 0.275 | 0 |
| 1990 | 2650.911 | 1364.75 | 7.929422 | 7.929422 | 7.929422 | 0.77 | 0.275 | 0 |
| 1991 | 2213.254 | 2097.845 | 5.71192 | 5.71192 | 5.71192 | 0.77 | 0.275 | 43.56266 |
| 1992 | 3030.593 | 3618.645 | 3.513522 | 3.513522 | 3.513522 | 0.77 | 0.275 | 470.8457 |
| 1993 | 3373.903 | 5572.599 | 4.595785 | 4.595785 | 4.595785 | 0.8 | 0.275 | 361.9524 |
| 1994 | 3222.35 | 4533.396 | 6.017697 | 6.017697 | 6.017697 | 0.8 | 0.275 | 680.6192 |
| 1995 | 2934.108 | 3693.957 | 6.506439 | 6.506439 | 6.506439 | 0.8 | 0.275 | 738.9115 |
| 1996 | 4313.063 | 3465.138 | 4.318527 | 4.318527 | 4.318527 | 0.8 | 0.275 | 748.049 |
| 1997 | 4809.896 | 4370.24 | 3.896701 | 3.896701 | 3.896701 | 0.8 | 0.21 | 846.9238 |
| 1998 | 4679.593 | 4349.155 | 5.395967 | 5.395967 | 5.395967 | 0.8 | 0.21 | 1113.616 |
| 1999 | 4864.912 | 4351.881 | 4.683055 | 4.683055 | 4.683055 | 0.8 | 0.21 | 824.9731 |
| 2000 | 4837.346 | 3331.766 | 1.974207 | 1.974207 | 1.974207 | 0.8 | 0.21 | 861.2455 |
| 2001 | 4625.358 | 3564.719 | 3.259863 | 3.259863 | 3.259863 | 0.8 | 0.21 | 659.4864 |
| 2002 | 4782.969 | 4871.982 | 2.745627 | 2.745627 | 2.745627 | 0.8 | 0.21 | 700.5142 |
| 2003 | 4407.27 | 4597.227 | 1.53435 | 1.53435 | 1.53435 | 0.8 | 0.21 | 483.5635 |

[a]Note that this value was replaced by the average value after 1972 in some of the runs for reasons mentioned in the text.

Table 2. Estimates of total shrimp caught (pounds) and offshore effort in the Gulf of Mexico shrimp trawl fishery (Data supplied by Jim Nance).

| year | total catch | Offshore Effort |
|---|---|---|
| 1945 | NA | 0 |
| 1946 | NA | 0 |
| 1947 | NA | 5900 |
| 1948 | NA | 12224 |
| 1949 | NA | 18549 |
| 1950 | NA | 24873 |
| 1951 | NA | 31198 |
| 1952 | NA | 37522 |
| 1953 | NA | 43847 |
| 1954 | NA | 50171 |

| | | |
|---|---|---|
| 1955 | NA | 56496 |
| 1956 | 64795194 | 62821 |
| 1957 | 56051583 | 69145 |
| 1958 | 66981149 | 75470 |
| 1959 | 66981149 | 81794 |
| 1960 | 82011765 | 95748 |
| 1961 | 41538725 | 94122 |
| 1962 | 45356453 | 92006 |
| 1963 | 76868390 | 106043 |
| 1964 | 69173035 | 117485 |
| 1965 | 78189172 | 117160 |
| 1966 | 76813099 | 127760 |
| 1967 | 97684323 | 131716 |
| 1968 | 78467115 | 127387 |
| 1969 | 81498967 | 155550 |
| 1970 | 97012941 | 152194 |
| 1971 | 94902893 | 146919 |
| 1972 | 97444205 | 168735 |
| 1973 | 75512817 | 145976 |
| 1974 | 78924936 | 148330 |
| 1975 | 74205779 | 121603 |
| 1976 | 91033933 | 154654 |
| 1977 | 118110932 | 174140 |
| 1978 | 120478481 | 205848 |
| 1979 | 90678170 | 221961 |
| 1980 | 101642362 | 185707 |
| 1981 | 128205586 | 176727 |
| 1982 | 85597585 | 173894 |
| 1983 | 78207645 | 171311 |
| 1984 | 102480285 | 191739 |
| 1985 | 114096238 | 196628 |
| 1986 | 130743691 | 226798 |
| 1987 | 109021484 | 241902 |
| 1988 | 89130291 | 205812 |
| 1989 | 104047890 | 221165 |
| 1990 | 107563380 | 211860 |
| 1991 | 107563380 | 223389 |
| 1992 | 93686414 | 216669 |
| 1993 | 86378948 | 204482 |
| 1994 | 90267765 | 195742 |
| 1995 | 93901029 | 176589 |
| 1996 | 101091922 | 189653 |
| 1997 | 86989124 | 207912 |

| | | |
|---|---|---|
| 1998 | 111924674 | 216999 |
| 1999 | 100419269 | 200475 |
| 2000 | 113808089 | 192073 |
| 2001 | 97706647 | 197644 |
| 2002 | 95668608 | 194186 |
| 2003 | 104551662 | 168153 |

Table 3. Weight, fecundity, and selectivity at age ($S_a$) for the commercial, recreational, and shrimp trawl fisheries. The MSY linked selectivity function at age is also presented.

| Age | Weight | Fecundity | Shrimp $S_a$ before 1998 | Shrimp $S_a$ 1998 and after | Commercial $S_a$ | Commercial Discard $S_a$ | Recreational Discard $S_a$ | Recreational Discard $S_a$ | MSY Linked $S_a$ | Fraction mature at age |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0.000 | 0.74 | 0.82 | 0.000 | 0.000 | 0.000 | 0.000 | 1.132 | 0.000 |
| 1 | 0.04 | 0.000 | 1 | 1.00 | 0.000 | 0.000 | 0.132 | 0.074 | 1.554 | 0.000 |
| 2 | 0.57 | 0.005 | 0.02 | 0.04 | 0.151 | 0.000 | 1.000 | 0.332 | 0.608 | 0.851 |
| 3 | 1.79 | 0.034 | 0 | 0.00 | 1.000 | 0.303 | 0.804 | 0.061 | 1.000 | 0.896 |
| 4 | 3.56 | 0.102 | 0 | 0 | 0.990 | 0.063 | 0.603 | 0.007 | 0.783 | 0.928 |
| 5 | 5.62 | 0.207 | 0 | 0 | 0.690 | 0.010 | 0.414 | 0.001 | 0.526 | 0.951 |
| 6 | 7.77 | 0.331 | 0 | 0 | 0.533 | 0.002 | 0.332 | 0.000 | 0.409 | 0.967 |
| 7 | 9.84 | 0.458 | 0 | 0 | 0.446 | 0.001 | 0.286 | 0.000 | 0.344 | 0.978 |
| 8 | 11.75 | 0.584 | 0 | 0 | 0.402 | 0.000 | 0.261 | 0.000 | 0.312 | 1.000 |
| 9 | 13.45 | 0.682 | 0 | 0 | 0.388 | 0.000 | 0.255 | 0.000 | 0.302 | 1.000 |
| 10 | 14.93 | 0.763 | 0 | 0 | 0.472 | 0.000 | 0.323 | 0.000 | 0.372 | 1.000 |
| 11 | 16.19 | 0.827 | 0 | 0 | 0.470 | 0.000 | 0.326 | 0.000 | 0.372 | 1.000 |
| 12 | 17.25 | 0.876 | 0 | 0 | 0.468 | 0.000 | 0.329 | 0.000 | 0.372 | 1.000 |
| 13 | 18.14 | 0.914 | 0 | 0 | 0.466 | 0.000 | 0.332 | 0.000 | 0.372 | 1.000 |
| 14 | 18.87 | 0.942 | 0 | 0 | 0.464 | 0.000 | 0.334 | 0.000 | 0.372 | 1.000 |
| 15 | 20.98 | 1.000 | 0 | 0 | 0.464 | 0.000 | 0.342 | 0.000 | 0.375 | 1.000 |

Table 4. The natural logarithm of deviates of predicted and observed recruitment for years 1962-2003. These values come from M. Ortiz's ASAP model run for these years produced on August 20, 2004.

| | Steepness | | |
|---|---|---|---|
| Year | 0.81 | 0.90 | 0.95 |
| 1962 | 0.024 | 0.017 | 0.011 |
| 1963 | 0.024 | 0.018 | 0.014 |
| 1964 | 0.023 | 0.019 | 0.015 |
| 1965 | 0.021 | 0.018 | 0.015 |
| 1966 | 0.020 | 0.017 | 0.015 |
| 1967 | 0.018 | 0.016 | 0.014 |
| 1968 | 0.017 | 0.015 | 0.014 |
| 1969 | 0.014 | 0.013 | 0.013 |
| 1970 | 0.012 | 0.012 | 0.012 |
| 1971 | 0.006 | 0.007 | 0.007 |
| 1972 | 0.840 | 0.852 | 1.111 |
| 1973 | -0.809 | -0.792 | -0.658 |
| 1974 | -0.650 | -0.663 | -0.583 |
| 1975 | -1.325 | -1.314 | -1.206 |
| 1976 | -0.040 | -0.063 | 0.013 |
| 1977 | -0.327 | -0.399 | -0.385 |
| 1978 | -0.815 | -0.882 | -0.895 |
| 1979 | 0.411 | 0.312 | 0.246 |
| 1980 | 0.579 | 0.497 | 0.409 |
| 1981 | 0.935 | 0.808 | 0.670 |
| 1982 | 0.098 | -0.042 | -0.202 |
| 1983 | -0.273 | -0.463 | -0.656 |
| 1984 | 0.458 | 0.254 | 0.043 |
| 1985 | -0.135 | -0.350 | -0.587 |
| 1986 | 0.195 | -0.012 | -0.237 |
| 1987 | 0.332 | 0.211 | 0.018 |
| 1988 | -0.047 | -0.180 | -0.378 |
| 1989 | 1.024 | 1.002 | 0.887 |
| 1990 | 0.769 | 0.879 | 0.826 |
| 1991 | 0.785 | 0.878 | 0.844 |
| 1992 | 0.249 | 0.309 | 0.281 |
| 1993 | 0.598 | 0.684 | 0.691 |
| 1994 | 0.256 | 0.372 | 0.415 |
| 1995 | 0.703 | 0.810 | 0.870 |
| 1996 | 0.188 | 0.281 | 0.353 |
| 1997 | -0.063 | 0.087 | 0.215 |
| 1998 | -0.188 | -0.018 | 0.129 |
| 1999 | 0.007 | 0.138 | 0.286 |
| 2000 | -0.503 | -0.410 | -0.266 |
| 2001 | -0.398 | -0.296 | -0.137 |
| 2002 | -0.530 | -0.390 | -0.213 |
| 2003 | -2.504 | -2.254 | -2.030 |

Table 5. The SEAMAP (age 1 abundance) and MRFSS (fish recruited to the recreational fisheries) relative abundance indices to which the SRA model was fitted. –1 means value not available.

| Year | SEAMAP (Miami) | Shrimp Trawl | Handline West | MRFSS | Handline East | Video | Larval B | SEAMAP Age 0 | SEAMAP Age 1 |
|---|---|---|---|---|---|---|---|---|---|
| 1967 | -1 | 2.68 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1968 | -1 | 3.39 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1969 | -1 | 2.03 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1970 | -1 | 2.76 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1971 | -1 | 2.15 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1972 | 34.63 | 2.52 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1973 | 9.87 | 3.41 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1974 | 6.59 | 2.69 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1975 | 8.90 | 2.06 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1976 | 7.26 | 1.41 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1977 | 8.18 | 1.26 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1978 | 16.51 | 0.72 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1979 | 6.95 | 0.47 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1980 | 20.04 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1981 | 16.92 | -1 | -1 | 0.69 | -1 | -1 | -1 | -1 | -1 |
| 1982 | 16.87 | -1 | -1 | 0.32 | -1 | -1 | -1 | -1 | -1 |
| 1983 | 6.63 | -1 | -1 | 1.07 | -1 | -1 | -1 | -1 | -1 |
| 1984 | 3.18 | -1 | -1 | 0.58 | -1 | -1 | -1 | -1 | -1 |
| 1985 | 6.14 | -1 | -1 | 0.39 | -1 | -1 | -1 | -1 | -1 |
| 1986 | 3.01 | -1 | -1 | 0.44 | -1 | -1 | 5.54 | -1 | -1 |
| 1987 | 5.29 | -1 | -1 | 0.48 | -1 | -1 | 10.06 | 3.02 | 4.03 |
| 1988 | 4.71 | -1 | -1 | 0.41 | -1 | -1 | 4.61 | 5.26 | 2.11 |
| 1989 | 3.20 | -1 | -1 | 0.29 | -1 | -1 | 6.12 | 17.12 | 1.96 |
| 1990 | 13.97 | -1 | -1 | 0.41 | -1 | -1 | 3.73 | 15.93 | 11.07 |
| 1991 | 5.96 | -1 | -1 | 0.69 | -1 | -1 | 2.88 | 19.73 | 4.79 |
| 1992 | 5.98 | -1 | -1 | 0.88 | -1 | 0.046 | 2.95 | 5.17 | 4.35 |
| 1993 | 6.22 | -1 | -1 | 0.80 | -1 | 0.072 | 6.85 | 11.03 | 3.87 |
| 1994 | 10.01 | -1 | -1 | 0.62 | -1 | 0.033 | 3.36 | 30.48 | 6.59 |
| 1995 | 7.41 | -1 | -1 | 0.58 | -1 | 0.069 | 8.02 | 28.67 | 5.10 |
| 1996 | 11.17 | -1 | 4.81 | 0.86 | 0.082 | 0.047 | 13.63 | 11.16 | 8.21 |
| 1997 | 7.78 | -1 | 4.06 | 1.23 | 0.092 | 0.097 | 11.06 | 23.15 | 5.84 |
| 1998 | 4.85 | -1 | 3.50 | 1.17 | 0.294 | -1 | -1 | 11.26 | 3.69 |
| 1999 | 3.40 | -1 | 3.09 | 1.21 | 0.182 | -1 | 15.60 | 20.37 | 2.27 |
| 2000 | 6.89 | -1 | 3.28 | 0.97 | 0.362 | -1 | 25.50 | 15.74 | 4.90 |
| 2001 | 4.25 | -1 | 3.08 | 0.91 | 0.462 | -1 | 14.94 | 13.79 | 2.04 |
| 2002 | 5.34 | -1 | 3.01 | 1.04 | 0.446 | 0.1411 | 22.65 | 12.28 | 4.30 |
| 2003 | 4.97 | -1 | 2.74 | 1.07 | 0.427 | -1 | -1 | -1 | 3.48 |

Table 6. Implications for SRA parameter estimates resulting from different inputs. Age of compensation is at 0 years just before settlement.

| Indices | *h /multiplier for pre-1973 SBC* | linked $S_a$ /stock-recruit residuals? | $R_0$ mil fish | $F_1$ in MSY ($yr^{-1}$) | $M_0$ ($yr^{-1}$) | $M_1$ ($yr^{-1}$) | $F_{MSY}$ ($yr^{-1}$) | $F_{0.1}$ | $N_{0,72}$/ $N_{0,1872}$ | MSY mil. lb | $Eggs_{MSY}$/ $Egg_{sunfished}$ | $Eggs_{04}$/ $Eggs_{MSY}$ | $Eggs_{04}$/ $Eggs_{unfished}$ | $F_{3,87-89}$ ($yr^{-1}$) | AIC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| up | 0.95 / 1 | yes/yes | 245 | NA | 0.5 | 0.3 | 0.117 | 0.093 | 3.0 | 201 | 0.34 | 3.19 | 1.10 | 0.002 | 7.90E06 |
| up | 0.95 / 1 | yes/yes | 163 | NA | 0.5 | 0.3 | 0.117 | 0.093 | 3.0 | 134 | 0.34 | 2.75 | 0.95 | 0.003 | 1.99E06 |
| up | 0.95 / 1 | yes/no | 245 | NA | 0.5 | 0.3 | 0.117 | 0.093 | 0.99 | 202 | 0.34 | 2.05 | 0.70 | 0.002 | 7.79E06 |
| up | 0.95 / 1 | no/yes | 245 | 0.68 | 0.5 | 0.3 | 0.136 | 0.120 | 3.0 | 74 | 0.09 | 12.5 | 1.10 | 0.002 | 7.90E06 |
| up | 0.95 / 1 | no/yes | 245 | 0 | 0.5 | 0.3 | 0.151 | 0.121 | 3.0 | 294 | 0.30 | 3.7 | 1.10 | 0.002 | 7.90E06 |
| up | 0.95 / 1 | yes/yes | 144 | NA | 0.5 | 0.3 | 0.117 | 0.093 | 3.0 | 119 | 0.34 | 2.6 | 0.89 | 0.004 | 1,196,419 |
| down | 0.95 / 1 | yes/yes | 144 | NA | 0.5 | 0.3 | 0.117 | 0.093 | 3.0 | 119 | 0.34 | 2.6 | 0.89 | 0.004 | 1,196,632 |
| all | 0.95 / 1 | yes/yes | 144 | NA | 0.5 | 0.3 | 0.117 | 0.093 | 3.0 | 119 | 0.34 | 2.6 | 0.89 | 0.004 | 1,196,713 |
| up | 0.95 / 1 | no/yes | 144 | 0.68 | 0.5 | 0.3 | 0.137 | 0.121 | 3.0 | 44 | 0.087 | 10.2 | 0.89 | 0.004 | 1,196,419. |
| up | 0.95 / 0.25 | no/yes | 69 | 0.68 | 0.5 | 0.3 | 0.136 | 0.120 | 3.0 | 21 | 0.088 | 5.37 | 0.47 | 0.01 | 200,361 |
| up | 0.95 / 1 | no/yes | 144 | 0 | 0.5 | 0.3 | 0.158 | 0.121 | 3.0 | 173 | 0.297 | 3.0 | 0.89 | 0.004 | 1,196,419. |
| up | 0.95 / 1 | yes/yes | 201 | NA | 1 | 0.6 | 0.117 | 0.093 | 3.0 | 74 | 0.34 | 2.4 | 0.84 | 0.007 | 4.09E05 |
| up | 0.95 / 1 | yes/yes | 364 | NA | 2 | 1 | 0.117 | 0.093 | 3.0 | 33 | 0.34 | 2.1 | 0.73 | 0.019 | 5.60E04 |
| up | 0.81 / 1 | yes/yes | 150 | NA | 0.5 | 0.3 | 0.101 | 0.093 | 2.2 | 113 | 0.36 | 2.3 | 0.85 | 0.004 | 1.46E06 |
| up | 0.81 / 1 | yes/yes | 382 | NA | 2 | 1 | 0.101 | 0.093 | 2.1 | 32 | 0.36 | 1.9 | 0.68 | 0.017 | 2.72E05 |
| up | 0.81 / 0.25 | yes/no | 303 | NA | 2 | 1 | 0.101 | 0.093 | 0.98 | 25 | 0.36 | 0.89 | 0.33 | 0.016 | 8.30E05 |
| up | 0.95 / 0.25 | yes/yes | 193 | NA | 2 | 1 | 0.117 | 0.093 | 3.0 | 18 | 0.34 | 0.99 | 0.34 | 0.041 | 1.10E04 |

h is steepness; linked $S_a$ refers to whether the MSY selectivity function links the fishing mortality rate between the directed fishery and the shrimp trawl bycatch mortality rates; $F_1$ in MSY indicates the value for the shrimp trawl bycatch fishing mortality rate assumed in the unlinked MSY calculation; $M_0$ and $M_1$ refer to the rates of natural mortality of age 0 and 1 fish; $F_{3,87-89}$ is the model predicted average value for fishing mortality rate on age 3 fish for years 1987-1989; the other terms are defined in the text. up refers to the upbending series, the MRFSS, larval bongo and video. down refers to the SEAMAP age 1 and early shrimp trawl. All refers to all five indices. In the first four rows, $R_0$ is set at 245 million, as in the high R0 case for the 1999 stock assessment. CATCHEM refers to the time series of STBC estimates provided from the

Table 7. Estimates of stock status under different input assumptions and age of compensation is at 1 and 2 years

| Age of recruits (years) | Indices / *multiplier for pre-1973 STBC* | *h* | linked $S_a$ /stock-recruit residuals | $R_0$ mil fish | $F_1$ in MSY ($yr^{-1}$) | $M_0$ ($yr^{-1}$) | $M_1$ ($yr^{-1}$) | $F_{MSY}$ ($yr^{-1}$) | $F_{0.1}$ | $N_{0,72}/N_{0,1872}$ | MSY mil. lb | $Eggs_{MSY}/Eggs_{unfished}$ | $Eggs_{04}/Eggs_{MSY}$ | $Eggs_{04}/Eggs_{unfished}$ | $F_{3,87\text{-}89}$ ($yr^{-1}$) | AIC | Max TAC (mp)[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | up / 1 | 0.95 | yes/yes | 366 | NA | 0.5 | 0.3 | 0.188 | 0.16 | 1.5 | 5.9 | 0.32 | 0.34 | 0.11 | 0.176 | 5.26E02 | 1.5/2.5 |
| 2 | down/ 1 | 0.95 | yes/yes | 366 | NA | 0.5 | 0.3 | 0.188 | 0.16 | 1.5 | 5.9 | 0.32 | 0.34 | 0.11 | 0.176 | 4.37E02 | 1.5/2.5 |
| 2 | down/ 1 | 0.95 | no/yes | 366 | 0.68 | 0.5 | 0.3 | 0.139 | 0.123 | 1.5 | 5.1 | 0.30 | 0.36 | 0.11 | 0.176 | 4.37E02 | 1.5/2.5 |
| 2 | down/ 1 | 0.95 | no/yes | 366 | 0 | 0.5 | 0.3 | 0.161 | 0.123 | 1.5 | 5.9 | 0.30 | 0.36 | 0.11 | 0.176 | 4.37E02 | 1.5/2.5 |
| 2 | down/ 1 | 0.94 | yes/no | 331 | NA | 0.5 | 0.3 | 0.182 | 0.16 | 0.531 | 6.4 | 0.32 | 0.53 | 0.17 | 0.143 | 7.23E02 | 3.5/4.5 |
| 2 | all/ 1 | 0.95 | yes/yes | 366 | NA | 0.5 | 0.3 | 0.188 | 0.16 | 1.5 | 5.9 | 0.32 | 0.34 | 0.11 | 0.176 | 7.01E02 | 1.5/2.5 |
| 2 | down/ 1 | 0.92 | yes/yes | 520 | NA | 1 | 0.6 | 0.174 | 0.16 | 1.2 | 6.0 | 0.33 | 0.47 | 0.15 | 0.157 | 5.68E02 | 2.0/3.0 |
| 2 | down/ 1 | 0.81 | yes/yes | 307 | NA | 1 | 0.6 | 0.138 | 0.138 | 1.4 | 8.5 | 0.37 | 1.0 | 0.37 | 0.085 | 2.23E03 | 5.5/6.5 |
| 2 | down/ 1 | 0.92 | no/yes | 520 | 0.68 | 1 | 0.6 | 0.124 | 0.123 | 1.2 | 4.9 | 0.30 | 0.51 | 0.15 | 0.157 | 5.68E02 | 2.0/3.0 |
| 2 | down/ 0.25 | 0.92 | no/yes | 511 | 0.68 | 1 | 0.6 | 0.124 | 0.123 | 1.2 | 4.8 | 0.31 | 0.51 | 0.16 | 0.151 | 5.87E02 | 2.0/3.0 |
| 2 | down/ 1 | 0.92 | no/yes | 520 | 0 | 1 | 0.6 | 0.155 | 0.123 | 1.2 | 6.1 | 0.30 | 0.51 | 0.15 | 0.157 | 5.68E02 | 2.0/3.0 |
| 2 | down/ 1 | 0.88 | no/yes | 1349 | 0.68 | 2 | 1 | 0.108 | 0.108 | 1.2 | 4.3 | 0.32 | 0.43 | 0.13 | 0.161 | 5.23E02 | 1.5/2.5 |
| 1 | down/ 1 | 0.95 | no/yes | 1067 | 0.68 | 1 | 0.6 | 0.136 | 0.120 | 1.5 | 3.3 | 0.15 | 1.0 | 0.15 | 0.141 | 6.67E02 | 4.0/4.5 |
| 1 | down/ 0.25 | 0.95 | no/yes | 984 | 0.68 | 1 | 0.6 | 0.136 | 0.120 | 1.7 | 3.1 | 0.15 | 1.1 | 0.17 | 0.126 | 8.57E02 | 4.0/4.0 |
| 1 | down/ 1 | 0.95 | no/yes | 1067 | 0 | 1 | 0.6 | 0.158 | 0.120 | 1.5 | 7.5 | 0.15 | 0.52 | 0.15 | 0.141 | 6.67E02 | 2.5/4.0 |
| 1 | down/ 1 | 0.90 | no/no | 669 | 0.68 | 1 | 0.6 | 0.113 | 0.113 | 0.49 | 3.7 | 0.16 | 0.47 | 0.075 | 0.109 | 1.24E03 | 0.5/1.0 |
| 1 | down/ 1 | 0.95 | no/yes | 583 | 0.68 | 0.5 | 0.3 | 0.136 | 0.120 | 1.5 | 4.1 | 0.15 | 1.5 | 0.23 | 0.110 | 1.19E03 | 6.5/6.5 |
| 1 | down/ 1 | 0.93 | no/yes | 2675 | 0.68 | 2 | 1 | 0.127 | 0.120 | 1.4 | 2.8 | 0.16 | 0.59 | 0.09 | 0.167 | 4.49E02 | 2.0/2.5 |
| 1 | down/ 1 | 0.90 | no/yes | 695 | 0.68 | 1 | 0.6 | 0.114 | 0.114 | 1.2 | 3.9 | 0.16 | 1.8 | 0.29 | 0.09 | 1.89E03 | 8.0/8.0 |

h is steepness; linked $S_a$ refers to whether the MSY selectivity function links the fishing mortality rate between the directed fishery and the shrimp trawl bycatch mortality rates; $F_1$ in MSY indicates the value for the shrimp trawl bycatch fishing mortality rate assumed in the unlinked MSY calculation; $M_0$ and $M_1$ refer to the rates of natural mortality of age 0 and 1 fish; $F_{3,87\text{-}89}$ is the model predicted average value for fishing mortality rate on age 3 fish for years 1987-1989; the other terms are defined in the text. up refers to the upbending series, the MRFSS, larval bongo and video. down refers to the SEAMAP age 1 and early shrimp trawl. All refers to all five indices. In the last column (a), the max TAC is the maximum TAC that would permit the stock to remain above $B_{msy}$ in year 2020/2032. The shaded cells in this column indicate runs that provided better fits to the ASAP fishing mortality rates.

**Appendix 1: The Population Dynamics Model for Gulf of Mexico Red Snapper**

The population dynamics model developed to capture key features of Gulf of Mexico red snapper population dynamics is described below. It is age-structured, relates recruitment to spawner-biomass by means of the Beverton-Holt stock-recruitment relationship, applies gear selectivity-at-age based on estimates derived from catch-age models and maturity and weight at age based on agreed values from the April, August and December 2004 SEDAR workshops. The base case values for model parameters that were fixed are given in Tables 1, 3 and 4. Equations below show how the calculations are done with density dependence at either age 0 or age 2 years. For brevity, equations for density dependence at age 1 year are not shown but are easily derived from the equations for density dependence at age 2.

A. Resource Dynamics

The dynamics of animals aged 0 years and above, are governed by the following equations. For ease of computation, it is assumed that the recreational fishery occurs at the beginning of the year before natural mortality.

$$N^{C}_{y,a} = N^{R}_{y,a}(1 - S^{R}_{a} H^{R}_{y})\,(1 - S^{RD}_{a} H^{R}_{y}) \qquad 1 \le a \le m \qquad (1.1)$$

where $N^{R}_{y,a}$ is the number of animals of age $a$ at the start of year $y$ just before recreational fishing,

$N^{C}_{y,a}$ is the number of animals of age $a$ in year $y$ just after recreational fishing,

$H^{R}_{y}$ is the directed recreational exploitation rate for the retained catch in year $y$,

$S^{R}_{a}$ is the selectivity at age $a$ for red snapper retained in the directed recreational fishery,

$S^{RD}_{a}$ is the fraction of fish at age discarded dead in recreational fishery, relative to the fraction of fish retained in the fully selected age group in the recreational fishery (it is assumed that recreational discards occur only after 1987).

$m$ is the maximum (lumped) age-class (all animals in this and the previous age-class are recruited and mature).

The commercial harvest is assumed to occur during the middle of the year, following the recreational fishery.

$$N^{S}_{y,a} = N^{C}_{y,a} \exp\left(M_{a}/2\right)(1 - S^{C}_{a} H^{C}_{y})\,(1 - S^{CD}_{a} H^{C}_{y}) \qquad 1 \le a \le m \qquad (1.2)$$

where $N^{C}_{y,a}$ is the number of animals of age $a$ just before commercial fishing in year $y$ (it is assumed that commercial discards start occurring in 1986),

$N^{S}_{y,a}$ is the number of animals of age *a* just after commercial fishing in year *y* and just before bycatch in the shrimp fishery in year *y*,

$H^{C}_{y}$ is the directed commercial exploitation rate for the retained catch in year *y*,

$S^{C}_{a}$ is the selectivity at age *a* for red snapper retained in the directed commercial fishery,

$S^{CD}_{a}$ is the fraction of fish at age *a* discarded dead in commercial, relative to the fraction of fish retained in the fully selected age group in the commercial fishery (it is assumed that discards occur only after 1984).

$M_a$ is the annual instantaneous rate of natural mortality at age *a* on animals ($yr^{-1}$); *M* for ages 0 and 1 are distinct ($M_0$, $M_1$), and *M* for ages 2+ ($M_2$) are assumed to be the same.

Abundance at age in the following year is obtained as follows:

$$N^{R}_{y+1,a+1} = N^{S}_{y,a}\exp\left(\frac{M_a}{a+1}\right)(1 - S^{S}_{a} H^{S}_{y}) \qquad 0 \le a \le 1$$

$$N^{R}_{y+1,a+1} = N^{S}_{y,a}\exp(M_2 / 2) \qquad 2 \le a \le m-1 \qquad (1.3)$$

$$N^{R}_{y+1,m} = \left(N^{S}_{y,m} + N^{S}_{y,m-1}\right)\exp(M_2 / 2) \qquad a = m$$

Note that a + 1 is in the denominator of the first equation because age 0 fish are assumed to recruit half way through the year and the value for the rate of natural mortality ($M_0$) for the initial year only applies to the latter half of the year. Thus, $M_0$ is divided by 1. In contrast, age 1 fish already have had $M_1$ /2 applied for the first half of the year (Equation 1.2) and thus the natural mortality for the 2nd half of the year also need to be applied. Thus $M_1$ needs to be divided by 2.

If density dependence occurs at the end of age 1, then the following are applied to fish at the end of age 1 to predict abundance of fish at the beginning of age 2 in the next year:

$$N^{S'}_{y,1} = N^{S}_{y,1}\exp\left(\frac{M_a}{2}\right)(1 - S^{S}_{1} H^{S}_{y}) \qquad (1.3.1)$$

$$N^{R}_{y+1,2} = \left(\frac{N^{S'}_{y,1}}{1 + \beta\exp(M_0 + M_1)\, N^{S'}_{y,1}}\right) \qquad (1.3.2)$$

Equation 1.3.2 implies that as abundance of age 2 fish approaches zero, the natural mortality rate in the density dependent equation, approaches zero.

B.0 Births under density dependence at age 0

$$N^{R}_{y,0} = \left( \frac{E_y}{\alpha + \beta \ E_y} \right) e^{\varepsilon_y} \tag{1.4}$$

where $E_y$ is the eggs spawned by mature animals during year:

$$E_y = 0.5 \sum_{a=a_r}^{m} f_a \quad N^{S}_{y,a} \tag{1.5}$$

$f_a$ is fecundity at age (Table 3).

$w_a$ (further below) is the mass of a fish of age $a$ (assumed to be constant throughout the year) (Table 3):

$$w_a = \delta_1 \, (L_a)^{\delta_2} \tag{1.6}$$

$$L_a = L_\infty (1 - e^{-\kappa \ (a - t_0)}) \tag{1.7}$$

$\varepsilon_y$ is the recruitment residual for year y, $\varepsilon_y$ were based on subtracting the base case Beverton-Holt model predictions from the ASAP base case estimates of annual recruitment for years from 1961-2003, and

$\alpha, \beta$ are Beverton-Holt stock-recruitment function parameters.

B.2 Births under density dependence at age 2

$$N^{R}_{y,0} = \left( \frac{E_y}{\alpha} \right) e^{\varepsilon_y} \tag{1.4.1}$$

C.0 Initial conditions under density dependence at age 0

Were there no fluctuations in recruitment, the resource would be assumed to be at its unexploited equilibrium level, with the corresponding age-structure, at the start of exploitation (year $y_1$). The initial numbers-at-age are given by the equations

$$N_{y_1,0} = R_0 \qquad a = 0$$

$$N_{y_1,1} = R_0 \exp(-M_0) \qquad a = 1$$

$$N_{y_1,2} = R_0 \exp(-M_0 - M_1) \qquad a = 2$$

$$\begin{aligned} N_{y_1,a} &= R_0 \exp\{-(a-1)M_2 - M_1 - M_0\} && 3 \le a \le m-1 \\ N_{y_1,m} &= R_0 \exp\{-(m-1)M_2 - M_1 - M_0\} / (1 - \exp(-M_2)) && a = m \end{aligned} \tag{1.9}$$

where $R_0$ is the number of 0-year-olds at the deterministic equilibrium that corresponds to an absence of harvesting. A value for average unfished recruited stock biomass $B_0$ at the middle of the year is calculated from the value for the virgin recruitment, $R_0$, using the equation:

$$B_0 = \left\{ w_1 \, N_{y1,1} S_1^A \exp\left(-M_1/2\right) + \sum_{a=2}^{m} \; w_a N_{y1,a} S_a^A \exp\left(-M_2/2\right) \right\} \qquad (1.10)$$

where $S_a^A$ is the average of the selectivity at age *a* for recreational and commercial fisheries; the averaged selectivity at age is normalized such that the maximum average selectivity at age is set equal to 1.

Values for the stock-recruit parameters α and β are calculated from the values of $R_0$ and the "steepness" of the stock-recruit relationship (*h*). The "steepness" is the fraction of $R_0$ to be expected (in the absence of recruitment variability) when the mature biomass is reduced to 20% of its pristine level (Francis 1992), so that:

$$\alpha = \tilde{B}_0^S \frac{1-h}{4h}$$

$$\beta = \frac{5h-1}{4hR_0}$$

$$\tilde{B}_0^S = 0.5 \left\{ \sum_{a=a_r}^{m-1} f_a \exp(-(a-2)M_2 - M_0 - M_1 - M_2/2) + \frac{f_m \exp(-(m-2)M_2 - M_0 - M_1 - M_2/2)}{(1-\exp(-M_2))} \right\}$$

(1.11)

C.2 Initial Conditions Under Density Dependence at Age 2 years

The abundance of eggs produced at equilibrium unfished conditions is given by:

$$E_0 = \frac{\alpha \times R_0}{1 - \beta \times R_0}$$

The abundance of newly recruited age 0 fish is given by

$$N_{0,0} = \frac{E_0}{\alpha}$$

The abundance of age 1 fish at the beginning of the year is given by:

$$N_{1,0} = N_{0,0} \times \exp\left(-M_0\right)$$

The abundance of age 1 fish at the end of the year prior to density dependent survival is given by:

$$N'_{1,0} = N_{1,0} \times \exp(-M_1)$$

The abundance of age 2 fish at the beginning of the year after density dependence is given by:

$$N_{2,0} = \frac{N'_{1,0}}{1 + \beta \times \exp(M_0 + M_1) \times N'_{1,0}}$$

The abundance of fish from age three until the plus group is given by:

$$N_{a,0} = N_{2,0} \times \exp(-(a-2) \times M_2) \qquad \text{for a = 3 to } m\text{-1}$$

$$N_{m,0} = N_{2,0} \times \frac{\exp(-(m-2) \times M_2)}{1 - \exp(-M_2)} \qquad \text{for } a = m.$$

D. Catches

The exploitation rate during year *y* for fishery *f*, $H_y^f$**,** is calculated using the equation

$$H_y^f = C_y^f \,/\, B_y^f \qquad (1.12)$$

where $C_y^f$ is the catch during year *y* and $B_y^f$ is the stock abundance available to fishery *f* at the time of year that the fishery is assumed to occur.

For each fishery *f*:

$$B_y^R = \sum_{a=1}^{m} N_{y,a}^R S_a^R w_a$$

$$B_y^C = \sum_{a=1}^{m} N_{y,a}^C S_a^C w_a \exp(-M_a/2) \qquad (1.13)$$

$$B_y^S = N_{y,0}^S S_{0,y}^S \exp(-M_0/2) + N_{y,1}^S S_{0,1}^S$$

where $N_{y,a}^f$ is the abundance of fish in year *y* of age *a*, just prior to the operation of fishery *f* and

$S_{a,y}^f$ is the fraction of fish of age *a* that are vulnerable to fishery *f*. For shrimp by-catch, it is assumed that the selectivity function changes in 1998 following the introduction of the mandatory use of red snapper by-catch reduction devices.

E. Maximum Sustainable Yield Calculation

The harvest rate that gives maximum sustainable yield was found by grid search. The base case scenario documented here assumes that there is a long-run average expected future value for the fishing mortality rates on age 0 and 1 ($F_0$ and $F_1$) caused by shrimp trawl bycatch that reflects some expected reduction in shrimp fishing effort and some particular mandatory red snapper bycatch reduction device that operates with temporally stable efficiency. For each candidate harvest rate the following quantities are computed:

E.1 Fraction of animals surviving to each age under density dependence at age 0

$$
\begin{aligned}
G_1 &= \exp(-F_0 - M_0)\left(1 - S_0^{A} H\right)\left(1 - S_0^{AD} H\right) && a = 1 \\
G_2 &= G_1 \exp(-F_1 - M_1)\left(1 - S_1^{A} H\right)\left(1 - S_1^{AD} H\right) && a = 2 \\
G_a &= G_{a-1} \exp(-M_2)\left(1 - S_{a-1}^{A} H\right)\left(1 - S_{a-1}^{AD} H\right) && 3 \le a \le m-1 \qquad (1.14) \\
G_m &= \frac{G_{m-1} \exp(-M_2)\left(1 - S_{m-1}^{A} H\right)\left(1 - S_{m-1}^{AD} H\right)}{\left(1 - \exp(-M_2)\left(1 - S_m^{A} H\right)\left(1 - S_m^{AD} H\right)\right)} && a = m
\end{aligned}
$$

where $S_a^A$ is the average of the selectivity at age for the directed recreational and commercial fisheries, and $S_a^{AD}$ is the average the fraction of fish at age discarded dead in commercial and recreational fisheries, relative to the fraction of fish retained in the fully selected age group in the recreational and commercial fisheries. Note that if a linked selectivity function is applied, then $F_0$ and $F_1$ are set to 0, the linked selectivity function analogous to that in Schirripa and Legault (1999) is applied for $S_a^A$ and $S_a^{AD}$ is set to 0 since the linked selectivity values include all sources of fishing mortality.

Under density dependence at the end of age 1, the fraction of fish at age (beginning of year) is given by:

$G_2 = 1$

$$
\begin{aligned}
G_a &= G_{a-1} \exp(-M_2)\left(1 - S_{a-1}^{A} H\right)\left(1 - S_{a-1}^{AD} H\right) && 3 \le a \le m-1 \\
G_m &= \frac{G_{m-1} \exp(-M_2)\left(1 - S_{m-1}^{A} H\right)\left(1 - S_{m-1}^{AD} H\right)}{\left(1 - \exp(-M_2)\left(1 - S_m^{A} H\right)\left(1 - S_m^{AD} H\right)\right)} && a = m \\
G_1 &= \frac{SBPR(H)}{\alpha} \exp(-F_0 - M_0)\left(1 - S_0^{A} H\right)\left(1 - S_0^{AD} H\right)
\end{aligned}
$$

E.2 Recruited stock biomass per recruit as a function of harvest rate

$$
\begin{aligned}
SBPR(H) &= w_1 G_1 S_1^A \exp(-M_1/2)\left(1 - 0.5 S_1^A H\right)\left(1 - 0.5 S_1^{AD} H\right) \\
&+ w_2 G_2\ S_2^A \exp(-M_2/2)\left(1 - 0.5 S_2^A H\right)\left(1 - 0.5 S_2^{AD} H\right) \qquad (1.15) \\
&+ \sum_{a=3}^{m} w_a G_a S_a^A \exp(-M_a/2)\left(1 - 0.5 S_a^A H\right)\left(1 - 0.5 S_a^{AD} H\right)
\end{aligned}
$$

E.3 Yield per recruit as a function of harvest rate (H)

$$YPR(H) = w_1 G_1 S_1^A H \exp(-M_1/2)\left(1-0.5S_1^{AD}H\right) \qquad a=1$$
$$+ w_2 G_2\ S_2^A H \exp(-M_2/2)\left(1-0.5S_2^{AD}H\right) \qquad a=2 \qquad (1.16a)$$
$$+ \sum_{a=3}^{m} w_a G_a S_a^A H \exp(-M_a/2)\left(1-0.5S_a^{AD}H\right) \qquad 3 \le a \le m$$

If a linked selectivity function is applied then the term $S_a^A$ which is the total selectivity function for all fishing and bycatch mortality under linked selectivity is replaced by the fraction retained in the landed catch $L_a^A$:

$$L_a^A = \frac{S_a^A - S_a^{AD}}{1 - H\ S_a^{AD}}. \qquad (1.16b)$$

E.4 Eggs per recruit as a function of harvest rate (H)

$$EPR(H) = f_2 G_2 \exp(-M_2/2)\left(1-0.5S_2^A H\right)\left(1-0.5S_2^{AD}H\right)$$
$$+ \sum_{a=3}^{m} f_a G_a \exp(-M_a/2)\left(1-0.5S_a^A H\right)\left(1-0.5S_a^{AD}H\right) \qquad (1.17)$$

E.5 The total equilibrium eggs spawned given the eggs per recruit is obtained by the following.

$$E(H) = \frac{EPR(H) - \alpha}{\beta} \qquad (1.18)$$

Under density dependence at age 2 years, the equilibrium eggs spawned is obtained from:

$$E(H) = \frac{EPR(H) - \alpha \times \exp(Z)}{\beta \times \exp(M_0 + M_1)}$$

where Z = $M_0 + M_1 + F_0 + F_1 + F_0^D + F_1^D$, and $F_0^D$ and $F_1^D$ are the total fishing and directed fishery discard mortality rates for ages 0 and 1. With density dependence at the end of age 0, the F and M terms for age 1 are omitted from the equations 18.

E.6 The total equilibrium recruits obtained given the total eggs is obtained by the following.

$$R(H) = \frac{E(H)}{\alpha + \beta\ E(H)} \qquad (1.19)$$

Under density dependence at age 2 years, the equilibrium abundance of age 2 recruits is obtained from:

$$R(H) = \frac{E(H)}{\alpha \times \exp(Z) + \beta \times \exp(M_0 + M_1) \times E(H)}$$

With density dependence at the end of age 0, the F and M terms for age 1 year are omitted from the equations 19.

E.7 The total yield is obtained by the product of the total equilibrium recruits and the yield per recruit.

$$Y(H) = R(H)\,YPR(H) \qquad (1.20)$$

E.8 The equilibrium recruited stock biomass at MSY is obtained by the product of total equilibrium recruits and the recruited stock biomass per recruit.

$$SB(H) = R(H)\,SBPR(H) \qquad (1.21)$$

The maximum sustainable yield harvest rate is approximated by the harvest rate *H* that provides maximum *Y(H)*.

F. Data and Likelihood Function

The lognormal log likelihood function for incorporating *d* relative abundance series is given by

$$\lambda = \sum_{j=1}^{d}\left(-\sum_{i=1}^{n_j}\left(\frac{0.5}{\sigma_j^2}\log\left(O_{i,j}/\left(q_j B_{i,j}\right)\right)^2\right)\right) \qquad (1.22)$$

where *d* is the number of indices, $n_j$ is the number of observations in series *j*, $O_{I,j}$ is the *i*th observation in series *j*, $q_j$ is the constant of proportionality for series *j*, $B_{I,j}$, is the annual stock biomass corresponding to observation $O_{I,j}$, $\sigma_j$ is the pre-set standard deviation in the natural logarithm for residual errors between observed values and model predicted values for each annual index of abundance in series *j*.

Based on equation 1.22, the maximum likelihood estimate (MLE) of $q_j$ is obtained from:

$$q_j^{MLE} = \exp\left(\frac{\sum_{i=1}^{n_j}\log\left(\frac{O_j}{B_{i,j}}\right)^2}{n_j}\right) \qquad (1.23)$$

$\sigma_j$ typically reflects the relative goodness of fit between the model predicted trend in biomass and the trend in the observed values. $\sigma_j$ is typically estimated when there are at least 20 years of observations. When the number of years in a series is relatively few, the value for $\sigma_j$ is usually fixed beforehand; this is done based on previous experience in other fisheries (McAllister et al. 1994). The higher the $\sigma_j$, the less the weighting of the series relative to the others.

Because the number of years in each series was very few, the value for each $\sigma_j$ was fixed based on previous experience and the understanding that each series is new and there is uncertainty over whether each can actually track trends in abundance. Thus, the values for $\sigma_j$ that were chosen are on the higher end of the range of values typically applied and reflect a small degree of scepticism about the potential of each series to closely track relative trends in abundance. For the baseline run, each index was given a CV of 0.6

A likelihood function for the average fishing mortality rate of age 3 fish for years 1987-1989 based on ASAP was also computed. This assumed that the ASAP value is normally distributed about the SRA value with a SD of 0.1.

G. Projections

To evaluate the potential consequences of alternative future fisheries management options under various plausible scenarios for population dynamics, a population model projection module was constructed. This used the same population dynamics model equations and assumptions as described above, e.g., for modelling mortality, growth and recruitment. This model component simply takes the abundance at age at the end of the estimation model and projects the abundance at age into the future for a pre-specified number of years, taking into account the pre-specified inputs for annual TACs for the directed fishery, the split in TAC between recreational and commercial fleets, annual projected values for shrimp trawl bycatch, and specifications for whether changes to size limits will occur.

If there is to be an elimination of the size limit, for example for the recreational fishery, then the selectivity at age equations for the retained catch and discarded dead catch from the recreational fishery are combined into a single selectivity function to approximate the effective selectivity if the recreational catch including both previously retained and discarded fish is set equal to the TAC.

$$S_a^{R''} = 1 - \exp\left( -\left( -\ln\left(1 - \frac{S_a^{RD}}{U_{DR}}\right) - \ln\left(1 - S_a^R\right)\right)\right) \qquad (1.24)$$

where $U_{DR}$ is the fraction of released fish dying. The maximum value for $S_a^R$ of 1, is set to very slightly less than 1.

Likewise, the new selectivity of the commercial fleet, if all catch was retained in the open season and commercial fin fish bycatch fisheries were stopped when the total quota was obtained can be approximated by:

$$S_a^{C''} = 1 - \exp\left( - \left( - \ln\left( 1 - \frac{S_a^{CD}}{U_{DC}} \right) - \ln\left(1 - S_a^{C}\right)\right)\right) \tag{1.25}$$

where $U_{DR}$ is the fraction of released fish dying. The maximum value for $S_a^C$ of 1, is set to very slightly less than 1.