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

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Executive Summary

1. An age structured population dynamics model of Gulf of Mexico red snapper (*Lutjanus campechanus*) was formulated to evaluate the implications of density dependence at age 0, 1 or 2 years and uncertainties in key parameter inputs for evaluations of stock status and population projections.

2. The fish killed by shrimp trawl bycatch, commercial and recreational fishing were modelled using the commercial catch data, recreational catch data and annual shrimp trawl bycatch estimates made available for the December 2004 SEDAR workshop. This model projects the population from the year 1872, from when the first records of catches are provided. Shrimp trawl bycatch records start in 1948.

3. It was necessary to incorporate deviates of estimated recruitment from those predicted in the ASAP procedure in order to project the model beyond the very large shrimp trawl removal in 1972. Otherwise use of deterministic estimates of recruitment could not permit parameter estimation.

4. Fishery selectivities at age for the retained catch was modelled to be stationary over time, though in actual practice it is likely that there have been some changes in fishery selectivities over time. The selectivity at age for the recreational and the aggregated commercial fleets was approximated by using the partial fishing mortality rate (F) values at age based on results in the ASAP 1962-2003 stock assessment. In-season discard selectivity at age for the recreational fleet and commercial fleets were modelled separately also using partial F values for in-season discards based on results from the ASAP assessment. The mortality from out of season discards, however, was modelled to be lumped with landed catch.

5. To compute maximum sustainable yield (MSY) and MSY-related reference points, the 1999 NMFS assessment utilized a linked selectivity function that incorporated all sources of estimated fishing, shrimp trawl bycatch and discard mortality average over the years 1995-1997. This calculation assumes that the trawling effort in the shrimp fishery is linked to the fishing effort in the red snapper directed fisheries. To instead maintain independence of shrimp effort in the MSY calculation, a suggestion was made in the August SEDAR workshop to also compute MSY reference points using fixed shrimp trawl fishery bycatch fishing mortality rates set equal to the average of the estimated values in the most recent years. This alternative approach to MSY reference point computation was also applied in the current paper and resulted in much lower estimates of MSY and the SSB at MSY relative to unfished conditions for density dependence (recruitment) set at age 0 and age 1 years, but not with density dependence at age 2 years.

6. SRA model runs using the historic catch time series from 1872 to the present were conducted to evaluate the plausibility of stock-recruit parameter estimates obtained in stock assessments fitted to shorter time series.

7. Under density dependence at age 0, and using the 1999 ASAP 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. It was not possible to obtain values for fishing mortality rates as high as those from ASAP or VPA. If h is set at 0.95 and R_0 is set at 245 million, 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 those in ASAP assessments (about 0.3 yr^{-1}). The estimate of spawner potential ($Eggs_{04}/Eggs_{unfished}$) was implausible, i.e., at 110% of unfished conditions. This implausibly high 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.

8. With recruitment set at age 0, and when R_0 and constants of proportionality for abundance indices were freed up and estimated and the model was fitted to different datasets, 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 ASAP assessments. For example, under a variety of conditions, and different sets of abundance indices used, the estimates of $Eggs_{04}/Eggs_{unfished}$ were between 73 and 89% and $F_{3,87\text{-}89}$ were between 0.004 and 0.02 yr^{-1}.

9. With recruitment set at either age 1 or age 2 years 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. Estimates of $Eggs_{04}/Eggs_{unfished}$ ranged between 9% and 37% and $F_{3,87\text{-}89}$ ranged between 0.09 and 0.18 yr^{-1}. The Akaike information criterion (AIC), a common goodness of fit criterion, is far smaller (better) for these density dependence assumptions than the age 0 one.

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 assessments. While the details of the results might be different from the ASAP assessment, 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 fish.

Methods and Data Inputs

The equations for the age-structured population dynamics model are reported 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, then 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 penalty function was applied to constrain the average SRA fishing mortality rate 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. The red snapper MSY calculation should thus 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} should 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 also 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. 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. 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 base case parameter values for steepness (h), average unfished recruitment (R_0) and natural mortality rate values used in (Schirripa and Legault 1999), gives estimates of 1998 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 $Eggs_{04}$ / $Eggs_{msy}$ = 326%) (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).

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 leads to a potential inconsistency and 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 will only give a highly 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 are not 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 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} (0.119 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 (244 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) (4494 million pounds as opposed to 3930 million pounds). The average unfished total stock biomass ($totB_0$) that was 13,089 million pounds. The main reason for the differences between these results and the 1999 results is likely to be 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, 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 0.137, $totB_{MSY}$ dropped to 1169 million pounds, $Eggs_{msy}$/ $Eggs_{unfished}$ dropped to 0.087 and $Eggs_{04}/Eggs_{msy}$ increased to 12.6. 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 0.297. This indicates a very large trade-off in red snapper yield as a result of shrimp trawl bycatch.

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 144 million pounds. The estimated fishing mortality, $F_{3,\,87\text{-}89}$, from recreational and commercial fishing is 0.004 yr^{-1}. AIC = 1,971,932 (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 gave the same estimates. 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.

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 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 $M_0 = 1$, $M_1 = 0.6$, 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 90 million pounds but the $Eggs_{msy}$ / $Eggs_{unfished}$ reference point remained at 0.34.

When M_0 and M_1 were increased to at $M_0 = 2$, $M_1 = 1$, $Eggs_{04}/Eggs_{unfished}$ dropped to 0.733, 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 = 88,989) (Table 6). Thus, it appears that modifying the rates of natural mortality for age 0 and 1 fish cannot produce SRA results anywhere near to those in the ASAP assessment.

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 0.103, MSY decreased to 137 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. The estimate for $F_{3,\,87\text{-}89}$ remained very low at 0.017. The AIC was not as low as in the setting with steepness at 0.95 (AIC = 108,784.); this is mainly because the values for $F_{3,\,87\text{-}89}$ were highest under the run with M_0 = 2, M_1 = 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, 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 lowest AIC from the above runs with density dependence at age 0 came from the run with steepness set at 0.95 and M_0 = 2, M_1 = 1. The AIC was 88,898. The AIC with the change from recruitment at age 0 to age 2 is far lower indicating a much better fit of the model to the ASAP fishing mortality rate estimates (AIC=453) (Table 7) (Figure 3). The model, however 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., 0.191) and the MSY reference points were considerably lower (e.g., $totB_{unfished}$ = 266 mp and $totB_{MSY}$ = 84 mp). The estimate of $Eggs_{msy}/Eggs_{unfished}$ did not change much (under the linked selectivity assumption) with the estimate at 0.311. The estimate of $Eggs_{04}/Eggs_{unfished}$ was far lower at 0.108. MSY was much lower at 7.2 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 in 1972, R_{72}, would still lead to an overestimate of R_0.

Again, when the model was fitted to different abundance indices, the estimates did not change, only the AIC changed. For example, 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 364 (Table 7). AIC with all indices was 629. 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 7.36 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. The AIC obtained increased to from 363 to 513 (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 M0 and M1 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}, ($Eggs_{msy}/Eggs_{unfished}$ = 0.364) under the linked selectivity function. However, $F_{3,}$

$_{87\text{-}89}$ was lower at 0.085 yr^{-1} and the AIC increased substantially to 2788 (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. $M_0 = 1$, $M_1 = 0.6$ yr^{-1} were applied and the value for steepness was set at 0.92 but with the shrimp trawl bycatch selectivity unlinked to the directed fishery selectivity in the MSY calculation. Unlinking the selectivity here made far less of a difference in the MSY calculations than it did with density dependence at age 0. $Eggs_{msy}$ / $Eggs_{unfished}$ dropped slightly to 0.311. MSY dropped to 4.94 million pounds (Table 7). F_{msy} dropped to 0.123 yr^{-1}. For reasons stated above, the MSY calculations in subsequent analyses will be based on the use of an unlinked selectivity function.

Again with density dependence at age 2, with M_0 and M_1 to 2 and 1 yr^{-1}, the maximum steepness that could be incorporated was 0.88. The $Eggs_{msy}$ / $Eggs_{Unfished}$ = 0.315. $Eggs_{fin}$ / $Eggs_{Unfished}$ = 0.134, MSY was 4.35 million pounds. $F_{3,\,87\text{-}89}$ was 0.161 yr^{-1} and AIC was 463 (Table 7).

With density dependence set at age 1, steepness set at 0.95, and M_0 and M_1 = 1, 0.6 yr^{-1}, the stock assessment results are mostly similar to the instance with density dependence at age 2. 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 0.152, $Eggs_{04}$ / $Eggs_{unfished}$ was 0.154. The estimate of MSY was lower at 3.33 million pounds. $F_{3,\,87\text{-}89}$ 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 648 (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 1344. $Eggs_{msy}$ / $Eggs_{Unfished}$ was 0.152. $Eggs_{04}$ / $Eggs_{Unfished}$ increased to 0.226. The MSY increased slightly to 4.05 million pounds (Table 7). $F_{3,87\text{-}89}$ 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 383. $Eggs_{msy}$ / $Eggs_{Unfished}$ was 0.157 (Table 7) (Figure 4). $Eggs_{04}$ / $Eggs_{Unfished}$ decreased to 0.092. The MSY decreased slightly to 2.78 million pounds. $F_{3,87\text{-}89}$ dropped to 0.167 yr^{-1}.

Lower values for steepness at density dependence at age 1, gave poorer fits to the data (Table 7).

7. 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, there were relatively few runs that provided AIC values in the lower range of 380 to 700. These included the following:

1) Density dependence at age 1 with steepness set at 0.93, M_0 and M_1 to 2 and 1 yr^{-1},

2) Density dependence at age 1 with steepness at 0.95, and M_0 and M_1 = 1, 0.6 yr^{-1},

3) Density dependence at age 2, with steepness at 0.95, M_0, and M_1, at 0.5, and 0.3 yr^{-1}

4) Density dependence at age 2, with steepness at 0.92, $M_0 = 1$, $M_1 = 0.6$ yr^{-1}

5) Density dependence at age 2 with steepness at 0.88, M_0 and M_1 to 2 and 1 yr^{-1}

To limit the set of plausible scenarios for population dynamics in the projections, only these five options were considered in the projections. TACs of a) 0, b) 3, c) 6 and d) 9 million pounds were considered. Shrimp trawl bycatch scenarios included the following: a) shrimp bycatch stays at 20 million in future years, b) shrimp trawl bycatch remains at 10 million in future years, c) shrimp trawl bycatch removes 50% of the vulnerable population per year, d) shrimp trawl bycatch removes 30% of the vulnerable population per year.

The projection results are to be reported in a subsequent paper.

Conclusions

In conclusion, the trial runs with the SRA model indicate that current estimates of steepness (h) and R_0 are inconsistent with plausible time series of historic catches. The amount of depletion from unfished stock sizes is negligible if a steepness of 0.95 and value for R_0 of 245 are applied and plausible historic catch removals from directed fishing and shrimp trawl bycatch are assumed to have taken place starting in 1872 and projecting the model to the present. 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. No combination of parameter inputs will permit 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 but relatively insubstantial changes only. Unlinking the MSY selectivity function to the shrimp trawl fishery tends to increase F_{MSY}, decrease $Eggs_{MSY}$ and increase the estimate of $Eggs_{04}/Eggs_{MSY}$. Decreasing steepness tends to increase the estimate of R_0, and $Eggs_{MSY}$ and decrease F_{MSY} and the estimate of $Eggs_{04}/Eggs_{MSY}$. Increasing values for M_0 and M_1 increase slightly F_{MSY}, decrease $Eggs_{MSY}$ and increase the estimates of directed fishery fishing mortality rates.

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 sizes similar to those in the ASAP and VPA analyses. Estimates of fishing mortality rates and stock status similar to those in the ASAP assessment could be obtained from SRA runs with density dependence at either age 1 or age 2 years. However, a wider range of parameter input values could be found with plausible results for runs with density dependence at age 2 than at age 1. The empirical results of this paper therefore demonstrate that stock-recruit functions with recruitment at age 1 or 2 years rather than age 0, are plausible alternatives.

Density dependent survival rate during age 0 up to age 2 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. This paper demonstrates that the application of these alternative stock-recruit functions in SRA impact estimates of MSY reference points, stock status. The following paper will evaluate the potential impacts of modelling density dependence at age 1 or 2 on the importance of directed fishing as opposed to shrimp trawl bycatch in predictions of stock recovery responses to alternative stock-rebuilding plans.

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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.

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

1918	2951.858	0.22725	0	0.73	0.275	0
1919	3190.313	0.223366	0	0.73	0.275	0
1920	3437.882	0.224501	0	0.73	0.275	0
1921	3695.656	0.291396	0	0.73	0.275	0
1922	3960.971	0.383277	0	0.73	0.275	0
1923	4228.192	0.50826	0	0.73	0.275	0
1924	4124.565	0.676039	0	0.73	0.275	0
1925	4112.79	0.898598	0	0.73	0.275	0
1926	3999.859	1.189977	0	0.73	0.275	0
1927	4443.486	1.566571	0	0.73	0.275	0
1928	3871.058	2.047458	0	0.73	0.275	0
1929	4075.893	2.654413	0	0.73	0.275	0
1930	2787.054	3.412029	0	0.73	0.275	0
1931	2592.575	3.830926	0	0.73	0.275	0
1932	2827.342	4.286513	0	0.73	0.275	0
1933	2631.984	4.780584	0	0.73	0.275	0
1934	2429.603	5.314785	0	0.73	0.275	0
1935	3086.155	5.890943	0	0.73	0.275	0
1936	3645.371	6.510704	0	0.73	0.275	0
1937	3405.014	7.17583	0	0.73	0.275	0
1938	4115.701	7.887999	0	0.73	0.275	0
1939	4587.17	8.648841	0	0.73	0.275	0
1940	3312.824	9.460118	0	0.73	0.275	0
1941	3009.683	12.80659	0	0.73	0.275	0
1942	2362.992	17.09721	0	0.73	0.275	0
1943	1817.662	22.53226	0	0.73	0.275	0
1944	1949.72	29.34076	0	0.73	0.275	0
1945	1608.946	37.78298	0	0.73	0.275	0
1946	2643.203	48.15252	0	0.73	0.275	0
1947	2910.375	60.77911	0	0.73	0.275	0
1948	3194.103	76.03112	0.848977	0.73	0.275	0
1949	3978.195	94.31869	1.371668	0.73	0.275	0
1950	3169.166	116.0969	2.101978	0.73	0.275	0
1951	3494.457	140.0057	2.509344	0.73	0.275	0
1952	3899.216	168.017	2.962421	0.73	0.275	0
1953	3385.062	200.7233	3.006498	0.73	0.275	0
1954	3249.173	238.7917	3.928899	0.73	0.275	0
1955	3598.691	282.9713	3.698833	0.73	0.275	0
1956	4538.285	334.1022	4.768158	0.73	0.275	0
1957	4275.408	393.1257	5.672795	0.73	0.275	0
1958	7081.977	461.095	7.729918	0.73	0.275	0
1959	6839.453	539.1876	8.296415	0.73	0.275	0
1960	7418.007	628.719	6.667896	0.73	0.275	0
1961	7753.223	657.8243	6.554651	0.73	0.275	0
1962	7744.313	691.7879	6.407322	0.73	0.275	0
1963	6687.119	731.3563	7.384845	0.73	0.275	0
1964	6909.092	777.3437	8.181641	0.73	0.275	0
1965	7064.299	830.634	8.159014	0.73	0.275	0
1966	5894.394	892.1801	8.897167	0.73	0.275	0
1967	6852.379	963.0053	9.172676	0.73	0.275	0
1968	7467.295	1044.202	8.871226	0.73	0.275	0
1969	6364.226	1136.933	10.83247	0.73	0.275	0
1970	6683.695	1242.43	10.59877	0.73	0.275	0
1971	7286.014	1427.285	10.23141	0.73	0.275	0

1972	6927.454	1634.927	14.86188	0.73	0.275	0
1973	7277.02	1867.848	2.212646	0.73	0.275	0
1974	7873.31	2128.847	2.467823	0.73	0.275	0
1975	7209.204	1725.772	1.129401	0.73	0.275	0
1976	6349.176	1853.885	4.63033	0.73	0.275	0
1977	4931.373	2159.033	2.286835	0.73	0.275	0
1978	4502.738	2777.838	1.318508	0.73	0.275	0
1979	4329.963	3112.92	4.269384	0.73	0.275	0
1980	4368.303	4128.421	4.545789	0.73	0.275	0
1981	5277.517	4056.056	9.479662	0.73	0.275	0
1982	5998.928	3935.952	3.147868	0.73	0.275	0
1983	6476.349	6328.521	2.020572	0.73	0.275	0
1984	5669.45	3088.47	1.870269	0.77	0.275	0
1985	4189.092	2987.607	1.835249	0.77	0.275	0
1986	3700.486	2607.934	0.980124	0.77	0.275	0
1987	3068.614	2066.605	2.069539	0.77	0.275	0
1988	3960.064	2507.67	1.566913	0.77	0.275	0
1989	3098.797	2282.757	2.060401	0.77	0.275	0
1990	2650.911	1364.75	7.929422	0.77	0.275	0
1991	2213.254	2097.845	5.71192	0.77	0.275	43.56266
1992	3030.593	3618.645	3.513522	0.77	0.275	470.8457
1993	3373.903	5572.599	4.595785	0.8	0.275	361.9524
1994	3222.35	4533.396	6.017697	0.8	0.275	680.6192
1995	2934.108	3693.957	6.506439	0.8	0.275	738.9115
1996	4313.063	3465.138	4.318527	0.8	0.275	748.049
1997	4809.896	4370.24	3.896701	0.8	0.21	846.9238
1998	4679.593	4349.155	5.395967	0.8	0.21	1113.616
1999	4864.912	4351.881	4.683055	0.8	0.21	824.9731
2000	4837.346	3331.766	1.974207	0.8	0.21	861.2455
2001	4625.358	3564.719	3.259863	0.8	0.21	659.4864
2002	4782.969	4871.982	2.745627	0.8	0.21	700.5142
2003	4407.27	4597.227	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	linked S_a	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
NA	0.95	yes	245	NA	0.5	0.3	0.119	0.097	3.0	244	0.34	3.26	1.10	0.002	1.31E07
NA	0.95	no	245	0.68	0.5	0.3	0.137	0.121	3.0	74	0.09	12.6	1.10	0.002	1.31E07
NA	0.95	no	245	0	0.5	0.3	0.158	0.121	3.0	294	0.30	3.7	1.10	0.002	1.31E07
up	0.95	yes	144	NA	0.5	0.3	0.119	0.097	3.0	144	0.34	2.6	0.89	0.004	1.97E06
down	0.95	yes	144	NA	0.5	0.3	0.119	0.097	3.0	144	0.34	2.6	0.89	0.004	1.97E06
all	0.95	yes	144	NA	0.5	0.3	0.119	0.097	3.0	144	0.34	2.6	0.89	0.004	1.97E06
up	0.95	yes	201	NA	1	0.6	0.119	0.097	3.0	90	0.34	2.5	0.84	0.007	6.69E05
up	0.95	yes	364	NA	2	1	0.119	0.097	3.0	40	0.34	2.2	0.73	0.019	8.89E04
up	0.95	yes	150	NA	0.5	0.3	0.103	0.097	2.2	137	0.36	2.4	0.85	0.004	2.41E06
up	0.81	yes	381	NA	2	1	0.103	0.097	2.1	39	0.36	1.9	0.68	0.017	1.09E05

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.

Table 7. Implications for parameter estimates with different input assumptions. Age of compensation is at 2 years

Age of recruitment (years)	Indices	h	linked S_a	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	$Eggs_{MSY}/Eggs_{unfished}$	$Eggs_{04}/Eggs_{MSY}$	$Eggs_{04}/Eggs_{unfished}$	$F_{3,87-89}$ (yr^{-1})	AIC
2	up	0.95	yes	366	NA	0.5	0.3	0.191	0.16	1.5	7.2	0.31	0.35	0.11	0.176	4.53E02
2	down	0.95	yes	366	NA	0.5	0.3	0.191	0.16	1.5	7.2	0.31	0.35	0.11	0.176	3.64E02
2	all	0.95	yes	366	NA	0.5	0.3	0.191	0.16	1.5	7.2	0.31	0.35	0.11	0.176	6.29E02
2	down	0.92	yes	520	NA	1	0.6	0.177	0.16	1.2	7.4	0.33	0.47	0.15	0.157	5.13E02
2	down	0.81	yes	307	NA	1	0.6	0.139	0.139	1.4	10.3	0.36	1.0	0.37	0.09	2.8E03
2	down	0.92	no	520	0.68	1	0.6	0.123	0.123	1.2	4.9	0.31	0.50	0.15	0.157	5.13E02
2	down	0.88	no	201	0.68	2	1	0.108	0.108	1.2	4.3	0.32	0.43	0.13	0.161	4.63E02
1	down	0.95	yes	1067	0.68	1	0.6	0.137	0.121	1.5	3.3	0.15	1.0	0.15	0.141	6.48E02
1	down	0.95	yes	583	0.68	0.5	0.3	0.137	0.121	1.5	4.1	0.15	1.5	0.23	0.110	1.43E03
1	down	0.93	yes	2675	0.68	2	1	0.137	0.121	1.4	2.8	0.16	0.59	0.09	0.17	3.83E02
1	down	0.90	yes	695	0.68	1	0.6	0.114	0.114	1.2	3.9	0.16	1.8	0.29	0.09	2.35E03

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.

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 estimated derived from catch-age models and maturity and weight at age based on Schirripa and Legault (1999) and SEDAR (2004). 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.

$$N^S_{y,a} = N^C_{y,a}\exp(M_a/2)(1 - S^C_a H^C_y)(1 - S^{CD}_a H^C_y) \qquad 1 \le a \le m \qquad (1.2)$$

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:

$$
\begin{aligned}
N^R_{y+1,a+1} &= N^S_{y,a}\exp\left(\frac{M_a}{a+1}\right)(1-S^S_a H^S_y) && 0 \le a \le 1 \\
N^R_{y+1,a+1} &= N^S_{y,a}\exp(M_2/2) && 2 \le a \le m-1 \qquad (1.3) \\
N^R_{y+1,m} &= \left(N^S_{y,m}+N^S_{y,m-1}\right)\exp(M_2/2) && a = m
\end{aligned}
$$

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:

$$E_y = 0.5 \sum_{a=a_r}^{m} f_a \;\; N^S_{y,a} \tag{1.5}$$

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):

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

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

ε_y is the recruitment residual for year y, ε_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

α, β 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:

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

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

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:

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

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

$$H_y^f = C_y^f / B_y^f \tag{1.12}$$

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:

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

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

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

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

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

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 of 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 is given by:

$G_2 = 1$

$$
\begin{aligned}
G_a &= G_{a-1} \exp(-M_2)(1 - S_{a-1}^A H)(1 - S_{a-1}^{AD} H) & 3 \le a \le m-1\\
G_m &= \frac{G_{m-1} \exp(-M_2)(1 - S_{m-1}^A H)(1 - S_{m-1}^{AD} H)}{(1 - \exp(-M_2)(1 - S_m^A H)(1 - S_m^{AD} H))} & a = m
\end{aligned}
$$

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

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

Under density dependence at the end of age 1, the first term in the summation is left out.

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

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

Under density dependence at the end of age 1, the first term in the summation is left out.

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

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

This equation is the same for density dependence at age 0 and age 2.

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, 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.

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, the equilibrium abundance of age 2 recruits is obtained from:

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

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 ith 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 $O_{I,j}$, σ_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:

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

σ_j typically reflects the relative goodness of fit between the model predicted trend in biomass and the trend in the observed values. σ_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 σ_j is usually fixed beforehand; this is done based on previous experience in other fisheries (McAllister et al. 1994). The higher the σ_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 σ_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 σ_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 0.05.

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:

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

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.

Figure 1. Eggs/ $Eggs_{unfished}$ when R_0 is set at 245 million, steepness is 0.95, M_0=0.3, M_1 = 0.5 yr^{-1}. Density dependence is at age 0 and linked selectivity is used in the MSY calculation

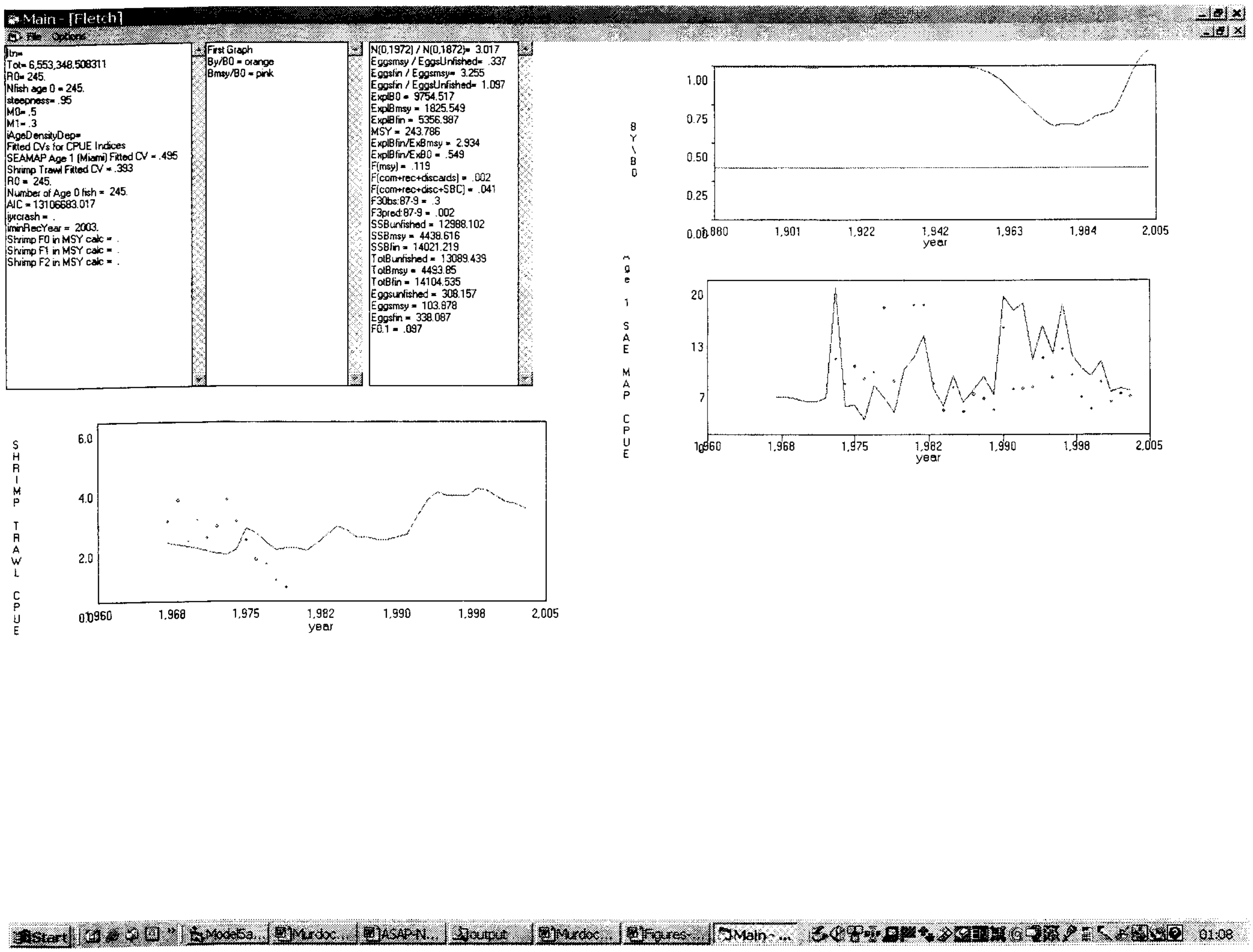

Figure 2. Eggs/ $Eggs_{unfished}$ when R_0 is estimated, steepness is 0.95, M_0=0.3, M_1 = 0.5 yr^{-1}. Density dependence is at age 0 and linked selectivity is used in the MSY calculation

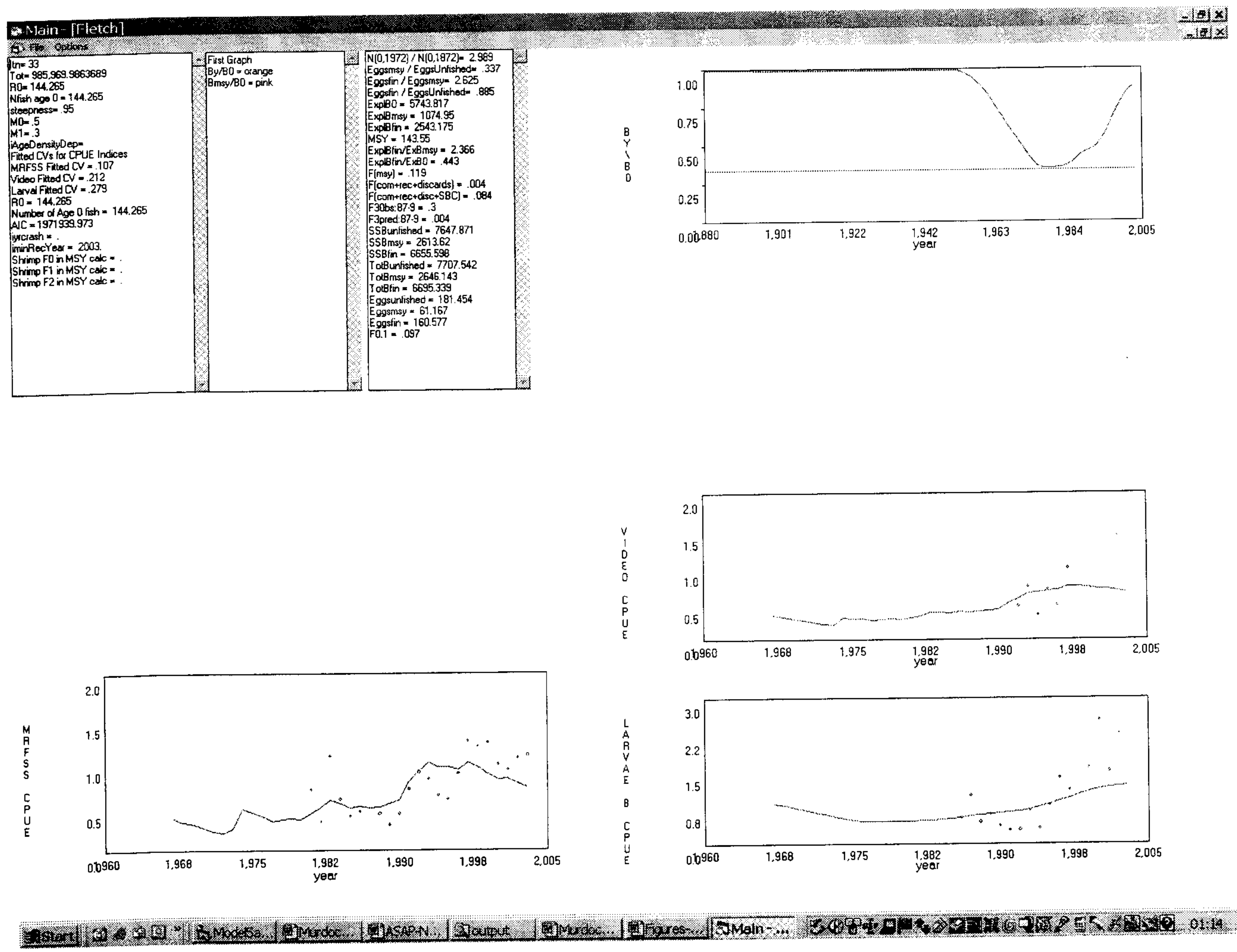

Figure 3. Eggs/ $Eggs_{unfished}$ when R_0 is estimated, steepness is 0.95, M_0=0.3, M_1 = 0.5 yr^{-1}. Density dependence is at age 2 and linked selectivity is used in the MSY calculation

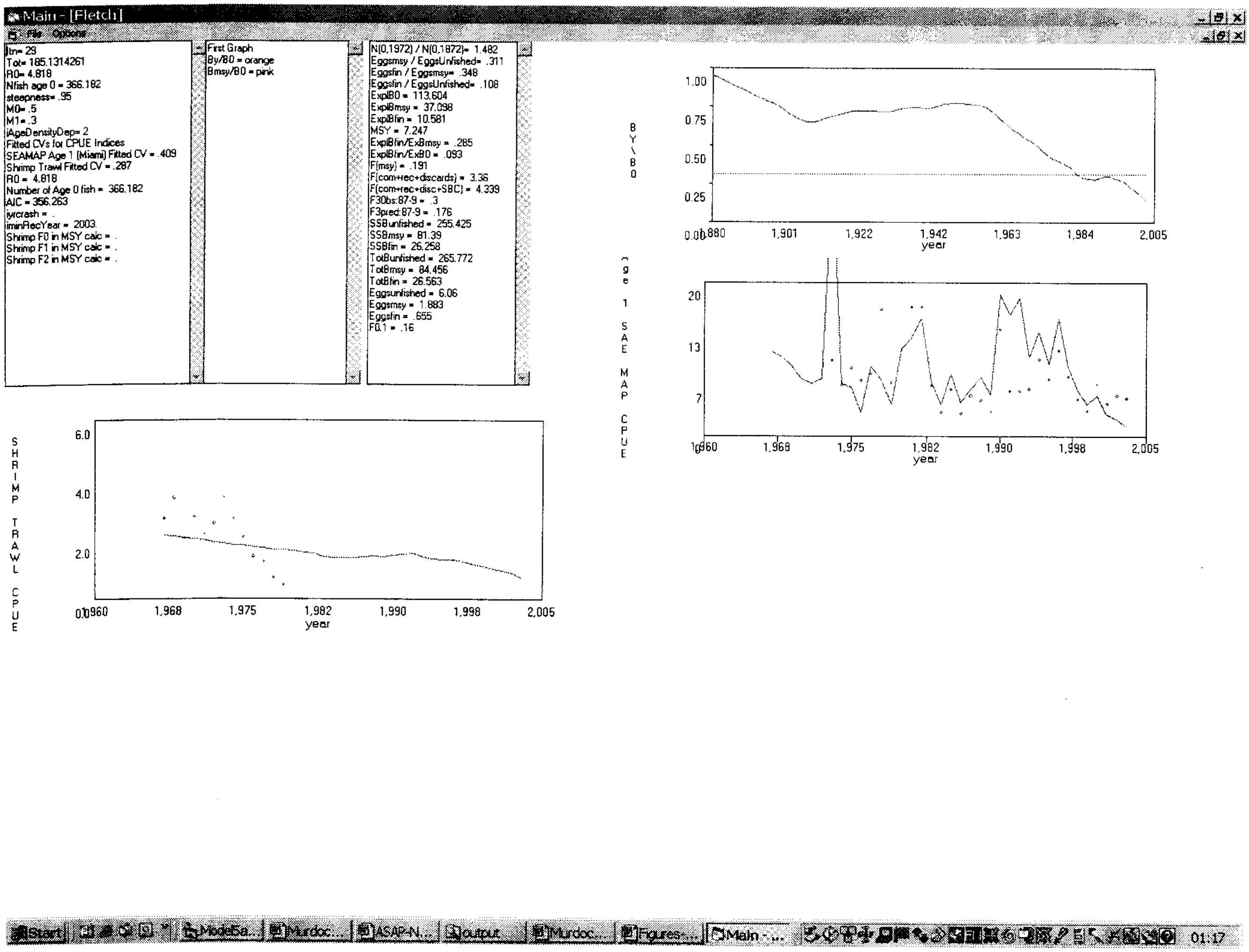

Figure 4. Eggs/ $Eggs_{unfished}$ when R_0 is estimated, steepness is 0.93, M_0=2, M_1 = 1 yr^{-1}. Density dependence is at age 1 and unlinked selectivity is used in the MSY calculation