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A population dynamics model for Gulf of Mexico red snapper that uses a historically extended catch time series and alternative methods to calculate MSY

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Executive Summary

1. A scenario-based age structured population dynamics model of Gulf of Mexico *Lutjanus campechanus* was extended to allow including data compiled for the August 2004 SEDAR workshop stock assessment and to enable population projections to evaluate the potential consequences of alternative management actions under plausible alternative settings for the population dynamics model inputs and functional form.
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 bycatch estimates reported in Schirripa and Legault (1999) and where possible updated values listed in the April 2004 SEDAR workshop report; the April 2004 SEDAR workshop report and many of the documents in the April SEDAR workshop did not include actual listings of values for most of the updated parameters and datasets, e.g., for shrimp bycatch, fecundity, mass at age, and relative abundance indices. Unlike the National Marine Fisheries Service (NMFS) assessment, this model projects the population from the year 1880, when the first records of catches are reported in Schirripa and Legault (1999). Shrimp bycatch is assumed to start occurring in 1946 and the values in unreported years are assumed to be equal to the average of reported shrimp trawl bycatch. This assumption is reasonable because reported shrimp catches back to 1956 suggest shrimp catches were high and are comparable to catches in the 1970's and later.
3. Fishery selectivity 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 selectivity 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 NMFS stock assessment. Discard selectivity at age for the recreational fleet and commercial fleets were modelled separately also using partial F values for discards also based on data and results in the NMFS assessment. Discard mortality rates are those provided in the April 2004 SEDAR workshop report. Commercial and recreational catches are also those provided in this report.
4. To compute maximum sustainable yield (MSY) and MSY-related reference points, the NMFS assessment utilized a linked selectivity function that incorporated all sources of estimated fishing and discard mortality average over the years 1995-1997. While this appears to be reasonable, the computation of MSY is not straightforward. For example, discards are counted as part of the MSY and the biomass at MSY (B_{MSY}) includes the portion of the population that is susceptible only to shrimp trawl bycatch. This may produce MSY reference points that are difficult to interpret because yield is typically interpreted as landed fish, not the sum of landed and discarded fish and stock biomass is usually interpreted as the stock biomass recruited to the directed fisheries. Unavoidable bycatch of fish not recruited to the directed fisheries could arguably be interpreted as a form of mortality akin to predation and perhaps should not be counted as part of B_{MSY}. Moreover, the recent estimated changes in shrimp trawl bycatch selectivity for age 0 and 1 fish, makes the use of the linked selectivity function based on estimates from 1995-1997 questionable. The modelling work in this paper explores some alternative MSY definitions. It is found that values for MSY reference points are sensitive to the manner in which MSY is defined and computed. It is thus recommended that further attention be given to how MSY reference points should be defined in the first place when there is unavoidable bycatch of the target species and estimated recent changes in selectivity.
5. The model was run from 1880 to the present using the National Marine Fisheries (NMFS) base case parameter values for steepness (h), average unfished recruitment (R_0) and natural mortality rates but starkly different estimates of 1998 stock status were obtained. If steepness is 0.95 and unfished average recruitment (R_0) is 245 million, then the computed current abundance is scarcely depleted ($B_{98}/B_0 = 0.78$). It is only using smaller values for h and R_0 that high estimated values for F in the 1990s can result.
6. When higher values for the rate of natural mortality at age 0 and age 1 (M_0, M_1) were applied, the estimates of R_0 increased markedly, and the estimates of F from recreational and commercial fishing also increased substantially.
7. Projection results were sensitive to the future values assumed for shrimp bycatch, the manner in which MSY was defined, the value for steepness that is applied, and the values assumed for M_0 and M_1, but only if they were much larger than assumed.
8. When size limits were removed for the recreational and commercial fisheries the recovery projections were slightly less because more smaller fish made up the TAC than before and this resulted in a higher harvest rate. In contrast, when fish are released when size limits are applied, a fraction of them survive.
9. The next extension of the model will be to build an alternative stock-recruit function with recruitment at age 2 rather than age 0, to model the density dependent survival rates of this reef fish during its settlement phase.

Introduction

Many of the inputs to the 1999 Gulf of Mexico *Lutjanus campechanus* stock assessment model (Schirripa and Legault 1999) remained fixed yet little no account of potential uncertainties in these inputs was given. Some of these parameters included the rate of natural mortality at age, and the "linked" vulnerability at age function used in computing MSY. In this paper, I present a scenario-based age structured population dynamics model of Gulf of Mexico *Lutjanus campechanus*. This model (termed "gaming model") has been constructed to help identify modelling assumptions and those parameters where uncertainty should be further taken into account in the red snapper stock assessment. The model is also applied to evaluate the potential consequences of alternative management policy options under plausible alternative assumptions for population dynamics model structures and assumptions.

There are many simplifying approximations utilized in the current form of the gaming model that will impact the model's results and make them different from those obtained in the NMFS assessment. While the details of the results might be different from the NMFS assessment, the age structured model applied still captures many of the key features of the population dynamics, fishery and bycatch and is applied not as an alternative stock assessment but instead as a gaming tool to evaluate the direction and relative magnitude of impacts on model outputs of various changes in modelling assumptions and model inputs.

This note reports on issues regarding the computation of MSY-related reference points in fisheries with large amounts of discarding, the potential inconsistency of current assumptions about stock-recruit parameters and historic records of catches, and implications of applying different values for the rate of natural mortality at age. A basic description of the population dynamics model developed and qualitative results are reported.

Methods and Data Inputs

The equations for the age-structured population dynamics model developed are reported in Appendix 1.

The model develop is age structured with a plus group at 15 years. However, the model is set up to allow the plus group to be changed easily to younger or older ages. The Beverton-Holt stock-recruit function is employed to predict age 0 recruits from the total number of eggs spawned, assuming a sex ratio of 50% females at age. The fish killed by commercial fishing were modelled using the catch data for the commercial fleets aggregated into single annual values. Recreational fishing mortality and shrimp bycatch mortality were modelled using recreational catch data and annual shrimp bycatch estimates reported in Schirripa and Legault (1999) and also SEDAR (2004) (Table 1).

Unlike the NMFS assessment, this model projected the population from the year 1880, when the first records of catches are reported in Schirripa and Legault (1999). The many missing values in commercial catches in some of the periods before the 1940s are filled by filling the catch just prior to each segment of missing years. Shrimp bycatch of juvenile red snapper is assumed to start occurring in 1946 and the values in unreported years before 1972 are assumed to be equal to the average of values after 1972. This appears to be reasonable because the reported shrimp catch from 1956 onwards still averages near to the post 1972 values and if red snapper abundance has been declining due to shrimp trawl bycatch, then it is possible that the roughly similar or smaller catches of shrimp after 1946 would lead to similar bycatches of red snapper also (Table 2). Also, using a time series of relatively large filled shrimp trawl bycatch values from 1946 to 1971 will help to test whether the current high fishing mortality rate values can be achieved under the values for steepness and average unfished recruitment (R_0) applied in the 1999 stock assessment. For example, if only very low fishing mortality rates result even when very high historic catches have been assumed, 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 for the retained catch was modelled to be stationary over time (Table 3). The selectivity at age for the recreational and commercial landings was approximated by using the 1998 partial fishing mortality rate (*F*) values at age for the recreational and the aggregated commercial fleets (Schirripa and Legault 1999); these are to be updated at the August 2004 workshop. These will be updated at the August SEDAR workshop. Discard selectivity at age for the recreational fleet and commercial fleets were modelled separately also using partial F values for discards also based on data and results in the NMFS assessment. These selectivity functions are to be updated based on base case results in the NMFS 2004 stock assessment (Table 3). These discards are modelled to have begun in 1985, after the first size based regulations were imposed in 1984. The values for weight and fecundity 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 NMFS assessment for the years 1984 to 1998 were re-computed and utilized in the gaming model to take into account the recent estimates of variations in cohort strength (Table 4). The model was fitted to the base case indices for the August 2004 assessment and recreational indices and a penalty function was applied to make the fishing mortality rate in 1998 close to that in the NMFS stock assessment.

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. For example, pre-recruit by-catch, such as those in the shrimp bycatch, are counted as part of the MSY. Also stock biomass that gives rise to MSY (B_{MSY}) includes parts of the population that are not considered to be recruited to the directed fishery. Such calculations may produce MSY reference points that are difficult to interpret. For example, yield is typically interpreted as landed fish that are marketable, not the sum of landed marketable fish and discarded fish. Unavoidable discard of undersize fish could arguably be interpreted as artificial mortality akin to predation but not normally as part of the yield. It is argued here that if it is unavoidable shrimp 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 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). F_{MSY} should then be found by adjusting the fishing mortality rate on the recruited population. 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.

Likewise, it could be argued that the computation of B_{MSY} should include only the parts of the population that could be considered to be recruited to the targeted recreational and commercial fisheries. B_{MSY} should not be computed to include also unrecruited parts of the population susceptible to other bycatch fisheries such as the shrimp trawl fishery.

Moreover, the use of a selectivity pattern that is known to no longer apply, due to recent changes in shrimp bycatch selectivity, make the use of the 1995-1997 linked selectivity function questionable.

The gaming model developed in this paper can 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 gaming model can be run with a fixed set of parameter value inputs or fitted to 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 and the MRFSS recreational index of abundance. The model was also fitted to estimates of fishing mortality rate for age 0 and 1 fish for years 1990 and

1998 from Schirripa and Legault's (1999) base case stock assessment run in order to constrain the model to model fishing mortality rates similar to those estimated in the NMFS stock assessment. The estimated values for age 0 and 1 fishing mortality rates in 1990 and 1998 that the gaming model was fitted to are as follows:

$F_{0,90} = 0.277$, $F_{1,90} = 1.275$

$F_{0,98} = 0.410$, $F_{1,98} = 1.000$

Half the shrimp trawl bycatch fishing mortality rate values for 1998 were applied for illustrative purposes in the alternative MSY calculations.

The gaming model can be projected into the future to evaluate the potential consequences of alternative fisheries management policies for Gulf of Mexico red snapper. These include alternative TAC policy options for the directed fishery and alternative assumptions about the future shrimp trawl bycatch of age 0 and age 1 red snapper. The gaming 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 MSY definitions. The implications of different values for M_0 and M_1 are also explored. Future policy options including different TACs, settings for shrimp 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.

Results and Discussion

Calculations using the gaming model reveal that the estimates of MSY reference points are sensitive to the manner in which MSY is defined and computed. Using the base case value for R_0 (245 million fish), and steepness of 0.95, and values for F_0 and F_1 similar to the mean estimates in 1995-1997 of Schirripa and Legault (1999), the value obtained for F_{MSY} (0.105 yr^{-1}) was not very different from that obtained in Schirripa and Legault (1999) (0.118 yr^{-1}) (Table 6). However, the value for MSY was somewhat less than the 1999 value (97.3 million pounds versus 108 million) and B_{MSY} was considerably lower than that obtained in Schirripa and Legault (1999) (947.13 million pounds as opposed to 3930 million pounds). The average unfished stock biomass (B_0) that was computed using the gaming model and the 1999 input values and the linked selectivity function is 2356 million pounds. The gaming model's estimate of B_0 is inconsistent with the very large 1999 B_{MSY} value, since with a Beverton Holt stock-recruit function, the B_{MSY} should be less than the average unfished abundance.

When the model was run from 1880 to the present using estimates of historic catches in Schirripa and Legault (1999), the 1999 base case parameter values for steepness (h), average unfished recruitment (R_0) and natural mortality in (Schirripa and Legault 1999), estimates of 1998 stock status starkly different from those in Schirripa and Legault (1999) were obtained. If steepness is 0.95 and unfished average recruitment (R_0) is 245 million as in Schirripa and Legault (1999), then the computed current abundance is hardly depleted at all (e.g., at about 81% of unfished abundance and about 200% of B_{MSY}), which is far more optimistic than obtained in the 1999 assessment (Table 6). It is only using much smaller values for steepness and/or R_0 that high values for F in the 1990s can result.

When steepness was fixed at 0.95 and the model was fitted to the SEAMAP and recreational CPUE data and constrained to give a high value for F in 1998, R_0 became 96.7 million and the depletion dropped to 45% of unfished average stock biomass (Table 6). The fishing mortality from recreational and commercial fishing (F_T) was 0.029. The maximum model predicted value for *F* on age 1 year fish (F_1) was 0.48, which was considerably less than those estimated in the 1999 assessment. It is noted here that in all instances in which the model was fitted to the SEAMAP and MRFSS data, in none of the instances, could the increasing trends from 1985 to 1995in these relative abundance series be obtained. In all instances, the model predicted trends given the catch history were either decreasing or remaining stable but not increasing as suggested by the SEAMAP and MRFSS indices (Table 5, Figures 1-10).

In instances in which the value for R_0 was freed up as an estimable parameter in the gaming model, trouble was experienced while fitting the model to data with the 1972 very high shrimp bycatch estimate (61.4 million young red snapper). It was impossible to obtain fishing mortality rates for age 1 (F_1) much higher than about 0.5 with this value included. In contrast, the 1999 estimates of F_1 were in the order of about 1. To obtain results with similarly high fishing mortality rates in the 1990s the very high 1972 shrimp bycatch value (61.4 million fish) was set equal to the average of estimates of shrimp bycatch after 1972 (26.2 million). When this was tried, the estimate of R_0 dropped to 68.9 million fish, B_{98}/B_{MSY} dropped to 0.54, B_{98}/B_0 dropped to 0.22 (Table 6). $F_{1,98}$ increased to 0.84 and the fishing mortality rate from the targeted fisheries increased to 0.09, and the total F was 0.57. However, MSY and B_{MSY} dropped to 27 million pounds and 267 million pounds.

When the fishing mortality rate from shrimp trawl bycatch became unlinked to the targeted fishing mortality rate in the MSY calculation considerable differences resulted (Table 6). The F_{MSY} increased to 0.23, B_{MSY} dropped to 119 million pounds and B_{98}/B_{MSY} increased to 1.2.

When steepness was set at 0.75 but keeping the MSY selectivity function linked, the F_{MSY} decreased to 0.088, MSY remained at 27 million pounds, B_{MSY} increased to 320 million pounds, $F_{1,98}$ increased to 0.89, B_{98}/B_{MSY} decreased to 0.48 (Table 6). Thus, estimates of reference points and stock status of red snapper are sensitive to the value for steepness applied. When the MSY selectivity function is unlinked, and the F_1 is set at 0.5, F_{MSY} changes to 0.14 (from 0.23 under similar conditions but steepness =0.95) and the B_{98}/B_{MSY} drops to 1.0.

When higher values for the rate of natural mortality at age 0 and age 1 (i.e., $M_0 = 2$, $M_1 = 1$) were applied, the estimates of R_0 increased markedly (to 358 million for steepness = 0.75 and MSY selectivity linked), and the estimates of F from recreational and commercial fishing also increased substantially (i.e., from about 0.08 to 0.21). The estimate of depletion also was lower with B_{98}/B_0 dropping to 0.18. When the MSY selectivity became unlinked and F_1 for MSY was set at 0.5, B_{98}/B_{MSY} dropped to 0.92 compared to 1.0 under lower values for M_0 and M_1. For an indication of the amount of MSY yield traded off as a result of bycatch in the shrimp trawl fishery, the shrimp bycatch mortality rates were set to zero. The MSY thus increased from 9.6 million pounds to 26 million pounds.

When the model was projected using 30 million snapper per year bycatch in the shrimp trawl fishery and a TAC of 9 million pounds under the scenario of steepness = 0.95 and R_0 = 245 million, and with the unlinked selectivity function for MSY calculation, the stock level remains very high, e.g, at about 80% of unfished stock biomass (Figure 1). If the model is fitted to the MRFSS and SEAMAP indices and R_0 is estimated but keeping h at 0.95, then the stock biomass decreases to the B_{MSY} level in 2020 (Fig. 2). If the settings are kept the same except that steepness is set at 0.75, instead, then the stock crashes in about 2015 (Fig. 3). Even with TAC levels lowered to 6 million, 3 million and 0 million tons per year, the stock still either cashes or continues to decrease in the future (Figs. 4-6). If the TAC is held at 9 million pounds and the bycatch in the shrimp trawl fishery is reduced to 20 million fish, then the stock increases from just below B_{MSY} to 140% of B_{MSY} (Fig. 7). This indicates that model results are still very sensitive to assumptions about shrimp bycatch and less sensitive to assumptions about future TAC. Under the same conditions, except increasing the values for M_0 and M_1 to 2 and 1, the stock starts from a lower level of depletion in 1998 and increases to 129% of B_{MSY} (Fig. 8). If the same conditions in Fig. 8 are applied except that the minimum size limit is removed from the recreational and commercial fisheries, then the stock shows a slower rate of increase (Fig. 9). This is because the fish that would have been released and possibly recovered are now counted as part of the TAC and more smaller fish are killed under the same TAC. If instead of modelling a constant number of juvenile red snapper killed in the shrimp fishery a constant fraction killed of 0.5 is modelled instead for future years, all other conditions being equal to those in Figure 7, then the rate of increase of the stock is less, at 120% of B_{MSY} in 2020 as opposed to 141% of B_{MSY} (Fig. 10).

Conclusions

In conclusion, the trial runs with the gaming 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 1880 and projecting the model to the present. If steepness is actually 0.95, only much smaller values of R_0 (e.g., 70 million fish as opposed to 245 million fish) can achieve the high levels of fishing mortality rate estimated in the 1999 stock assessment. If steepness were actually lower, e.g., 0.75, then possibly much larger values of R_0 may be plausible in order to achieve the high fishing mortality rates estimated over the last few decades.

Also changes in input values for M_0, M_1, steepness, and the manner in which MSY is calculated can produce markedly different estimates of stock status and biological reference points. Unlinking the MSY selectivity function to the shrimp trawl fishery tends to increase markedly F_{MSY}, decrease B_{MSY} and increase the estimate of B_{98}/B_{MSY}. Decreasing steepness tends to increase the estimate of R_0, and B_{MSY} and decrease F_{MSY} and the estimate of B_{98}/B_{MSY}. Increasing values for M_0 and M_1 increase slightly F_{MSY}, and to decrease markedly B_{MSY} and increase markedly the estimates of directed fishery fishing mortality rates.

Projection results were sensitive to the future values assumed for shrimp bycatch, the manner in which MSY was defined, the value for steepness that is applied, and the values assumed for M_0 and M_1, but only if they were much larger than assumed. This emphasizes the importance of taking into account uncertainty in these various inputs in the stock assessment of Gulf of Mexico red snapper. When size limits were removed for the recreational and commercial fisheries the recovery projections were slightly less because more smaller fish made up the TAC than before and this resulted in a higher harvest rate. In contrast, when fish are released when size limits are applied, a fraction of them survive and this results in slightly lower fishing mortality rates than when the size limits are abolished. If the harvest control rule to set the TAC was based on harvest rates, then the abolishment of the minimum size limit could instead have more positive results.

The next extension of the model will be to build an alternative stock-recruit function with recruitment at age 2 rather than age 0, to model the density dependent survival rates of this reef fish during its settlement phase. Bill Gazey has suggested this as a plausible alternative to the current stock-recruit function which assumes that density dependent survival rate occurs only just before settlement. 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 good reef habitat that serves as a refuge from predation. Such an alternative stock-recruit function could potentially impact estimates of MSY reference points, stock status, and predictions of stock recovery responses to alternative stock-rebuilding plans even more so than the various alterations evaluated in the current draft.

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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
1880	2743	NA	0	0.73	0.275
1887	206	NA	0	0.73	0.275
1888	3525	NA	0	0.73	0.275
1889	3790	NA	0	0.73	0.275
1890	4481	NA	0	0.73	0.275
1895	4886	NA	0	0.73	0.275
1897	6114	NA	0	0.73	0.275
1902	13609	NA	0	0.73	0.275
1908	12546	NA	0	0.73	0.275
1918	9430	NA	0	0.73	0.275
1923	11729	NA	0	0.73	0.275
1927	11899	NA	0	0.73	0.275
1928	10392	NA	0	0.73	0.275
1929	9903	NA	0	0.73	0.275
1930	7044	NA	0	0.73	0.275
1931	6094	NA	0	0.73	0.275
1932	6310	NA	0	0.73	0.275
1934	5704	NA	0	0.73	0.275
1936	7180	NA	0	0.73	0.275
1937	7312	NA	0	0.73	0.275
1938	7992	NA	0	0.73	0.275
1939	7801	NA	0	0.73	0.275
1940	6510	NA	0	0.73	0.275
1941	5551	NA	0	0.73	0.275
1942	4264	NA	0	0.73	0.275
1943	3826	NA	0	0.73	0.275
1944	4201	NA	0	0.73	0.275
1945	4532	NA	0	0.73	0.275
1946	5570	NA	2.62	0.73	0.275
1947	5544	NA	2.62	0.73	0.275
1948	7878	NA	2.62	0.73	0.275
1949	7888	NA	2.62	0.73	0.275
1950	6788	NA	2.62	0.73	0.275
1951	6811	NA	2.62	0.73	0.275
1952	9144	NA	2.62	0.73	0.275
1953	7728	NA	2.62	0.73	0.275
1954	8386	NA	2.62	0.73	0.275
1955	8863	NA	2.62	0.73	0.275
1956	8770	NA	2.62	0.73	0.275
1957	8541	NA	2.62	0.73	0.275
1958	9859	NA	2.62	0.73	0.275
1959	10219	NA	2.62	0.73	0.275
1960	10215	NA	2.62	0.73	0.275
1961	11887	NA	2.62	0.73	0.275
1962	12472	NA	2.62	0.73	0.275
1963	13326	NA	2.62	0.73	0.275
1964	14053	NA	2.62	0.73	0.275

1965	14055	NA	2.62	0.73	0.275
1966	13098	NA	2.62	0.73	0.275
1967	12498	NA	2.62	0.73	0.275
1968	11126	NA	2.62	0.73	0.275
1969	10018	NA	2.62	0.73	0.275
1970	8963	NA	2.62	0.73	0.275
1971	8886	NA	2.62	0.73	0.275
1972	8910	NA	6.14[a]	0.73	0.275
1973	8602	NA	2.17	0.73	0.275
1974	8938	NA	1.61	0.73	0.275
1975	8263	NA	1.43	0.73	0.275
1976	7530	NA	2.18	0.73	0.275
1977	5674	NA	2.31	0.73	0.275
1978	5045	NA	2.1	0.73	0.275
1979	4964	NA	2.12	0.73	0.275
1980	5012	NA	3.24	0.73	0.275
1981	5966	5514.51	3.23	0.73	0.275
1982	6409	2988.179	3.19	0.73	0.275
1983	7281	5665.68	2	0.73	0.275
1984	5742	1279.559	1.53	0.77	0.275
1985	4438	1625.191	1.74	0.77	0.275
1986	3965	3200.405	1.82	0.77	0.275
1987	3357	3364.977	2.29	0.77	0.275
1988	4060	2507.366	2.19	0.77	0.275
1989	3100	1996.582	2.66	0.77	0.275
1990	2662	1239.094	5.15	0.77	0.275
1991	2241	1935.677	4.51	0.77	0.275
1992	3043	3030.376	2.9	0.77	0.275
1993	3405	5294.582	3.24	0.8	0.275
1994	3252	4257.149	4.09	0.8	0.275
1995	2954	3254.362	4.31	0.8	0.275
1996	4351	5434.647	3.51	0.8	0.275
1997	4823	5444.966	3.92	0.8	0.21
1998	4694	6001.958	2.6	0.8	0.21
1999	4877	4931.518	2.6	0.8	0.21
2000	4844	4145.86	2.6	0.8	0.21
2001	4666	4567.668	2.6	0.8	0.21
2002	4823	5989.773	2.6	0.8	0.21
2003	4445	5989.773	2.6	0.8	0.21

[a]Note that this value was replaced by 2.62 in some of the runs for reasons mentioned in the text.

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

year	total catch
1956	64795194
1957	56051583
1958	66981149
1959	66981149
1960	82011765
1961	41538725
1962	45356453
1963	76868390

1964	69173035
1965	78189172
1966	76813099
1967	97684323
1968	78467115
1969	81498967
1970	97012941
1971	94902893
1972	97444205
1973	75512817
1974	78924936
1975	74205779
1976	91033933
1977	118110932
1978	120478481
1979	90678170
1980	101642362
1981	128205586
1982	85597585
1983	78207645
1984	102480285
1985	114096238
1986	130743691
1987	109021484
1988	89130291
1989	104047890
1990	107563380
1991	107563380
1992	93686414
1993	86378948
1994	90267765
1995	93901029
1996	101091922
1997	86989124
1998	111924674
1999	100419269
2000	113808089
2001	97706647
2002	95668608
2003	104551662

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. All values are derived from Schirripa and Legault (1999).

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
0	0	0	0.218766	0.412023	0	0	0	0	0.778773
1	0.1	0	1	1	1.62E-05	0	0.002008	0.012272	3.490007
2	0.5	0.007	0	0	0.004458	0	0.0454	0.235805	0.150241
3	1.3	0.367	0	0	0.370558	0.177965	0.677359	0.10598	0.633356
4	2.5	1.228	0	0	1	0.034774	1	0.006107	1
5	3.9	2.779	0	0	0.856684	0.002215	0.682694	0.000233	0.737422
6	5.4	5.124	0	0	0.627934	0.000149	0.422718	1.11E-05	0.48725
7	7	8.22	0	0	0.462786	8.86E-06	0.290838	0	0.345279
8	8.6	11.937	0	0	0.348775	6.36E-07	0.21603	0	0.259132
9	10.2	16.099	0	0	0.272769	0	0.16986	0	0.204686
10	11.6	20.524	0	0	0.207066	0	0.130405	0	0.155065
11	13	25.039	0	0	0.20579	0	0.131015	0	0.155065
12	14.2	29.5	0	0	0.204533	0	0.131695	0	0.155065
13	15.3	33.8	0	0	0.203212	0	0.132504	0	0.155065
14	16.3	37.851	0	0	0.201834	0	0.133421	0	0.155065
15	17.1	41.555	0	0	0.196692	0	0.137366	0	0.155065

Table 4. The relative recruit residuals utilized for years 1984-1998 in the gaming model.

Year	Relative recruit residual
1984	0.300313
1985	-0.5891
1986	-0.05643
1987	-0.32273
1988	-0.39941
1989	0.604616
1990	0.167984
1991	-0.07789
1992	-0.04873
1993	0.14046
1994	0.200134
1995	0.196681
1996	0.165755
1997	-0.15196
1998	0.010789

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

Year	SEAMAP	MRFSS
1972	2.613	-1
1973	2.727	-1
1974	1.539	-1
1975	1.011	-1
1976	1.111	-1
1977	1.114	-1
1978	0.524	-1
1979	1.438	-1
1980	2.212	-1
1981	2.457	0.26
1982	0.995	0.15
1983	0.223	1.05
1984	0.348	0.66
1985	0.429	0.31
1986	0.118	0.53
1987	0.295	0.86
1988	0.131	0.85
1989	0.111	0.84
1990	1.028	0.7
1991	0.449	1.24
1992	0.336	1.58
1993	0.459	1.29
1994	0.594	1.45
1995	0.728	1.4
1996	0.579	1.48
1997	0.518	1.65
1998	0.457	1.61

Table 6. Implications for parameter estimates with different input assumptions.

h	linked S_a	R_0 mil fish	F_1 in MSY (yr^{-1})	M_0 (yr^{-1})	M_1 (yr^{-1})	SBC_{72} =mean	F_{MSY} (yr^{-1})	MSY mil. lb	B_{MSY}	$F_{1,98}$ (yr^{-1})	F_{targ} (yr^{-1})	F_{all} (yr^{-1})	B_{98}/B_{MSY}	B_{98}/B_0	B_{MSY}/B_0
0.95	yes	245	NA	0.5	0.3	no	0.105	97	947	0.15	0.006	0.057	2.0	0.81	0.40
0.95	yes	97	NA	0.5	0.3	no	0.105	38	374	0.48	0.029	0.24	1.1	0.45	0.40
0.95	yes	69	NA	0.5	0.3	yes	0.105	27	267	0.84	0.091	0.57	0.54	0.22	0.40
0.95	no	69	0.5	0.5	0.3	yes	0.23	26	119	0.84	0.092	0.58	1.2	0.21	0.17
0.75	yes	79	NA	0.5	0.3	yes	0.088	27	320	0.89	0.084	0.60	0.48	0.20	0.42
0.75	no	79	0.5	0.5	0.3	yes	0.135	19	148	0.89	0.084	0.60	1.0	0.20	0.19
0.75	yes	358	NA	2	1	yes	0.090	14	159	0.60	0.21	0.54	0.43	0.18	0.41
0.75	no	358	0.5	2	1	yes	0.135	9.6	75	0.60	0.21	0.54	0.92	0.18	0.19
0.75	no	358	0	2	1	yes	0.180	26	154	0.60	0.21	0.54	0.44	0.17	0.39

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. SBC_{72} = mean indicates whether the shrimp trawl bycatch was set equal to the man of values after that date; $F_{1,98}$ is the model predicted value for fishing mortality rate on age 1 fish in 1998; F_{targ} refers to the total fishing mortality rate of the directed fishing fisheries combined but also including discards from the directed fisheries; Fall indicates the total fishing mortality rate from all sources of fishing mortality including shrimp trawl bycatch. The other commonly applied terms are defined in the text.

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 Table 1.1.

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 discards occur only after 1985).

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 1985).

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.

B. Births

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

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

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

w_a is the mass of a fish of age *a* (assumed to be constant throughout the year):

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

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

ε_y is the recruitment residual for year y, ε_y were based on subtracting the base case Beverton-Holt model predictions from the base case estimates of annual recruitment for years 1984 in Schirripa and Legault (1999), and

α, β are Beverton-Holt stock-recruitment function parameters.

C. Initial conditions

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

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

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

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

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

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:

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

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:

$$\begin{aligned} \alpha &= \tilde{B}_0^S \frac{1-h}{4h} \\ \beta &= \frac{5h-1}{4hR_0} \\ \tilde{B}_0^S &= 0.5 \left\{ \sum_{a=a_r}^{m-1} f_a \exp(-(a-2)M_2 - M_0 - M_1 - M_2/2) + \frac{f_m \exp(-(m-2)M_2 - M_0 - M_1 - M_2/2)}{(1-\exp(-M_2))} \right\} \end{aligned} \qquad (1.11)$$

D. Catches

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

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

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*:

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

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

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

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 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

$$G_1 = \exp(-F_0 - M_0)\left(1 - S_0^A H\right)\left(1 - S_0^{AD} H\right) \qquad a = 1$$

$$G_2 = G_1 \exp(-F_1 - M_1)\left(1 - S_1^A H\right)\left(1 - S_1^{AD} H\right) \qquad a = 2$$

$$G_a = G_{a-1} \exp(-M_2)\left(1 - S_{a-1}^A H\right)\left(1 - S_{a-1}^{AD} H\right) \qquad 3 \le a \le m-1 \qquad (1.14)$$

$$G_m = \frac{G_{m-1} \exp(-M_2)\left(1 - S_{m-1}^A H\right)\left(1 - S_{m-1}^{AD} H\right)}{\left(1 - \exp(-M_2)\left(1 - S_m^A H\right)\left(1 - S_m^{AD} H\right)\right)} \qquad a = m$$

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.

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

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

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

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

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

$$EPR(H) = w_2 G_2 \exp(-M_2/2)\left(1-0.5S_2^A H\right)\left(1-0.5S_2^{AD} H\right) \qquad a = 2$$
$$+\sum_{a=3}^{m} f_a G_a \exp\left(-M_a/2\right)\left(1-0.5S_a^A H\right)\left(1-0.5S_a^{AD} H\right) \qquad 3 \le a \le m \qquad (1.17)$$

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

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

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

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

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

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 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. Gaming model projection results for steepness = 0.95 and R_0 = 245 million, and using a non-linked MSY selectivity function with F_1 = 0.5. TAC=9 mil lb, 30 million young snapper caught per year in shrimp trawls. M_0 and M_1 are kept at 0.5 and 0.3 unless specified otherwise.

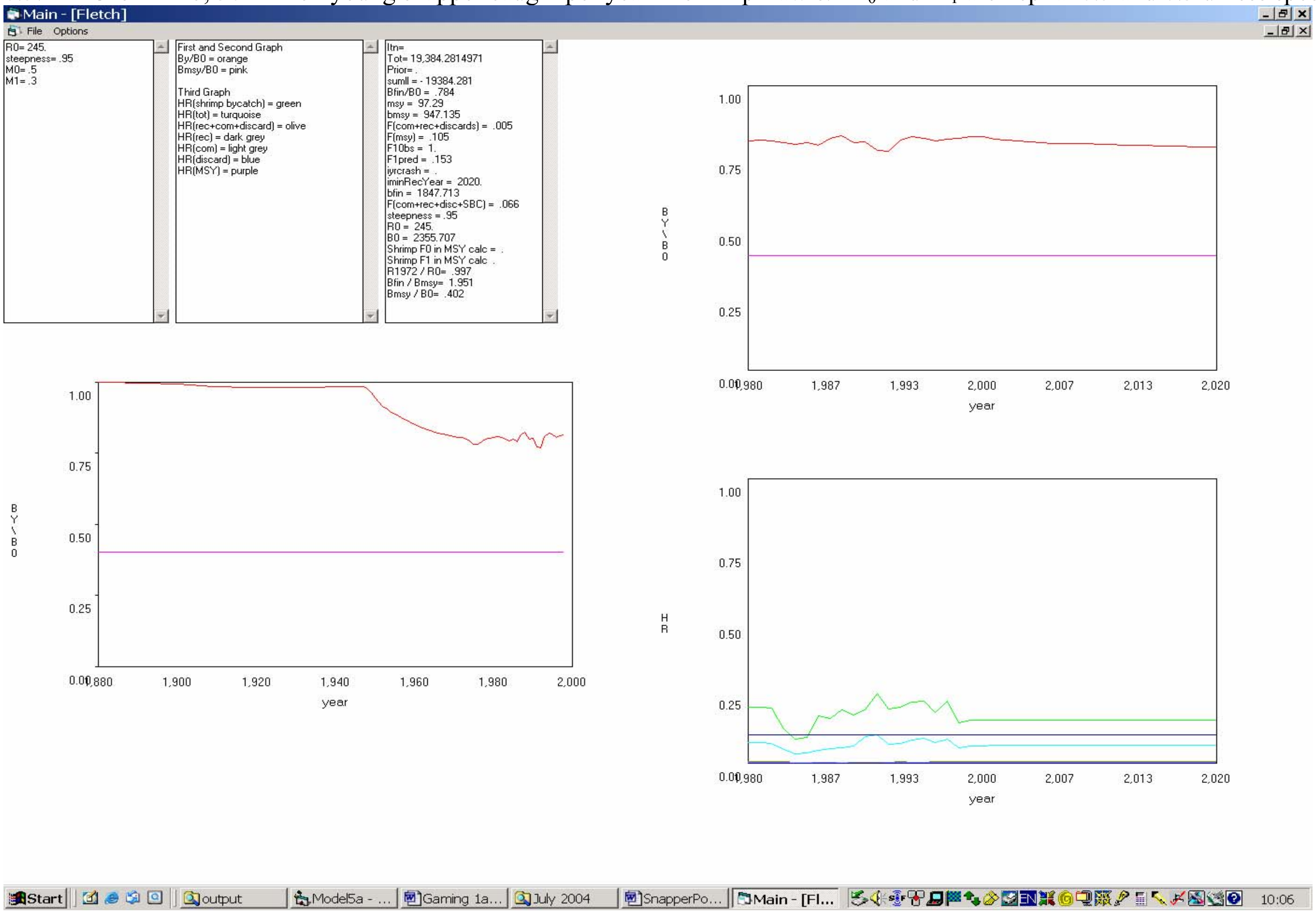

Figure 2. Gaming model projection results for steepness = 0.95, and using a non-linked MSY selectivity function with F_1 = 0.5. TAC=9 mil lb, 30 million young snapper caught per year in shrimp trawls. M_0 and M_1 are kept at 0.5 and 0.3 unless specified otherwise.

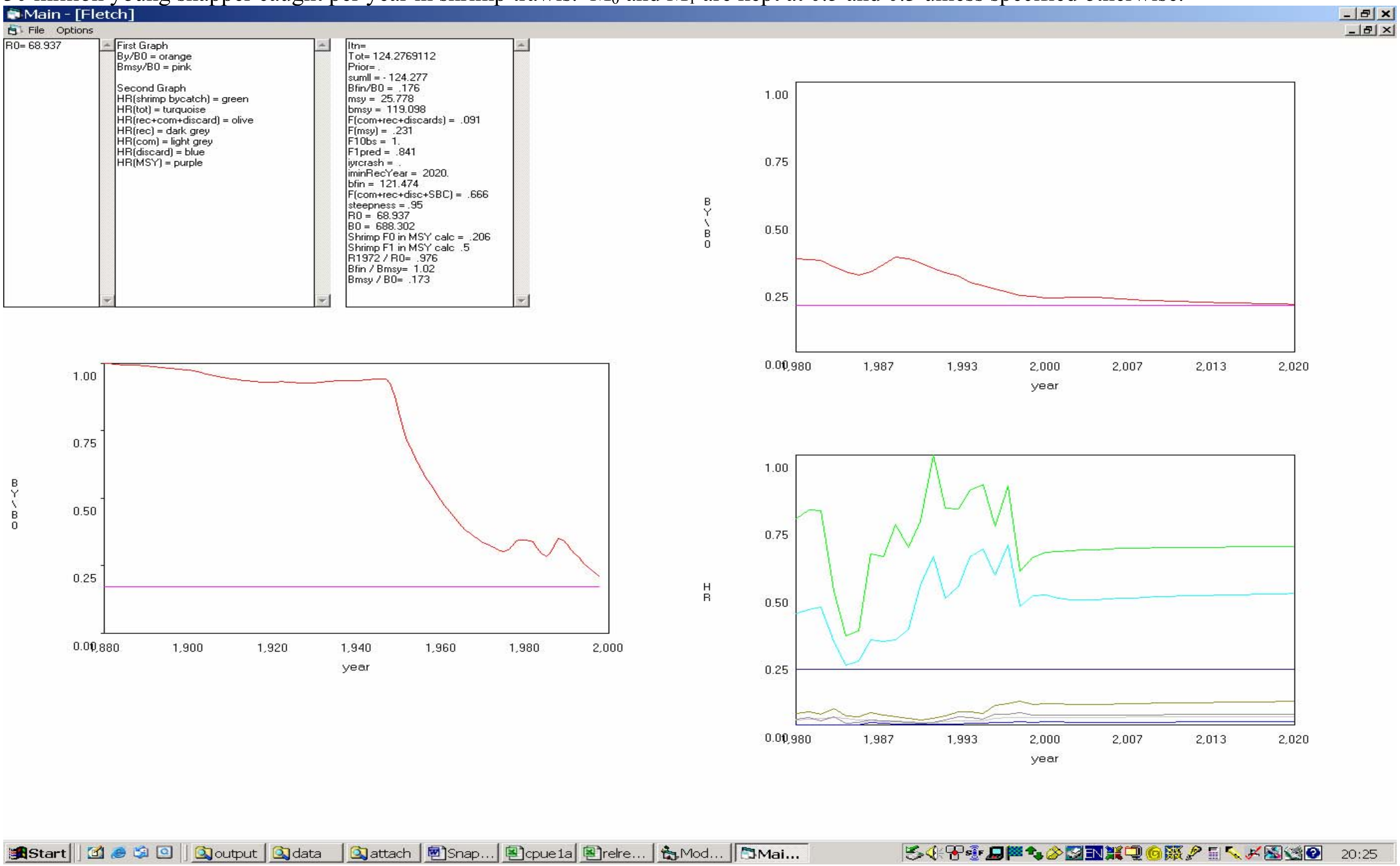

Figure 3. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with $F_1 = 0.5$. TAC=9 mil lb, 30 million young snapper caught per year in shrimp trawls.

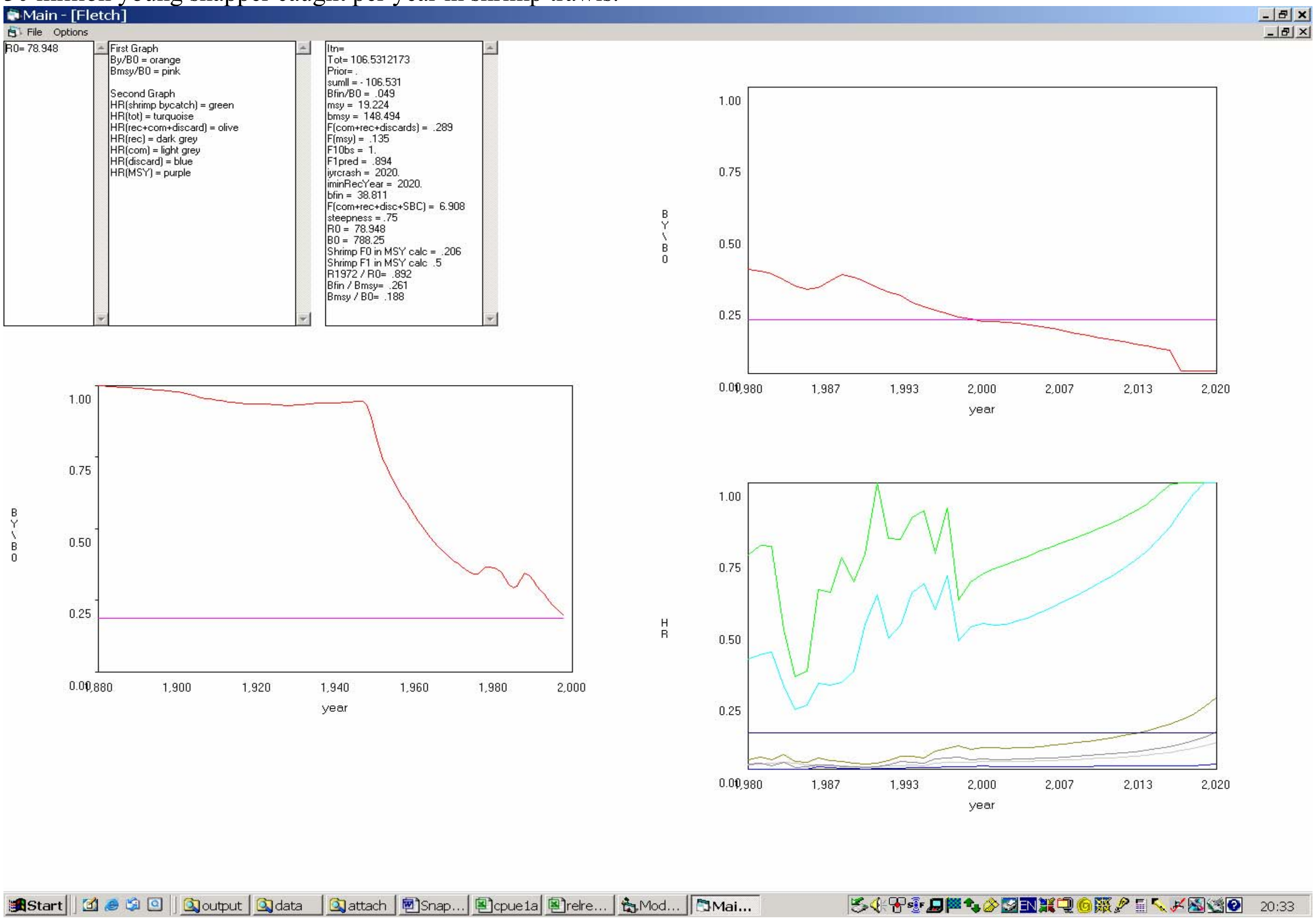

Figure 4. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with $F_1 = 0.5$. TAC=6 mil lb, 30 million young snapper caught per year in shrimp trawls.

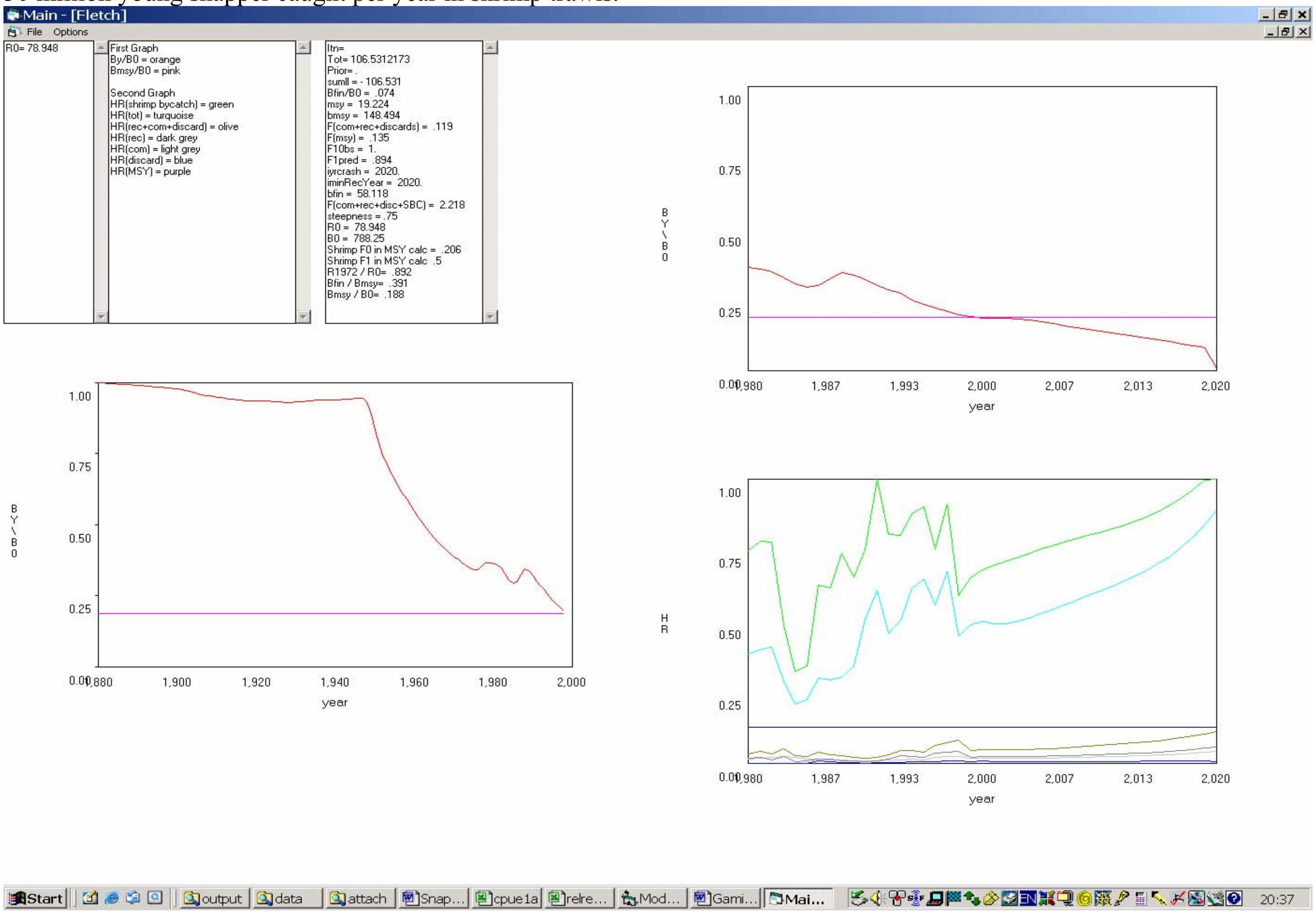

Figure 5. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with F_1 = 0.5. TAC=3 mil lb, 30 million young snapper caught per year in shrimp trawls.

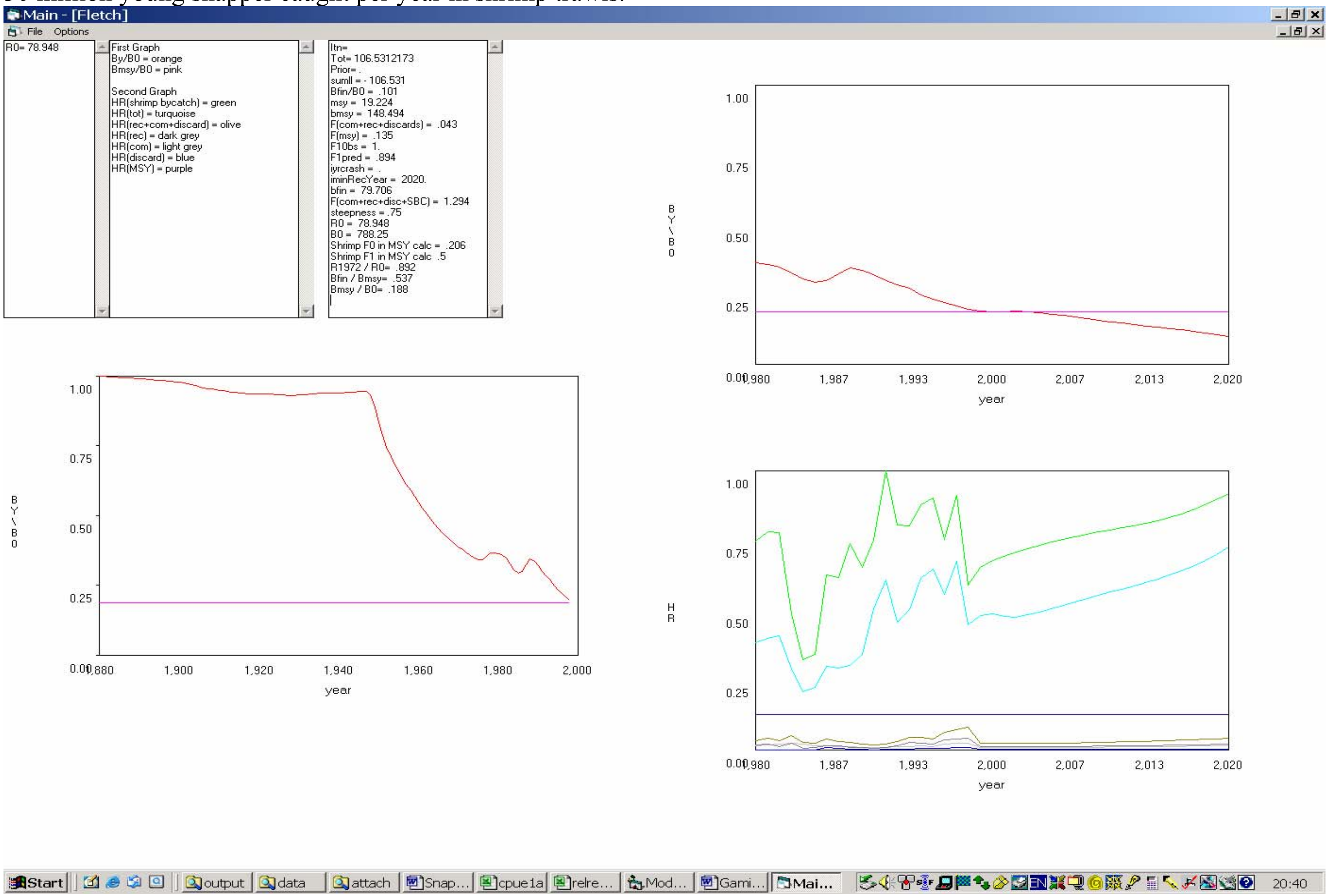

Figure 6. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with $F_1 = 0.5$. TAC=0 mil lb, 30 million young snapper caught per year in shrimp trawls.

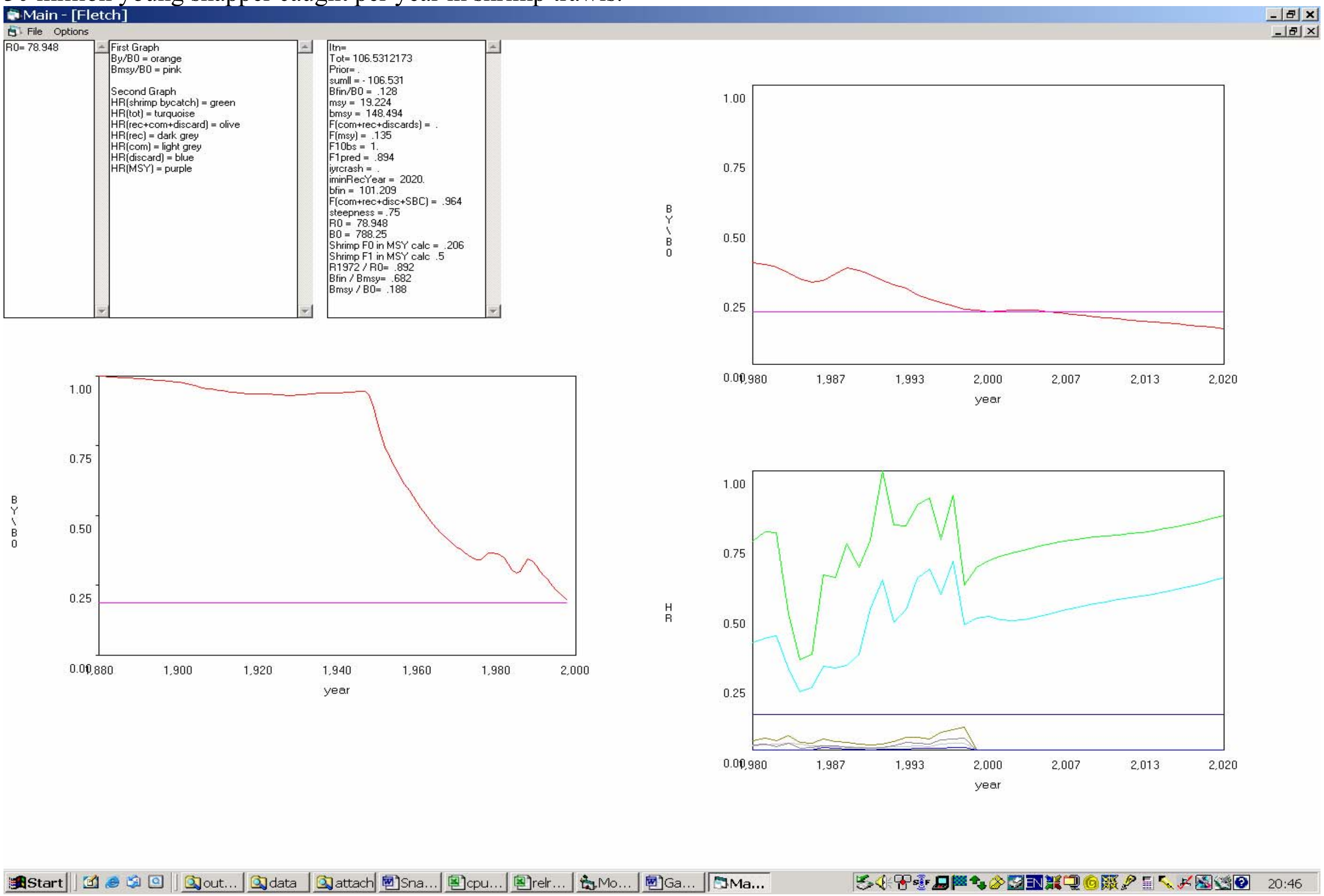

Figure 7. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with F_1 = 0.5. TAC=9 mil lb, 20 million young snapper caught per year in shrimp trawls.

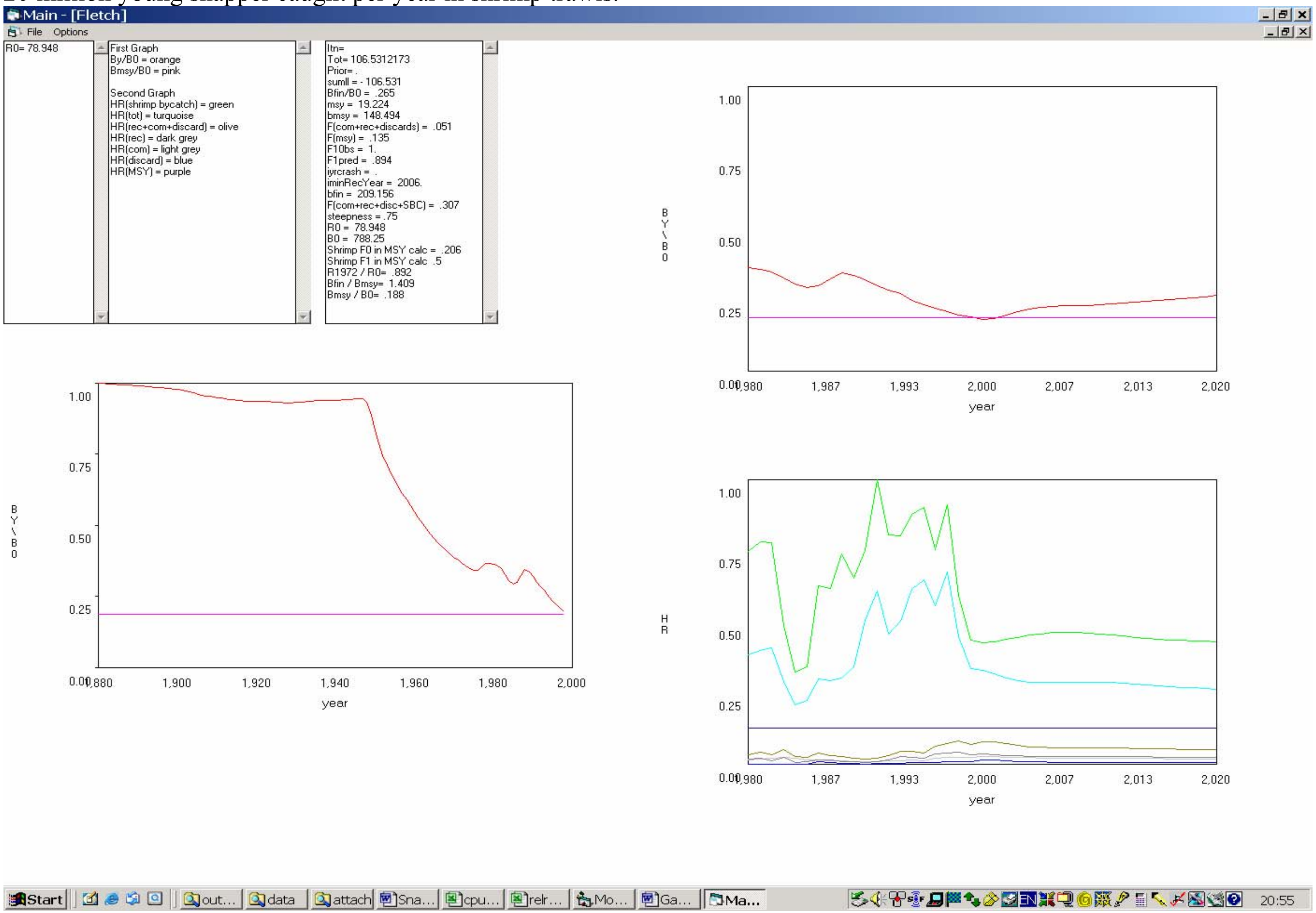

Figure 8. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with F_1 = 0.5. TAC=9 mil lb, 20 million young snapper caught per year in shrimp trawls. M_0 and M_1 are increased to 2 and 1.

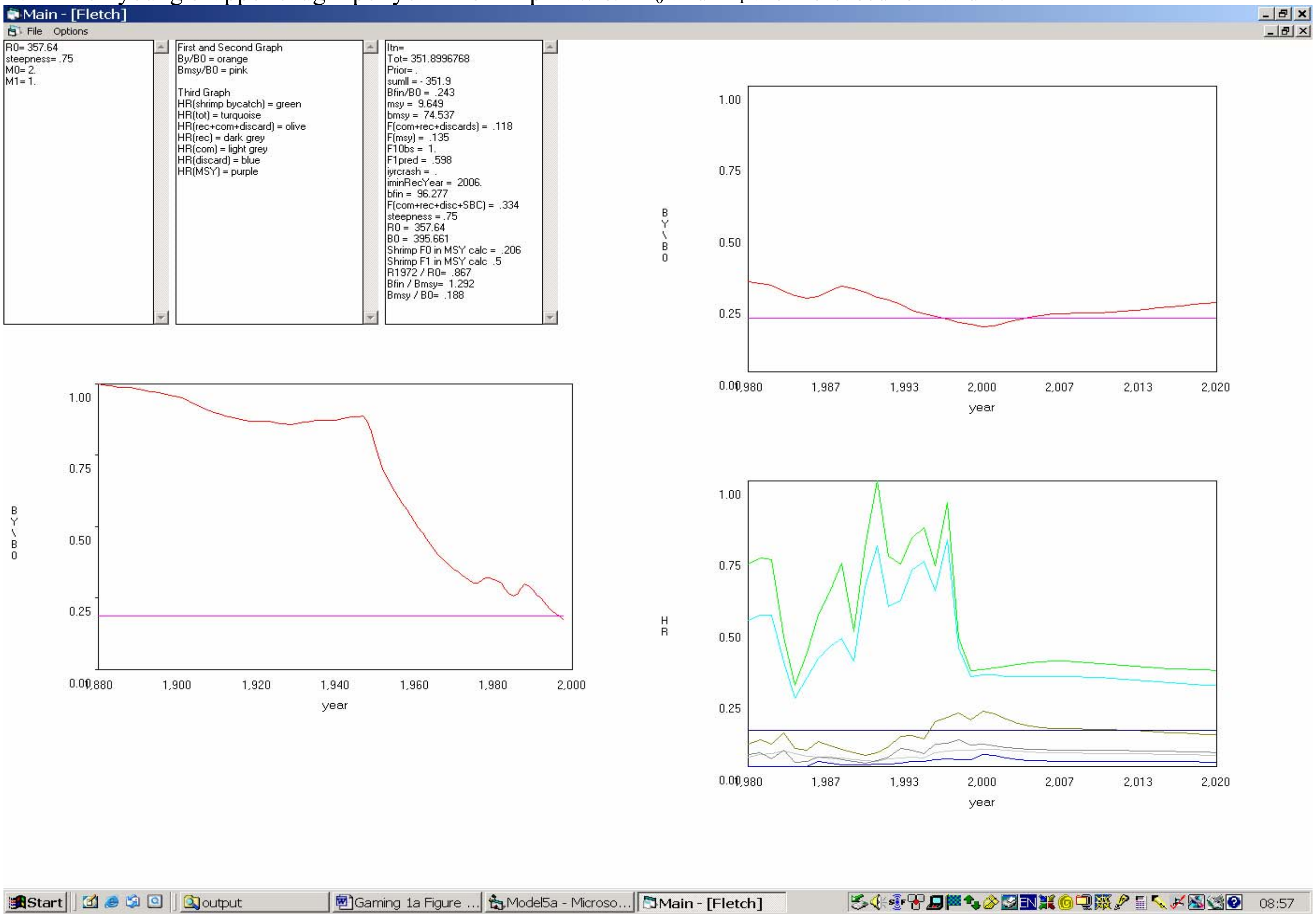

Figure 9. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with $F_1 = 0.5$. TAC=9 mil lb plus size limit is removed for both fisheries, 20 million young snapper caught per year in shrimp trawls. M_0 and M_1 are increased to 2 and 1.

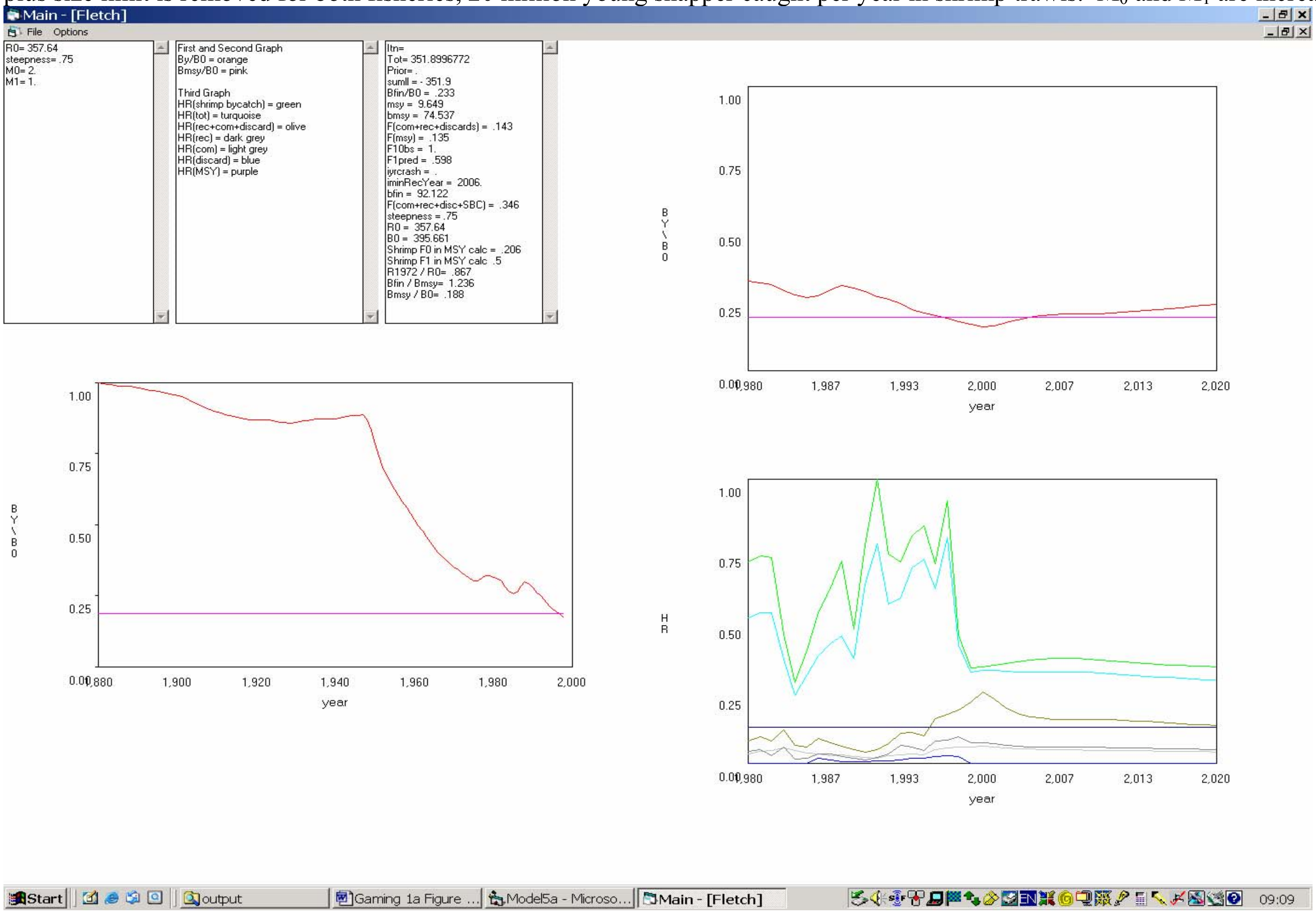

Figure 10. Gaming model projection results for steepness = 0.75, and using a non-linked MSY selectivity function with $F_1 = 0.5$. TAC=9 mil lb, harvest rate on young snapper caught per year in shrimp trawls is set at 0.5 in future years. M_0 and M_1 are set to 0.5 and 0.3.