# REVISED BOOTSTRAPPING OF A GULFWIDE IMPLEMENTATION OF AN AGE-STRUCTURED-ASSESSMENT-PROCEDURE (ASAP) FOR RED SNAPPER (*LUTJANUS CAMPECHANUS*) FROM 1962 TO 2003

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## INTRODUCTION

There was interest at the first red snapper assessment workshop in exploring the sensitivity of the assessment model to changes in natural mortality for young red snapper. The panel recommended that we examine the influence of early natural mortality by varying the rate on age-1 individuals ($M_1$) from 0.2 to 1 and keeping natural mortality on age-0 individuals ($M_0$) set equal to 5/3 the $M_1$ value. Finally, it was recommended that we maintain the *status quo* value of 0.1 for natural mortality on fish that were age-2 or older. The age-structured assessment procedure (ASAP) was not designed to allow bootstrapping of parameter values, so we were required to adapt the existing program to do so. Technically we did a bootstrap procedure in that we drew, with replacement, from a set of forty specified ($M_0$,$M_1$) pairs. However, these pairs were generated from a theoretical distribution of $M_1$ values so that the procedure was essentially a discretized Monte Carlo simulation.

This bootstrap procedure helps to assess the risk surrounding red snapper management as informed by an uncertain assessment. The logical first step in a risk assessment is to quantify input uncertainties and how they translate through the system (e.g., are they amplified or dampened), and bootstrapping across natural mortality values does so for one major source of uncertainty. However, these results should not be considered a full-blown risk assessment. For example, we did not address uncertainty in natural mortality rates for older red snapper. And, although we also examined the influence of running different values of the steepness parameter in the stock-recruitment relationship, we did not explicitly build in ranges for other parameter values. Additionally, any single model will fail to capture uncertainties in the structure of the system, about which any model has to make assumptions (although we did examine this issue elsewhere by running several models, see the summary by Brooks SEDAR7-AW-Appendix 2). As such, this bootstrapping procedure is likely to underestimate the uncertainties surrounding this assessment.

# METHODS

A series of executable files, batch files, and data procedures were combined to allow for bootstrapping, or multiple runs varying in parameter values, of the red snapper ASAP model. These steps included an optional preconditioning of the model, designed for when maximum recruitment and steepness of the stock-recruitment relationship were both fixed (not applicable to the 1962-2003 cases). The preconditioning determines an appropriate value for virgin biomass, which varies with natural mortality, by estimating that value in recent years (1984-2003) and then scaling this estimate up by a factor of 8.5. Second, 100 runs were conducted, which varied in their natural mortality values, by randomly drawing from input files, each of which represented a different value. Finally, a combination of an executable and batch file was used to search through the output files for data of particular interest and compile these into a single report file. This report file was then used to produce tables and charts.

Initial bootstrapping efforts focused on understanding the sensitivity of results to variations in the natural mortality rates on age-0 and -1 fish, but the procedure would need only minor modifications to bootstrap over multiple parameter values (e.g., steepness of the stock-recruitment curve). Natural mortality parameters were varied simultaneously on age-0 and age-1 individuals, with the age-0 natural mortality always set equal to 5/3 the value on age-1 fish. Making changes to the natural mortality rates required re-simulating age-composition from sampled size-composition (Turner SEDAR7-AW-18). This was performed prior to the bootstrapping, with the appropriate age-structure entered into forty different input files, each for a different value of $M_1$, ranging in 0.02 increments between 0.21 and 0.99. During the bootstrapping, these files were selected randomly from a truncated and discretized normal distribution of $M_1$ values, with mean 0.589. The pre-truncated distribution was created using a standard deviation of 0.2357 based on examination of empirical data (Nichols SEDAR7-AW-15). After truncation the standard deviation became 0.2186. In all other respects, the models were constructed the same as the base runs for the 1962-2003 Gulf-wide ASAP model (Cass-Calay et al. SEDAR7-RW-03). The difference between these three runs of the bootstrapping was the steepness of the stock-recruitment relationship. A value of 0.81 was used as it represented the median value from a meta-analysis of similar species (SEDAR7-DW report). A value of 0.95 was also tested because it was used in the last assessment due to its better fit to the data, a phenomenon we witnessed again here. Finally, an intermediate value of 0.9 was used.

The base properties of all projection models followed the base model configuration in Cass-Calay and colleagues (SEDAR7-RW-03). Except where noted, all results are presented as medians and 80% confidence intervals.

The details of the projections and MSY scenario assumptions were as follows. In the first set of runs, directed fleets were constrained to a catch of 9.12 million pounds while shrimp bycatch was assumed to be reduced by 40% starting in 2007, as a result of effort reduction, gear modifications, or both. MSY benchmarks were calculated in an unlinked, or current shrimp, manner, in which bycatch from the shrimp and closed season fleets were assumed to be an inherent uncontrollable part of the fishery. As such, MSY was calculated based on what productivity was left after the impact of the bycatch fleets.

In the second set of runs, directed fleets were also constrained to 9.12 mp, but the bycatch fleets were assumed to be linked. As such, MSY benchmarks were calculated by scaling down all fisheries simultaneously until maximum yields were achieved. In this scenario, bycatch was still assumed to be an inherent uncontrollable part of the system but at lower levels than the unlinked case. Additionally, the 40% reduction in shrimp bycatch was assumed so that the shrimp fleet in this scenario would be reduced to a greater degree than other sectors of the fishery.

In the third set of runs, projections were made assuming a directed catch of 9.12 mp annually, and no bycatch. In this manner, MSY benchmarks were calculated in the future assuming a selectivity pattern that represents only directed fishing.

## RESULTS

In general, the bootstrapping runs showed smooth behavior of the model to variations in natural mortality on age-0 and -1 fish (but see description below of MSY reference points and trajectories). Changes in parameter estimates appeared to be mostly gradual and relatively consistent across a wide range of $M_0$ and $M_1$ values at three different steepness levels and three different MSY benchmark scenarios. These results support the relatively stable behavior of this particular configuration of ASAP (Cass-Calay et al., SEDAR7-RW-03).

Changes in steepness had substantial influence on the model's conclusions. The model fit data best at the highest steepness value examined here (Tables 1-3), while the relative fit to different components stayed remarkably constant across the three values (Fig. 1). Most fishing mortality rate benchmarks (e.g., $F_{0.1}$, $F_{30\%SPR}$) dropped with increased steepness, although $F_{MSY}$ remained relatively stable or even increased slightly (unlinked case, Table 1). In contrast, the estimate of current fishing mortality ($F_{2004}$) rose (Table 1). As a result, our impression of the degree of overfishing increased with the steepness value we assumed (Tables 1-3). The dynamics surrounding spawning stock biomass were more complex because both the key benchmark ($SS_{MSY}$) and current estimate declined with increasing steepness (Tables 1-3). This decline was more pronounced in the current estimate. As a result, our impression of the degree to which the stock was overfished also increases with steepness (Tables 1-3). Yields as a percentage of maximum sustainable yield (MSY) were slightly greater at higher steepness in the unlinked case (Table 1) and slightly lower in the linked and no bycatch cases (Tables 2, 3).

Generally, the mean fit across the three steepness values and the forty M values was good. Catches were matched overall quite well, with the only major problem being matches to bycatch by the shrimp fleet prior to 1973, where all scenarios underestimated (Figs. 2-4). Indices did not fit as well (Figs. 5-7). The biggest problems were seen in the fit to the SEAMAP fishery-independent index of 1-year old abundance, where the model underestimated the values in early years, especially at low steepness (Figs. 5c-7c), and to the nominal shrimp CPUE index, which the model estimated was flatter than was observed (Figs. 5d-7d). The only other major difference was that the variability across M values was generally more pronounced for the video and larval bongo surveys at higher steepness values (Figs 5e,f-7e,f).

Observed recruitment patterns were quite consistent across steepness values (Fig. 8) with an apparent increase in the late 1980s and early 1990s and a recent dramatic decrease.

Trajectories were also generally similar across steepness values (Figs. 9-11, 13-15). Some patterns in trajectories have already been discussed in the context of reference points. The biggest difference between steepness values was in the sensitivity of the results to different early natural mortality rates, with greater sensitivity shown at lower steepness values. This characteristic can be seen in the extremely large confidence intervals for all of the MSY-ratio-based trajectory values in the year 1972 for the unlinked and no bycatch runs (Figs. 9-11). When $M_1$ was less than 0.35 (and therefore $M_0$ less than 0.5833) MSY reference points dropped to nearly 0, leading to tremendously large ratios (Fig. 12). However, this sensitivity was not seen when MSY reference points were calculated using linked selectivity (Figs 13-16). A more complex pattern of sensitivity was seen with respect to spawning stock biomass estimates. When steepness was low, the spawning stock biomass estimates were most variable in recent years; when steepness was high, variability was most pronounced in early years (Figs. 9-11, 13-15).

Projections also showed interesting patterns. The median projections of spawning stock ratio (relative to MSY) and transitional spawning potential ratios (tSPR) were nearly identical across all three steepness values (Figs. 17-19). The exception to this rule was tSPR in the unlinked case, which was lower at higher steepness values (Fig. 17). Perhaps more interesting and informative, the sensitivity of the spawning stock biomass and tSPR projections decreased with increasing steepness.

Natural mortality also played an important role in our impression of the stock. The best fits occurred at high natural mortality rates regardless of the steepness value (Figs 20a-28a). High M values also corresponded with the lowest stock size benchmarks and MSY values (Figs. 20b-28b), with greater sensitivity to M values under the no bycatch and especially the linked selectivity case, and at higher steepness values across all selectivity cases. High M values additionally corresponded with the most pessimistic current fishing mortality ratios (Figs. 20c-28c). Sensitivities to M values were more pronounced at lower steepness values and less pronounced in the linked selectivity case. Current spawning stock status showed more complex patterns, generally decreasing with increasing M but not necessarily at high steepness values (Figs. 20d-28d). Status in 2032 was generally insensitive to changes in M in the linked selectivity case but did show higher F ratios and lower SS ratios with higher Ms in the unlinked case (Figs. 20e,f-28e,f).

## DISCUSSION

Many of the conclusions reached here, in particular those related to different steepness assumptions, confirmed findings presented elsewhere (Cass-Calay et al. SEDAR7-RW-03). The bootstrapping procedures provided insight into the sensitivity of model conclusions to changes in early natural mortality rates, and interaction between this sensitivity and steepness. In this respect, it was shown that the model fit best at high levels of early natural mortality irrespective of steepness values. This does not necessarily mean that high steepness is the right answer, though. With higher steepness, the model was able to largely free recruitment from density-dependence, and as a result could adapt better to changes in natural mortality by devising different overall levels of recruitment. Lowering steepness values assumes a stronger pattern in expected recruitment and would constrain the model’s ability to explain cohort strengths across a wide range of early natural mortality rates.

These procedures did identify a number of sensitivities and sensitivity-steepness interactions. The greatest sensitivities were the MSY reference points (MSY, $SS_{MSY}$, $F_{MSY}$) as estimated for 1972 with low early natural mortality, particularly at low steepness. These reference points are a factor of the global selectivity pattern of all fisheries. The model did allow the selectivity of each fleet to vary on occasion, but assumed constant selectivity within fleets from 1962 until 1990. The other way selectivity can differ is when the relative impact of different fleets varies. It is apparent in Figs. 2-4 that 1972 was characterized by unusually large shrimp bycatch. As such, the MSY reference points in that year would be shifted towards the shrimp selectivity pattern on juvenile fish. Consequently, the related MSY reference points were unusually low and the ratios of status relative to MSY in that year high. The low early natural mortality values exacerbated this problem because it put a greater emphasis of bycatch mortality on these life stages. In contrast, using a linked selectivity pattern reduced this problem because this approach required reducing the impact of shrimp bycatch proportionally to other fleets when calculating MSY benchmarks.

Other sensitivities to early natural mortality rates included recruitment levels (Fig. 8), which are intuitive because the number of red snapper that recruit to the directed fisheries are largely influenced by recruitment, early natural mortality, and bycatch in the shrimp fishery (for which there were estimates available). As such, it is not surprising that recruitment varied with changes in early natural mortality rates. Estimated spawning stock size and fishing mortality rates were also sensitive to changes in early natural mortality (Figs. 9c,e-11c,e, 13c,e-15c,e), especially at low steepness. Status criteria also showed sensitivities to early natural mortality rates, particularly at low steepness and when MSY benchmarks were calculated with unlinked fleet selectivities (Figs. 20-28).

Regarding status, it is important to reiterate that the MSY reference points presented here are based on key assumptions regarding the makeup of the fishery. In previous assessments, MSY reference points were determined using linked fleet selectivities. In other words, the reference points were determined by manipulating the impacts of all fleets up or down until maximum catches could be achieved. Here we also examined runs that assumed only the directed fleets would be manipulated up and down, with bycatch fleets (closed season, shrimp bycatch) held at current levels unless specified otherwise (e.g., the 40% reduction in shrimp bycatch starting in 2007), and also runs that assumed no bycatch from 2004 onwards. This issue can be looked at across a continuum, with assuming current bycatch levels (i.e., unlinked) on one end (in other words, asserting that bycatch is beyond our control) and no bycatch on the other. Depending on these assumptions, natural mortality levels, and steepness values, current status could be considered as good as a fishing mortality ratio of 0.2 and a spawning stock biomass ratio of 1.75 (unlinked selectivities, low steepness, low M) or as bad as a fishing mortality ratio of 2 and a spawning stock biomass ratio of 0.12 (linked selectivities, high steepness, moderate M, Fig. 25c,d). Sorting out the selectivity cases will require a policy-level decision about how much we should assume control over bycatch when determining the potential performance of a fishery. Other uncertainties are scientific in nature (e.g., steepness, M values). These should be addressed by not only highlighting the degree of uncertainty, but also what are the potential consequences of basing management on values that turn out to be incorrect.

**Table 1**. Benchmark Statistics for 1962-2003 Gulf-wide ASAP bootstraps UNLINKED CASE.

| **Model Description** | Run A | | | Run B | | | Run C | | |
|---|---|---|---|---|---|---|---|---|---|
| Steepness | 0.81 | | | 0.9 | | | 0.95 | | |
| **Benchmark Statistic** | **Median** | **10% conf** | **90% conf** | **Median** | **10% conf** | **90% conf** | **Median** | **10% conf** | **90% conf** |
| $F_{0.1}$ | 0.227 | 0.225 | 0.230 | 0.208 | 0.202 | 0.215 | 0.189 | 0.186 | 0.194 |
| $F_{MAX}$ | 0.306 | 0.303 | 0.309 | 0.282 | 0.275 | 0.290 | 0.258 | 0.255 | 0.265 |
| $F_{30\%SPR}$ | 0.118 | 0.111 | 0.129 | 0.046 | 0.043 | 0.053 | 0.000 | 0.000 | 0.028 |
| $F_{40\%SPR}$ | 0.051 | 0.045 | 0.062 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| $F_{MSY}$ | 0.198 | 0.194 | 0.202 | 0.209 | 0.206 | 0.215 | 0.213 | 0.212 | 0.216 |
| $F_{2004}$ | 0.082 | 0.049 | 0.134 | 0.157 | 0.101 | 0.212 | 0.224 | 0.184 | 0.236 |
| MSY | 21,220,550 | 16,766,820 | 28,171,000 | 17,855,400 | 16,292,880 | 21,201,900 | 17,074,550 | 16,169,850 | 17,735,400 |
| Yield$_{'04}$ | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 |
| $SS_{MSY}$ | 42,129,200 | 30,357,300 | 58,577,400 | 23,971,000 | 18,523,840 | 32,244,100 | 14,985,250 | 12,639,800 | 18,352,000 |
| $SS_{2004}$ | 51,968,950 | 27,697,460 | 92,889,200 | 17,891,850 | 10,683,880 | 33,157,500 | 7,605,535 | 6,397,410 | 11,270,000 |
| $tSPR_{2004}$ | 0.330 | 0.268 | 0.388 | 0.149 | 0.122 | 0.194 | 0.069 | 0.067 | 0.076 |
| $F_{1962}/F_{MSY}$ | 2.279 | 1.968 | 2.523 | 2.571 | 2.375 | 2.865 | 3.279 | 2.964 | 3.494 |
| $F_{2004}/F_{MSY}$ | 0.411 | 0.244 | 0.688 | 0.750 | 0.472 | 1.031 | 1.056 | 0.866 | 1.096 |
| $F_{2032}/F_{MSY}$ | 0.157 | 0.112 | 0.221 | 0.174 | 0.135 | 0.216 | 0.170 | 0.147 | 0.204 |
| Yield$_{'62}$/MSY | 0.405 | 0.358 | 0.440 | 0.455 | 0.423 | 0.479 | 0.510 | 0.473 | 0.561 |
| Yield$_{'04}$/MSY | 0.430 | 0.324 | 0.544 | 0.511 | 0.430 | 0.560 | 0.534 | 0.514 | 0.564 |
| Yield$_{'32}$/MSY | 0.303 | 0.233 | 0.385 | 0.334 | 0.277 | 0.392 | 0.349 | 0.304 | 0.412 |
| $SS_{1962}/SS_{MSY}$ | 0.187 | 0.171 | 0.198 | 0.161 | 0.148 | 0.173 | 0.147 | 0.142 | 0.153 |
| $SS_{2004}/SS_{MSY}$ | 1.233 | 0.912 | 1.586 | 0.746 | 0.577 | 1.028 | 0.521 | 0.494 | 0.614 |
| $SS_{2032}/SS_{MSY}$ | 2.092 | 1.833 | 2.300 | 2.064 | 1.930 | 2.242 | 2.230 | 2.194 | 2.255 |
| Objective Fn | 12098 | 11521 | 12669 | 11226 | 10734 | 11753 | 10619 | 10243 | 11063 |

**Table 2**. Benchmark Statistics for 1962-2003 Gulf-wide ASAP bootstraps LINKED CASE.

| **Model Description** | Run A | | | Run B | | | Run C | | |
|---|---|---|---|---|---|---|---|---|---|
| Steepness | 0.81 | | | 0.9 | | | 0.95 | | |
| **Benchmark Statistic** | **Median** | **10% conf** | **90% conf** | **Median** | **10% conf** | **90% conf** | **Median** | **10% conf** | **90% conf** |
| $F_{0.1}$ | 0.272 | 0.239 | 0.353 | 0.216 | 0.190 | 0.291 | 0.176 | 0.160 | 0.211 |
| $F_{MAX}$ | 0.350 | 0.309 | 0.453 | 0.280 | 0.250 | 0.375 | 0.233 | 0.215 | 0.274 |
| $F_{30\%SPR}$ | 0.408 | 0.356 | 0.532 | 0.328 | 0.289 | 0.441 | 0.273 | 0.249 | 0.324 |
| $F_{40\%SPR}$ | 0.310 | 0.270 | 0.405 | 0.248 | 0.218 | 0.335 | 0.205 | 0.186 | 0.245 |
| $F_{MSY}$ | 0.299 | 0.262 | 0.387 | 0.259 | 0.230 | 0.347 | 0.224 | 0.206 | 0.264 |
| $F_{2004}$ | 0.313 | 0.291 | 0.326 | 0.395 | 0.386 | 0.446 | 0.460 | 0.400 | 0.512 |
| MSY | 18,773,350 | 16,739,000 | 21,206,620 | 27,978,250 | 23,613,100 | 30,295,200 | 37,980,700 | 33,759,810 | 39,180,200 |
| $Yield_{'04}$ | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 |
| $SS_{MSY}$ | 96,519,600 | 70,570,950 | 129,045,000 | 75,135,350 | 54,614,200 | 99,657,500 | 60,163,450 | 41,954,600 | 82,668,100 |
| $SS_{2004}$ | 51,968,950 | 27,697,460 | 92,889,200 | 17,891,850 | 10,683,880 | 33,157,500 | 7,605,535 | 6,397,410 | 11,270,000 |
| $tSPR_{2004}$ | 0.330 | 0.268 | 0.388 | 0.149 | 0.122 | 0.194 | 0.069 | 0.067 | 0.076 |
| $F_{1962}/F_{MSY}$ | 3.161 | 2.990 | 3.281 | 3.742 | 3.661 | 3.909 | 4.761 | 4.577 | 4.883 |
| $F_{2004}/F_{MSY}$ | 1.000 | 0.834 | 1.220 | 1.510 | 1.269 | 1.701 | 2.002 | 1.904 | 2.048 |
| $F_{2032}/F_{MSY}$ | 0.214 | 0.212 | 0.218 | 0.149 | 0.146 | 0.162 | 0.105 | 0.101 | 0.122 |
| $Yield_{'62}/MSY$ | 0.141 | 0.123 | 0.167 | 0.145 | 0.123 | 0.171 | 0.140 | 0.116 | 0.178 |
| $Yield_{'04}/MSY$ | 0.486 | 0.430 | 0.545 | 0.326 | 0.301 | 0.386 | 0.240 | 0.233 | 0.270 |
| $Yield_{'32}/MSY$ | 0.355 | 0.336 | 0.378 | 0.255 | 0.249 | 0.282 | 0.196 | 0.186 | 0.235 |
| $SS_{1962}/SS_{MSY}$ | 0.044 | 0.042 | 0.047 | 0.033 | 0.031 | 0.036 | 0.026 | 0.023 | 0.031 |
| $SS_{2004}/SS_{MSY}$ | 0.538 | 0.392 | 0.720 | 0.238 | 0.196 | 0.333 | 0.132 | 0.126 | 0.151 |
| $SS_{2032}/SS_{MSY}$ | 1.654 | 1.569 | 1.723 | 1.733 | 1.724 | 1.745 | 1.885 | 1.853 | 1.906 |
| Objective Fn | 12098 | 11521 | 12669 | 11226 | 10734 | 11753 | 10619 | 10243 | 11063 |

**Table 3**. Benchmark Statistics for 1962-2003 Gulf-wide ASAP bootstraps NO BYCATCH CASE.

| **Model Description** | Run A | | | Run B | | | Run C | | |
|---|---|---|---|---|---|---|---|---|---|
| Steepness | 0.81 | | | 0.9 | | | 0.95 | | |
| **Benchmark Statistic** | **Median** | **10% conf** | **90% conf** | **Median** | **10% conf** | **90% conf** | **Median** | **10% conf** | **90% conf** |
| $F_{0.1}$ | 0.225 | 0.219 | 0.229 | 0.200 | 0.186 | 0.211 | 0.167 | 0.159 | 0.179 |
| $F_{MAX}$ | 0.302 | 0.296 | 0.307 | 0.271 | 0.255 | 0.284 | 0.230 | 0.221 | 0.245 |
| $F_{30\%SPR}$ | 0.280 | 0.276 | 0.282 | 0.258 | 0.245 | 0.268 | 0.225 | 0.216 | 0.238 |
| $F_{40\%SPR}$ | 0.212 | 0.208 | 0.214 | 0.195 | 0.184 | 0.203 | 0.168 | 0.161 | 0.178 |
| $F_{MSY}$ | 0.235 | 0.231 | 0.239 | 0.239 | 0.225 | 0.250 | 0.216 | 0.208 | 0.230 |
| $F_{2004}$ | 0.081 | 0.049 | 0.133 | 0.156 | 0.101 | 0.211 | 0.222 | 0.183 | 0.234 |
| MSY | 50,323,550 | 40,471,490 | 63,173,100 | 53,650,000 | 44,070,050 | 63,624,600 | 56,997,050 | 42,537,180 | 70,682,700 |
| Yield'$_{04}$ | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 | 9,120,000 |
| $SS_{MSY}$ | 82,306,850 | 61,060,510 | 109,070,000 | 63,176,700 | 46,751,450 | 82,581,700 | 50,619,600 | 35,815,550 | 68,628,000 |
| $SS_{2004}$ | 51,968,950 | 27,697,460 | 92,889,200 | 17,891,850 | 10,683,880 | 33,157,500 | 7,605,535 | 6,397,410 | 11,270,000 |
| $tSPR_{2004}$ | 0.330 | 0.268 | 0.388 | 0.149 | 0.122 | 0.194 | 0.069 | 0.067 | 0.076 |
| $F_{1962}/F_{MSY}$ | 2.279 | 1.968 | 2.523 | 2.571 | 2.375 | 2.865 | 3.279 | 2.964 | 3.494 |
| $F_{2004}/F_{MSY}$ | 0.345 | 0.207 | 0.577 | 0.654 | 0.406 | 0.938 | 1.030 | 0.797 | 1.116 |
| $F_{2032}/F_{MSY}$ | 0.086 | 0.065 | 0.113 | 0.078 | 0.063 | 0.099 | 0.070 | 0.055 | 0.097 |
| Yield'$_{62}$/MSY | 0.405 | 0.358 | 0.440 | 0.455 | 0.423 | 0.479 | 0.510 | 0.473 | 0.561 |
| Yield'$_{04}$/MSY | 0.181 | 0.144 | 0.225 | 0.170 | 0.143 | 0.207 | 0.160 | 0.129 | 0.214 |
| Yield'$_{32}$/MSY | 0.181 | 0.144 | 0.225 | 0.170 | 0.143 | 0.207 | 0.160 | 0.129 | 0.214 |
| $SS_{1962}/SS_{MSY}$ | 0.187 | 0.171 | 0.198 | 0.161 | 0.148 | 0.173 | 0.147 | 0.142 | 0.153 |
| $SS_{2004}/SS_{MSY}$ | 0.631 | 0.454 | 0.852 | 0.283 | 0.229 | 0.402 | 0.158 | 0.150 | 0.177 |
| $SS_{2032}/SS_{MSY}$ | 2.336 | 2.146 | 2.482 | 2.402 | 2.256 | 2.539 | 2.475 | 2.380 | 2.561 |
| Objective Fn | 12098 | 11521 | 12669 | 11226 | 10734 | 11753 | 10619 | 10243 | 11063 |

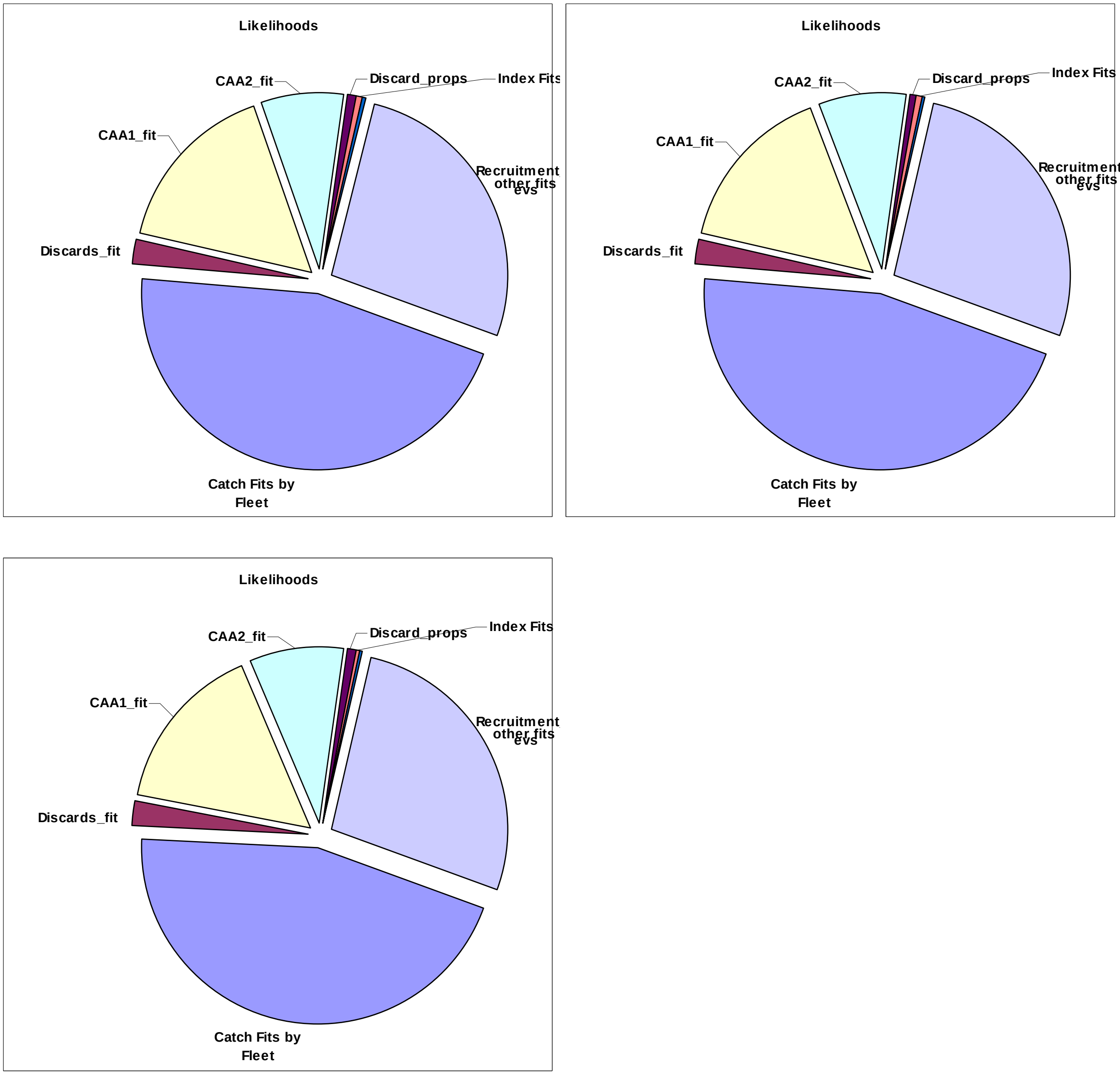



**Figure 1**. Mean fits to various model components for steepness values of (A) 0.81, (B) 0.9, and (C) 0.95. Overall model fits presented in Table 1. UNLINKED CASE BUT CONSISTENT FOR ALL.

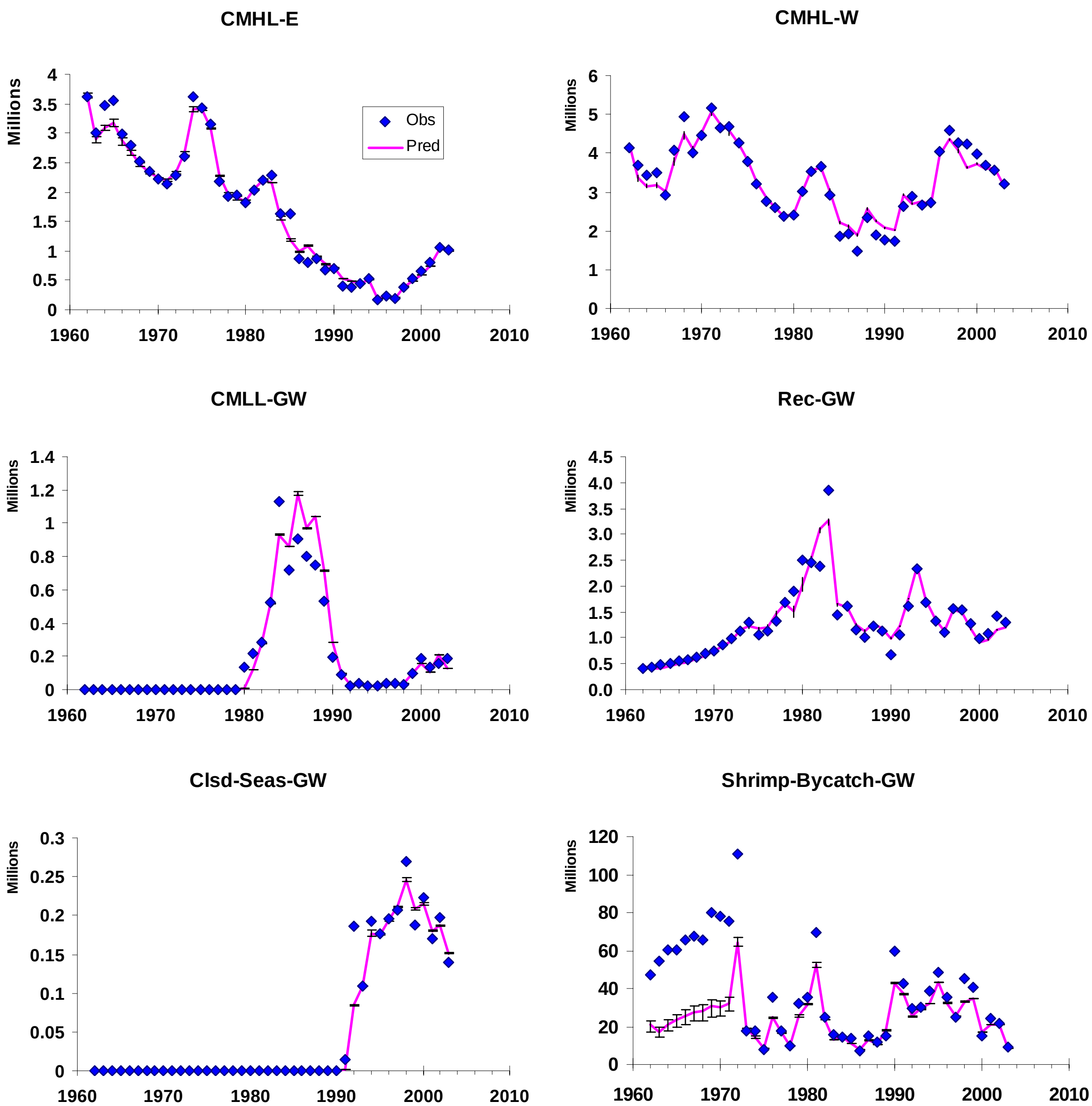



**Figure 2**. Mean observed and predicted catch values for the model with a steepness of 0.81. (A) Commercial handline E (B) Commercial handline W, (C) Commercial longline Gulf-wide, (D) Recreational handline, (E) Closed season discards, and (F) shrimp fleet bycatch. UNLINKED CASE BUT CONSISTENT FOR ALL.

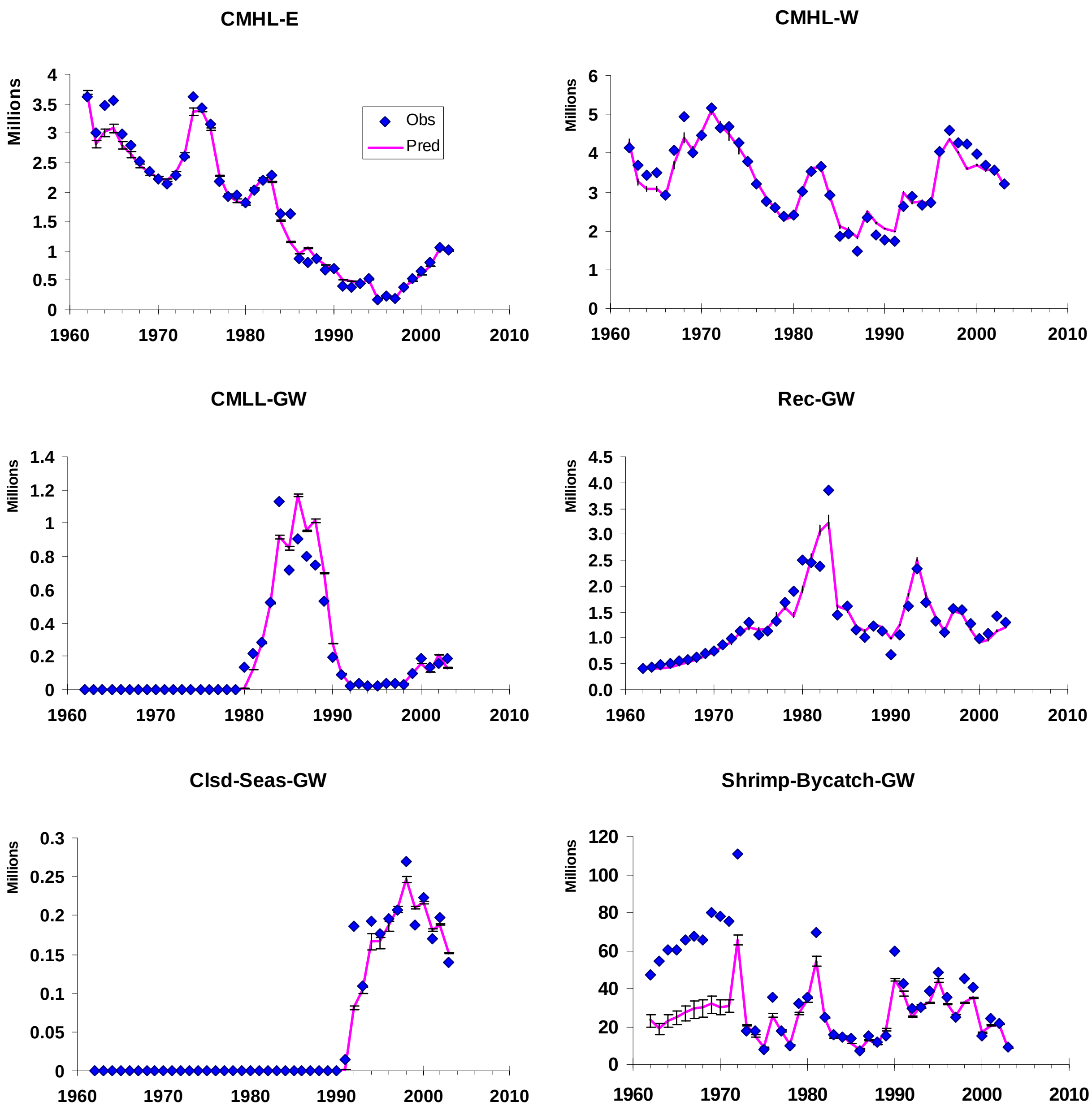



**Figure 3**. Mean observed and predicted catch values for the model with a steepness of 0.9. (A) Commercial handline E (B) Commercial handline W, (C) Commercial longline Gulf-wide, (D) Recreational handline, (E) Closed season discards, and (F) shrimp fleet bycatch. UNLINKED CASE BUT CONSISTENT FOR ALL.

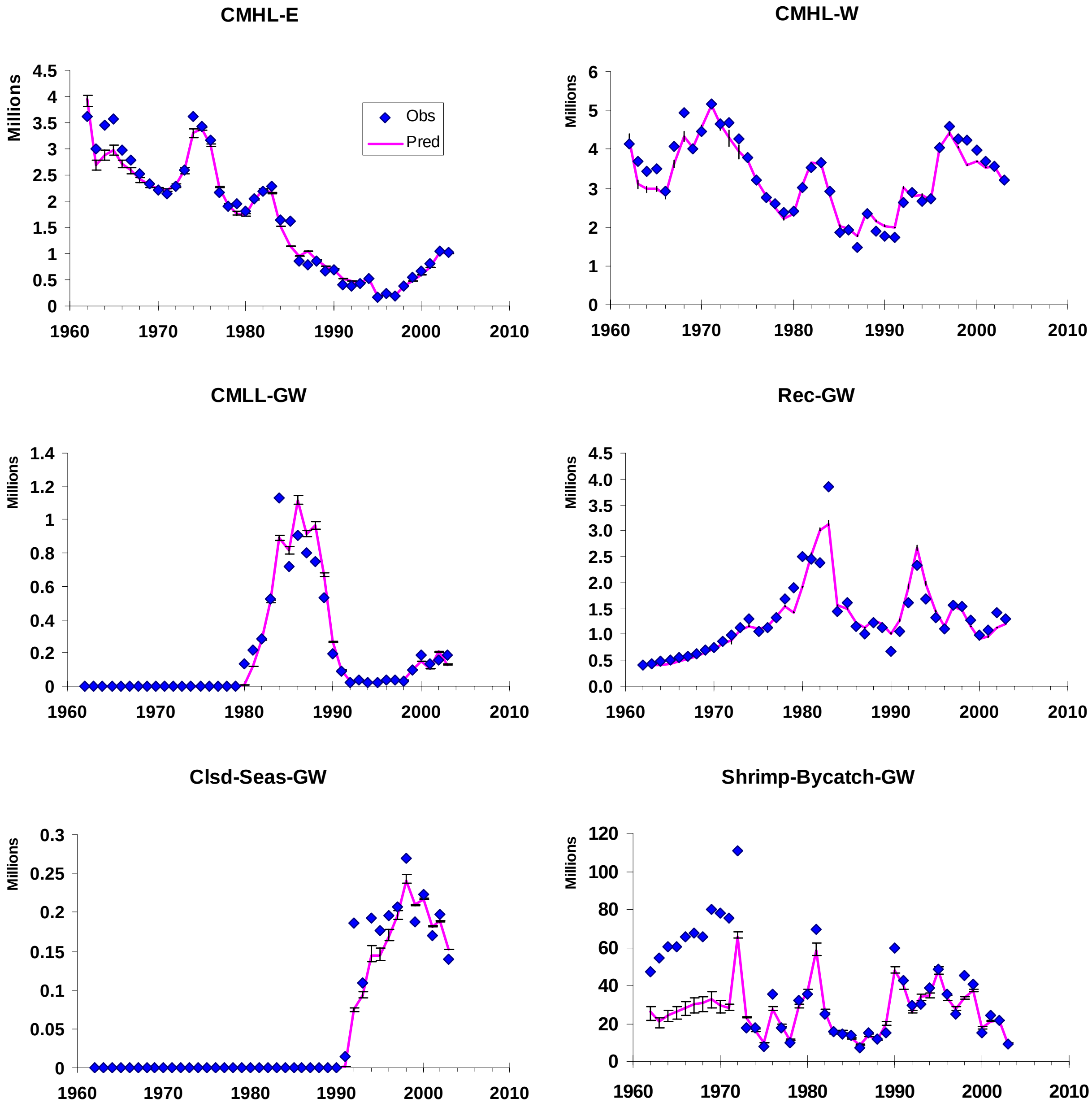



**Figure 4**. Mean observed and predicted catch values for the model with a steepness of 0.95. (A) Commercial handline E (B) Commercial handline W, (C) Commercial longline Gulf-wide, (D) Recreational handline, (E) Closed season discards, and (F) shrimp fleet bycatch. UNLINKED CASE BUT CONSISTENT FOR ALL.

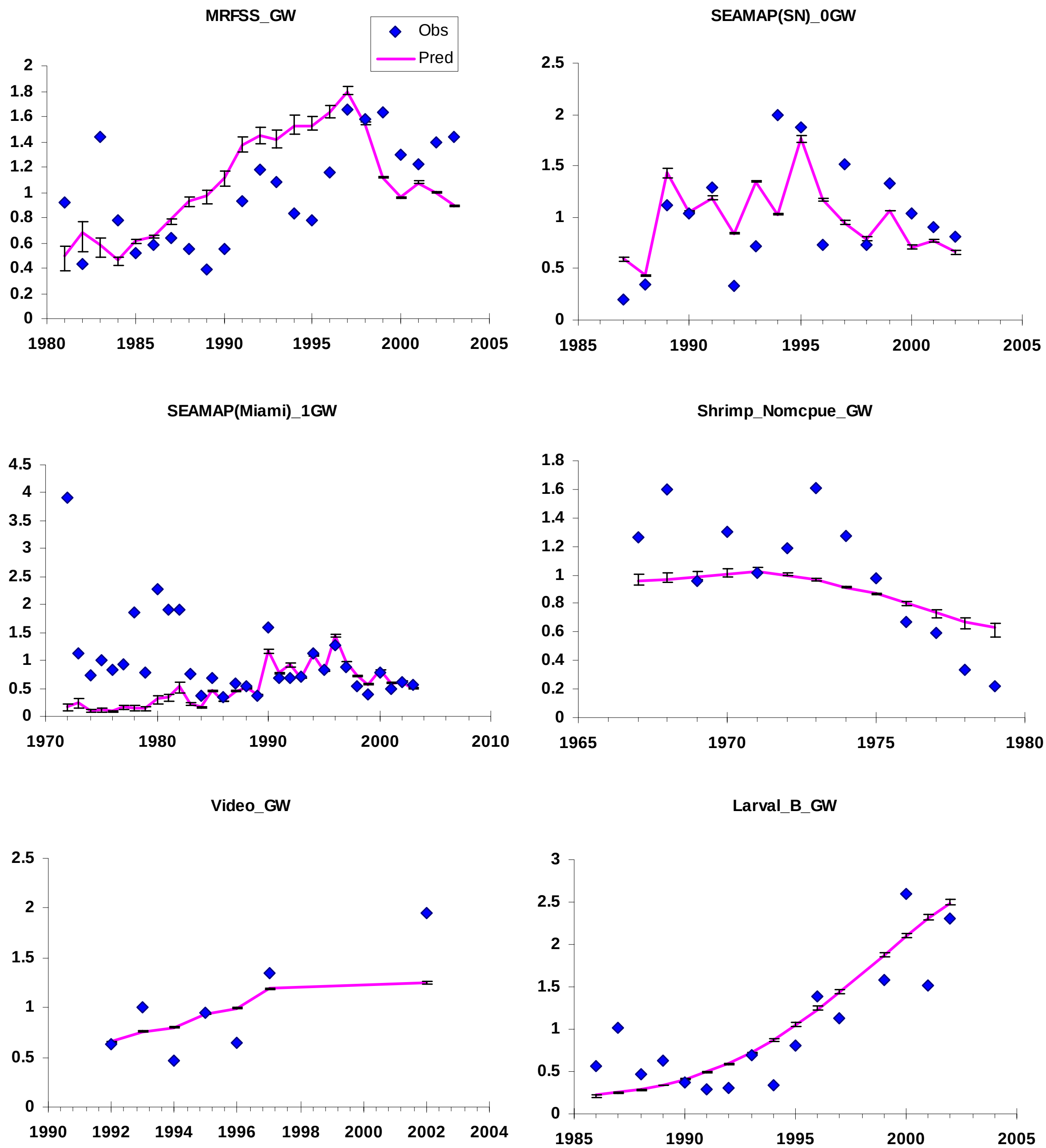



**Figure 5**. Mean observed and predicted Gulf-wide index values for the model with a steepness of 0.81. (A) Marine Recreational Fishery Statistical Survey,(B) nominal CPUE for adult fish from shrimp vessels, (C) SEAMAP fishery-independent survey 0 year olds compiled by Scott Nichols (REF), (D) SEAMAP 1 year olds compiled by SEFSC Miami, (E) video survey, and (F) larval bongo tow survey. UNLINKED CASE BUT CONSISTENT FOR ALL.

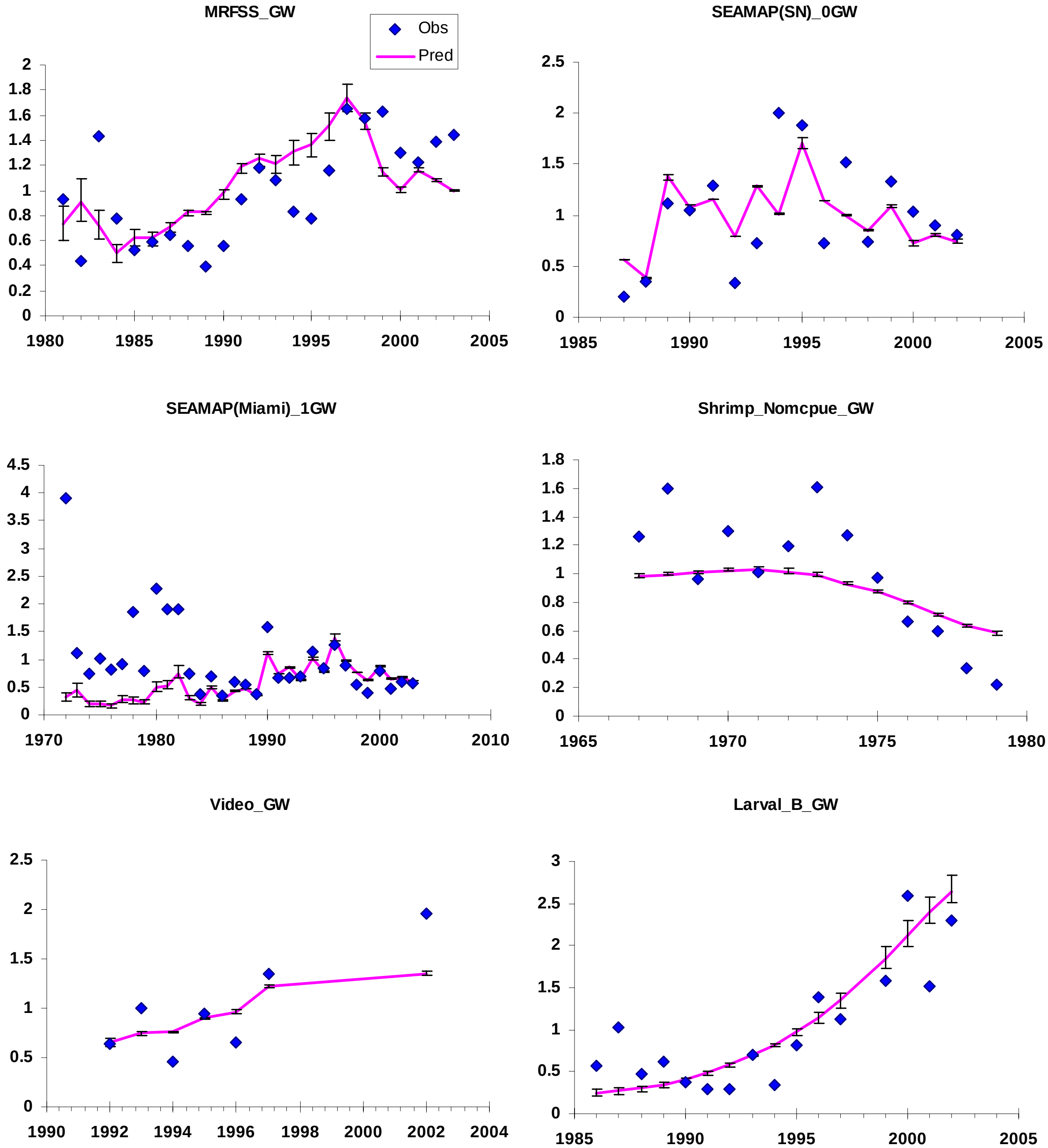



**Figure 6**. Mean observed and predicted Gulf-wide index values for the model with a steepness of 0.9. (A) Marine Recreational Fishery Statistical Survey,(B) nominal CPUE for adult fish from shrimp vessels, (C) SEAMAP fishery-independent survey 0 year olds compiled by Scott Nichols (REF), (D) SEAMAP 1 year olds compiled by SEFSC Miami, (E) video survey, and (F) larval bongo tow survey. UNLINKED CASE BUT CONSISTENT FOR ALL.

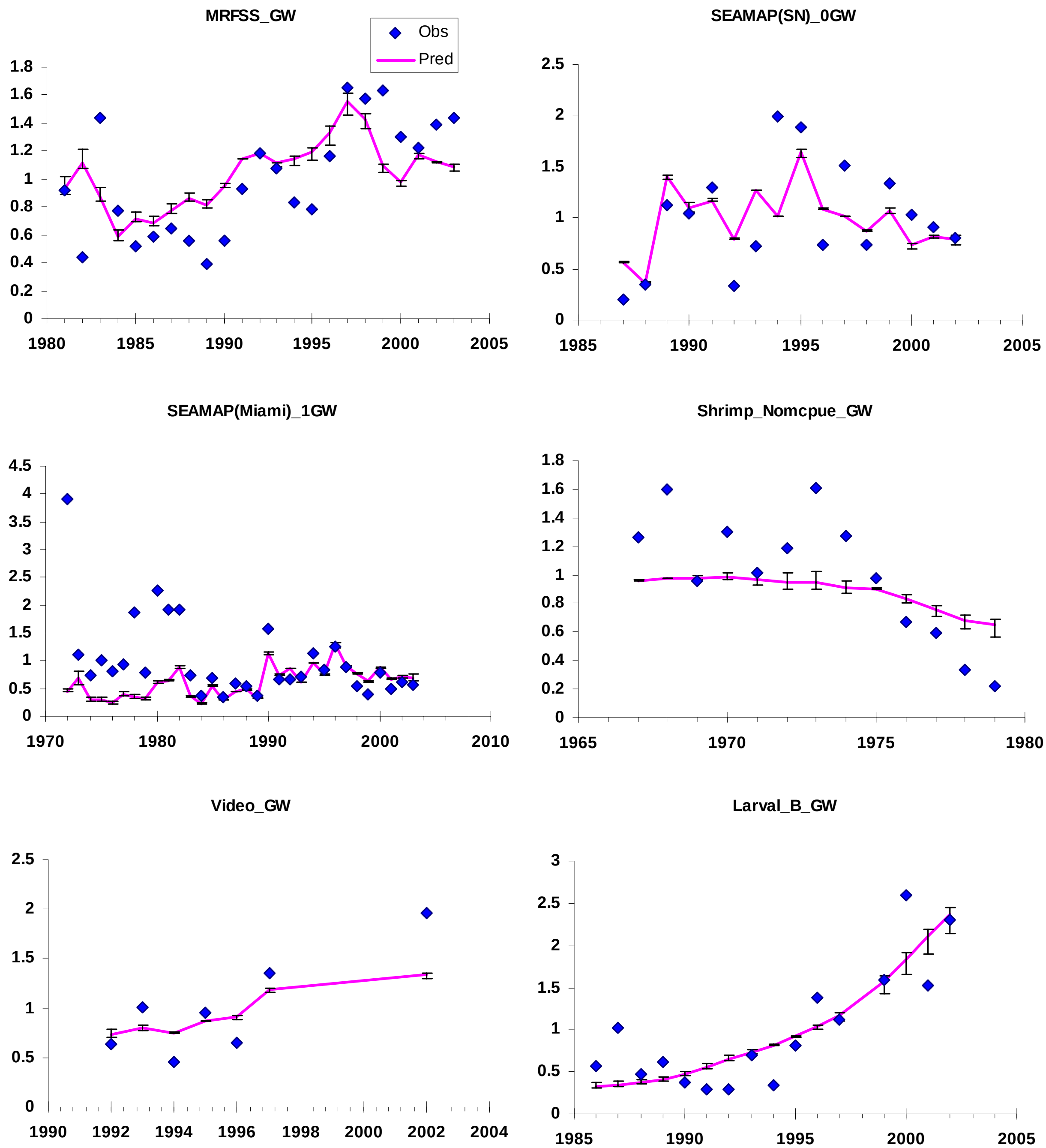
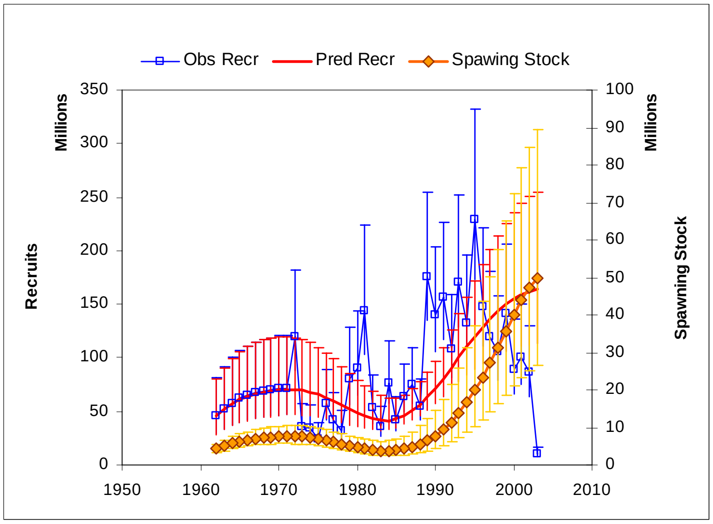
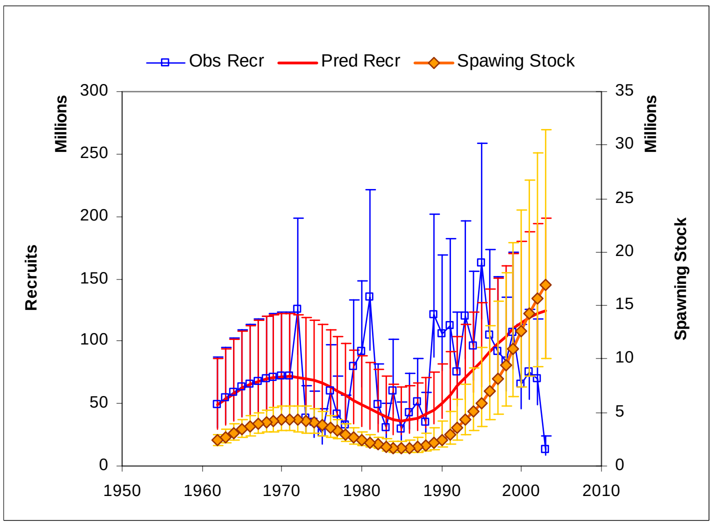



**Figure 7**. Mean observed and predicted Gulf-wide index values for the model with a steepness of 0.95. (A) Marine Recreational Fishery Statistical Survey,(B) nominal CPUE for adult fish from shrimp vessels, (C) SEAMAP fishery-independent survey 0 year olds compiled by Scott Nichols (REF), (D) SEAMAP 1 year olds compiled by SEFSC Miami, (E) video survey, and (F) larval bongo tow survey. UNLINKED CASE BUT CONSISTENT FOR ALL.



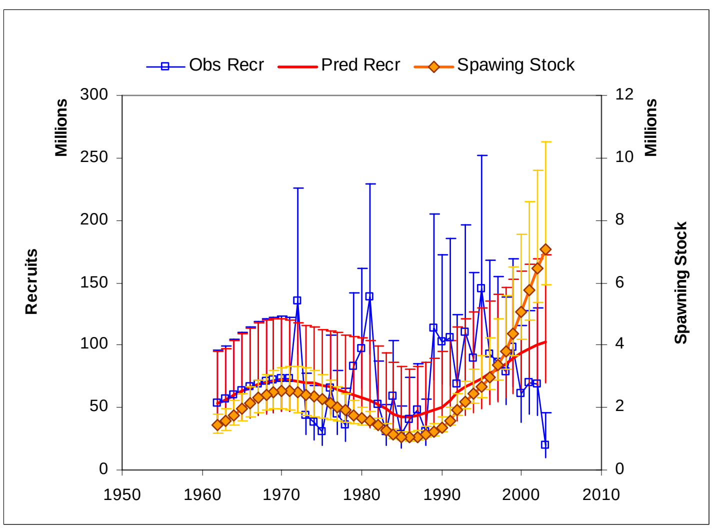




**Figure 8**. Spawning stock and observed (estimated) and predicted recruitment over time at steepness of (A) 0.81, (B) 0.9, and (C) 0.95. UNLINKED CASE BUT CONSISTENT FOR ALL.

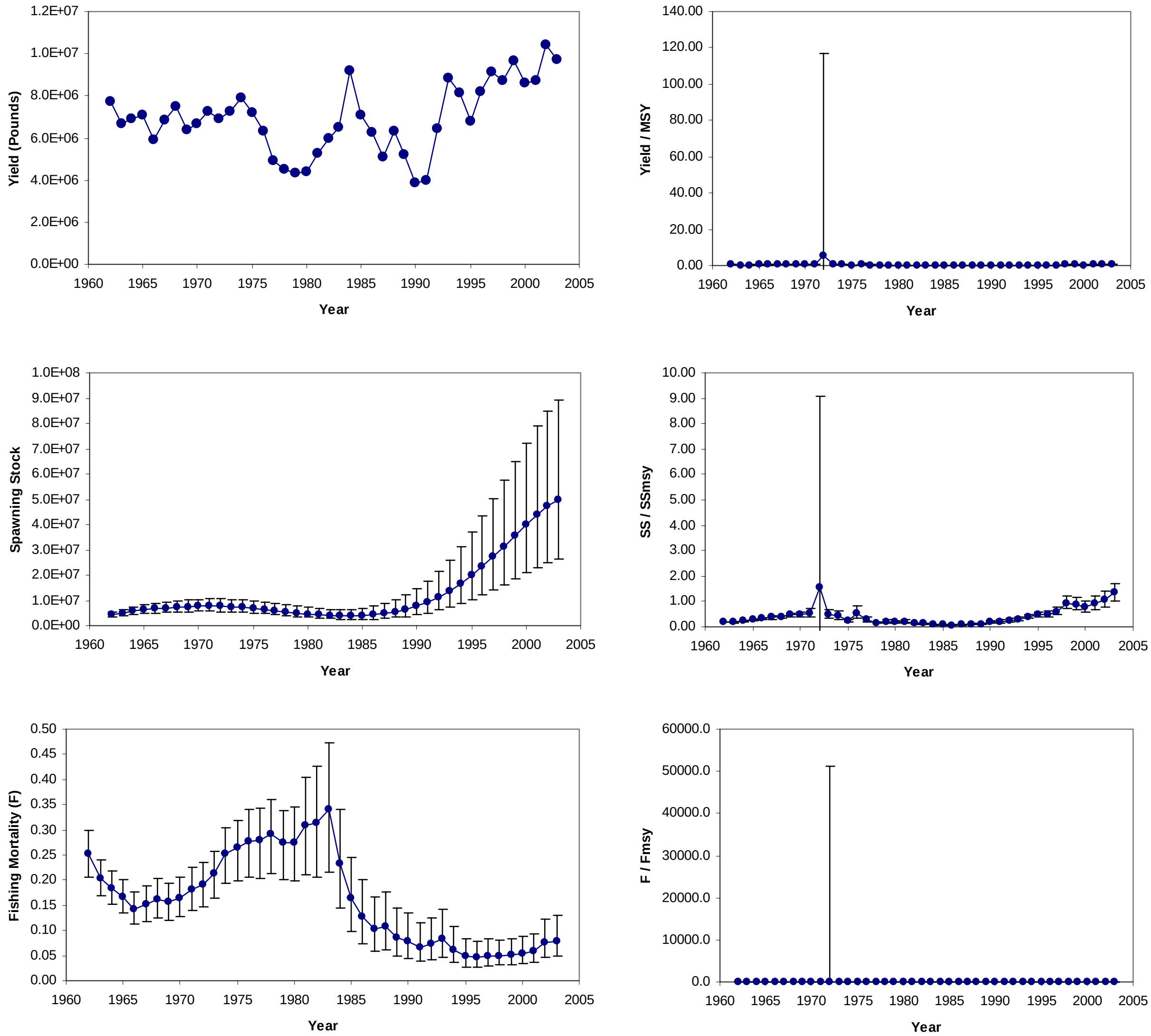



**Figure 9**. Trajectories for steepness 0.81. (A) yield, (B) ratio of yield to MSY, (C) spawning stock biomass, (D) ratio of SS to $SS_{MSY}$, (E) fishing mortality, (F) ratio of F to $F_{MSY}$. UNLINKED CASE BUT CONSISTENT FOR NO BYCATCH CASE.

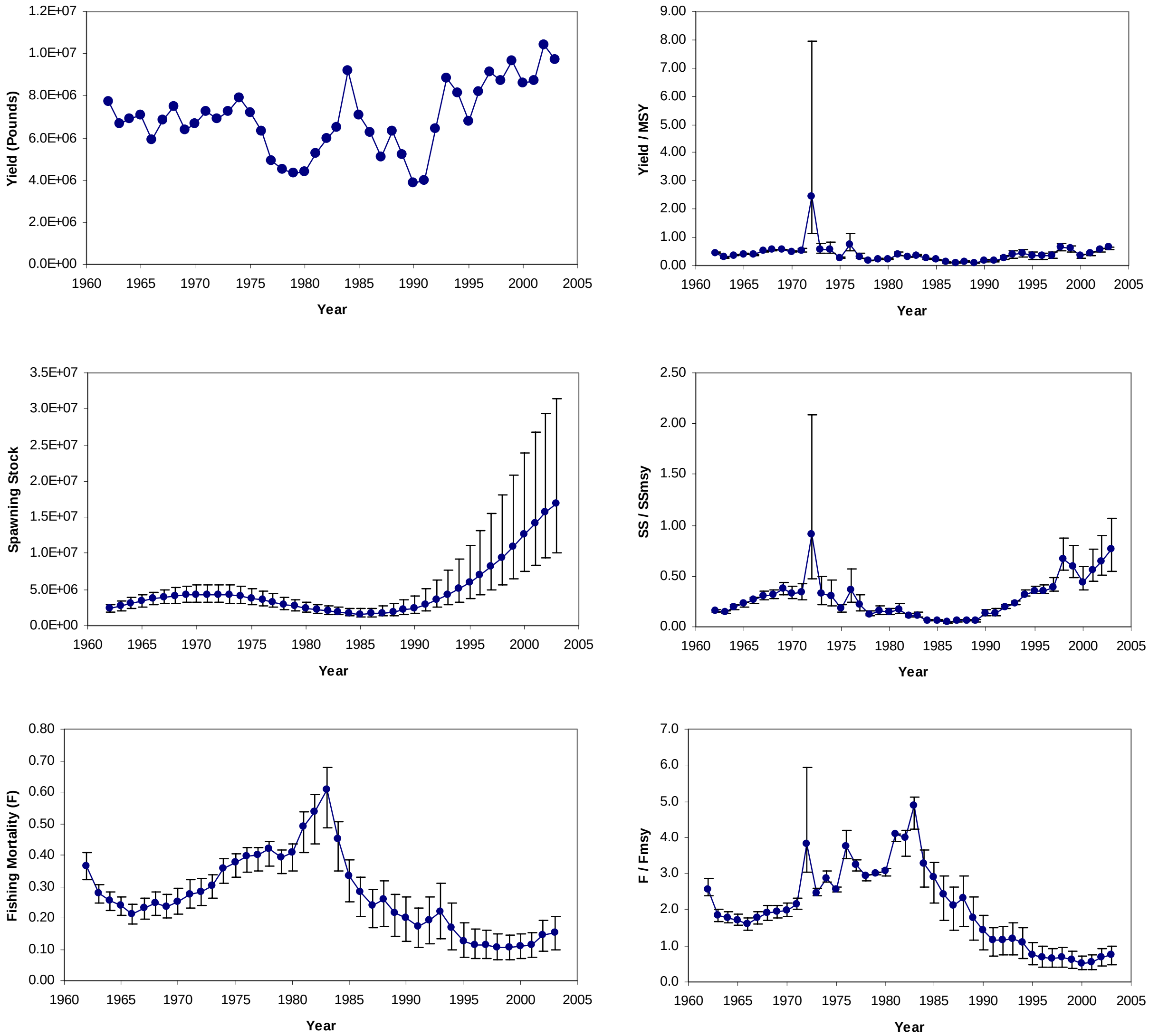



**Figure 10**. Trajectories for steepness 0.9. (A) yield, (B) ratio of yield to MSY, (C) spawning stock biomass, (D) ratio of SS to $SS_{MSY}$, (E) fishing mortality, (F) ratio of F to $F_{MSY}$. UNLINKED CASE BUT CONSISTENT FOR NO BYCATCH CASE.

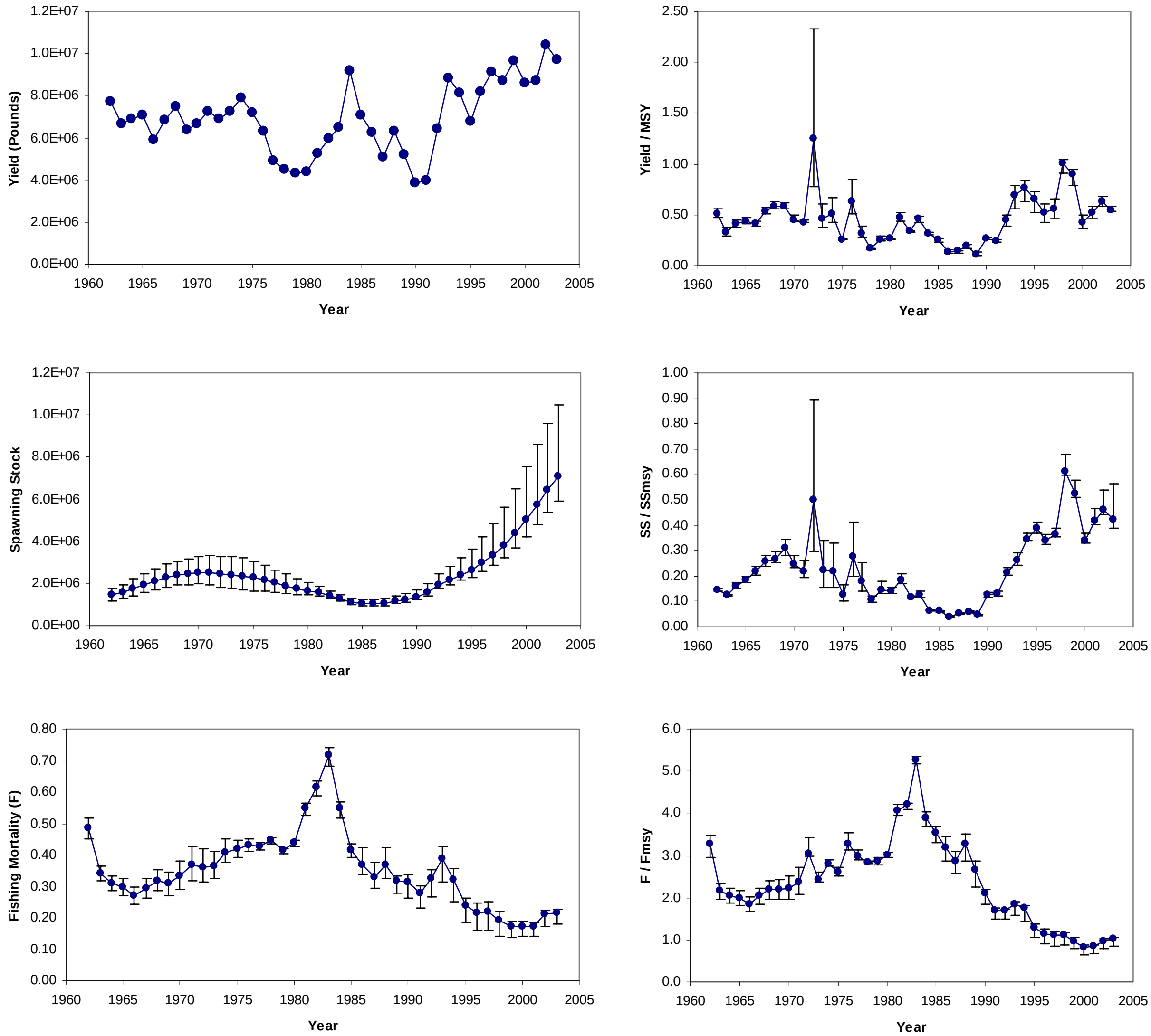



**Figure 11**. Trajectories for steepness 0.95. (A) yield, (B) ratio of yield to MSY, (C) spawning stock biomass, (D) ratio of SS to $SS_{MSY}$, (E) fishing mortality, (F) ratio of F to $F_{MSY}$. UNLINKED CASE BUT CONSISTENT FOR NO BYCATCH CASE.

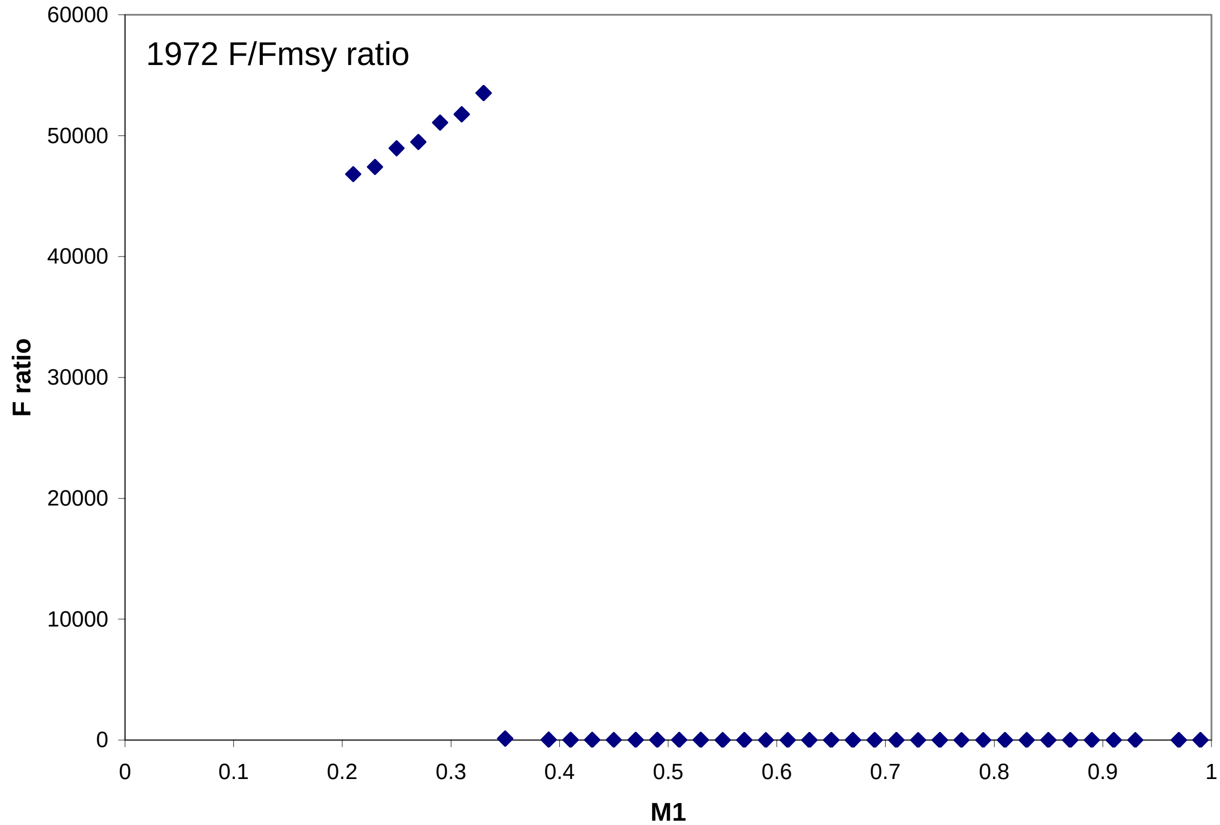



**Figure 12**. Sensitivity of the MSY parameters in 1972 when natural mortality rates for 0- and 1-year olds are relatively low ($M_1 < 0.35$, $M_0 < 0.5833$) shown here for steepness of 0.81 (other steepnesses showed similar but not quite so extreme behavior). Similar spikes were noted in $SS_{MSY}$ and $F_{MSY}$ values, as evidenced in Figs. 9-11. UNLINKED CASE BUT CONSISTENT FOR NO BYCATCH CASE.

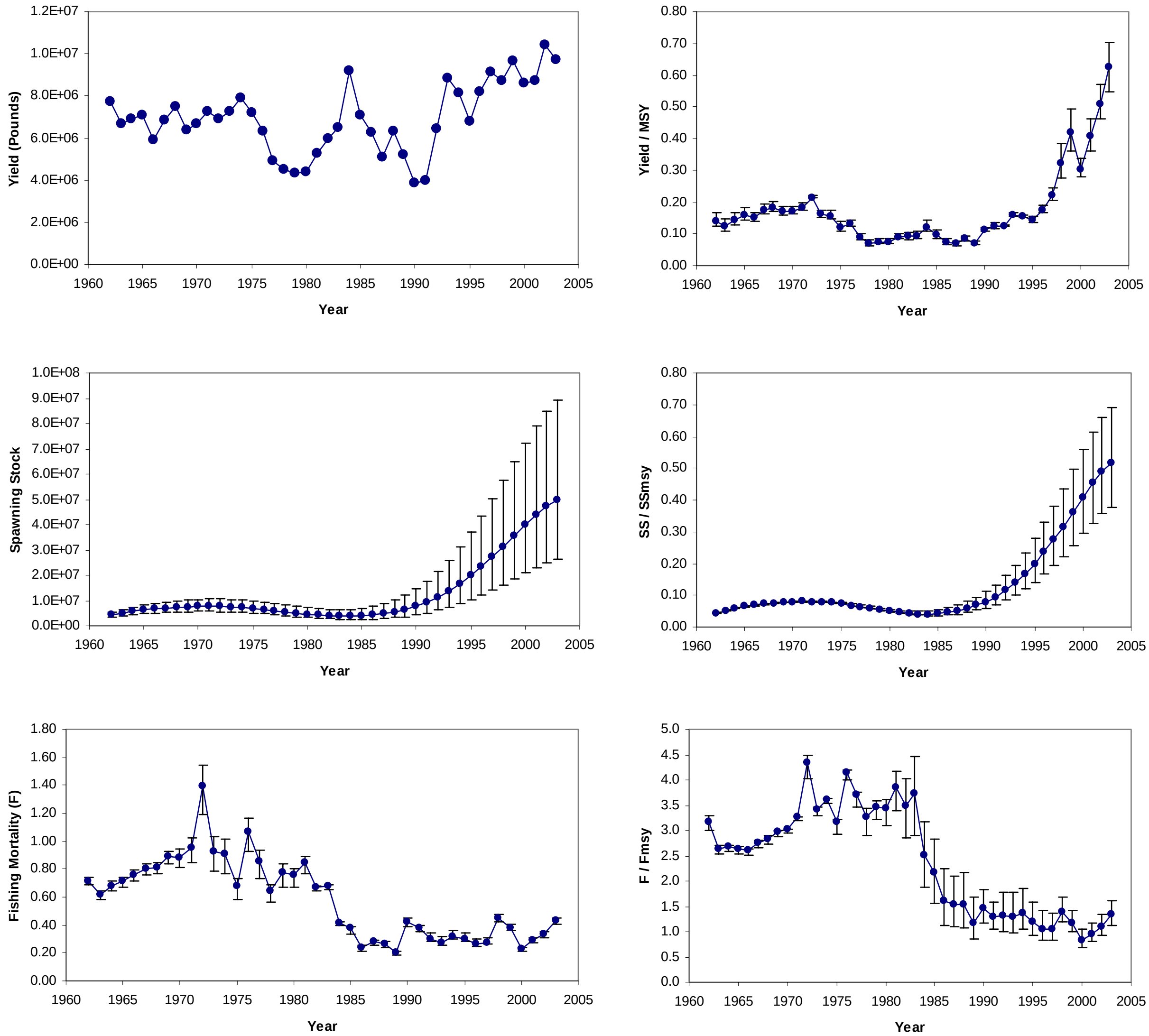



**Figure 13**. Trajectories for steepness 0.81. (A) yield, (B) ratio of yield to MSY, (C) spawning stock biomass, (D) ratio of SS to $SS_{MSY}$, (E) fishing mortality, (F) ratio of F to $F_{MSY}$. LINKED CASE.

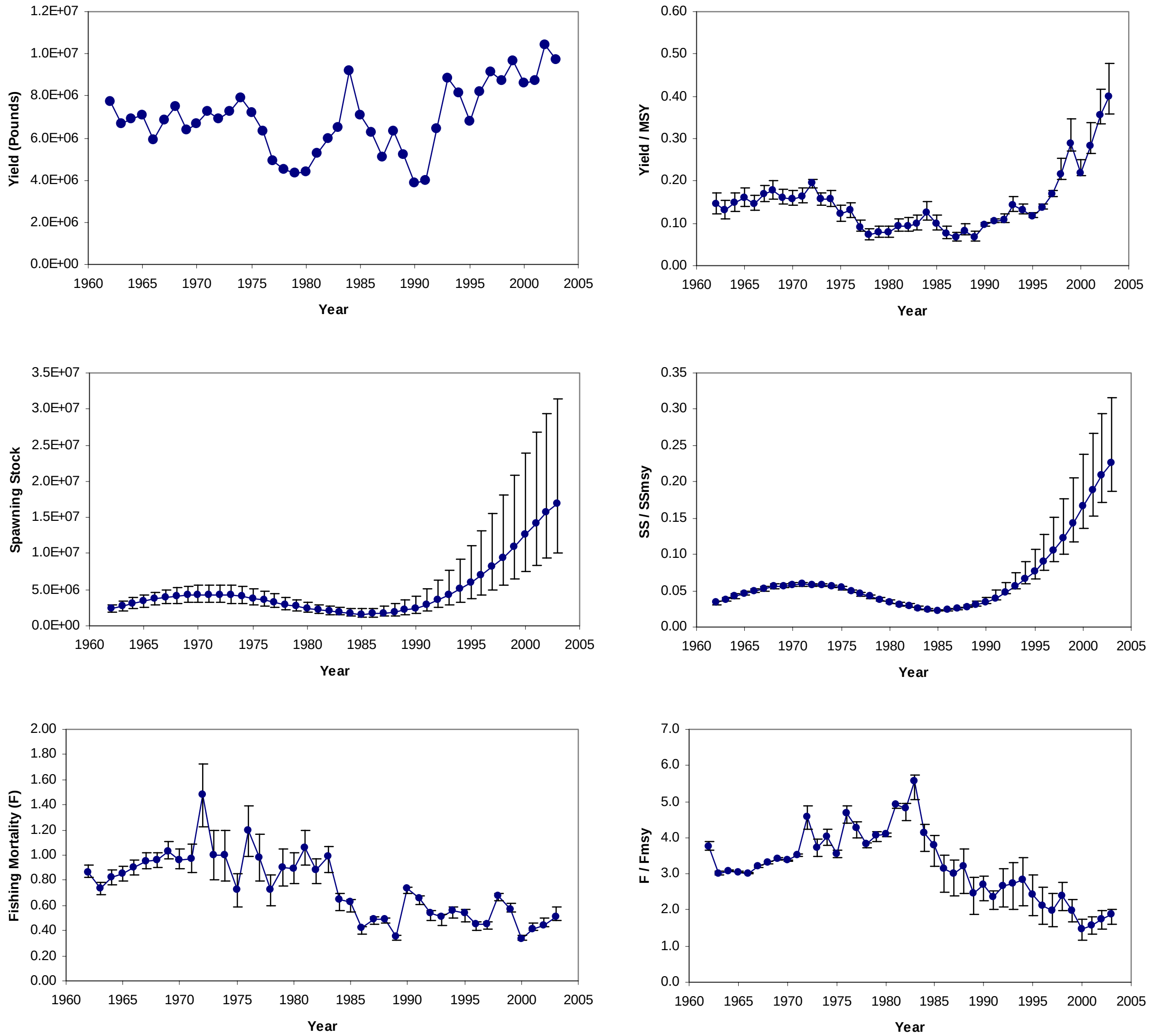



**Figure 14**. Trajectories for steepness 0.9. (A) yield, (B) ratio of yield to MSY, (C) spawning stock biomass, (D) ratio of SS to $SS_{MSY}$, (E) fishing mortality, (F) ratio of F to $F_{MSY}$. LINKED CASE.

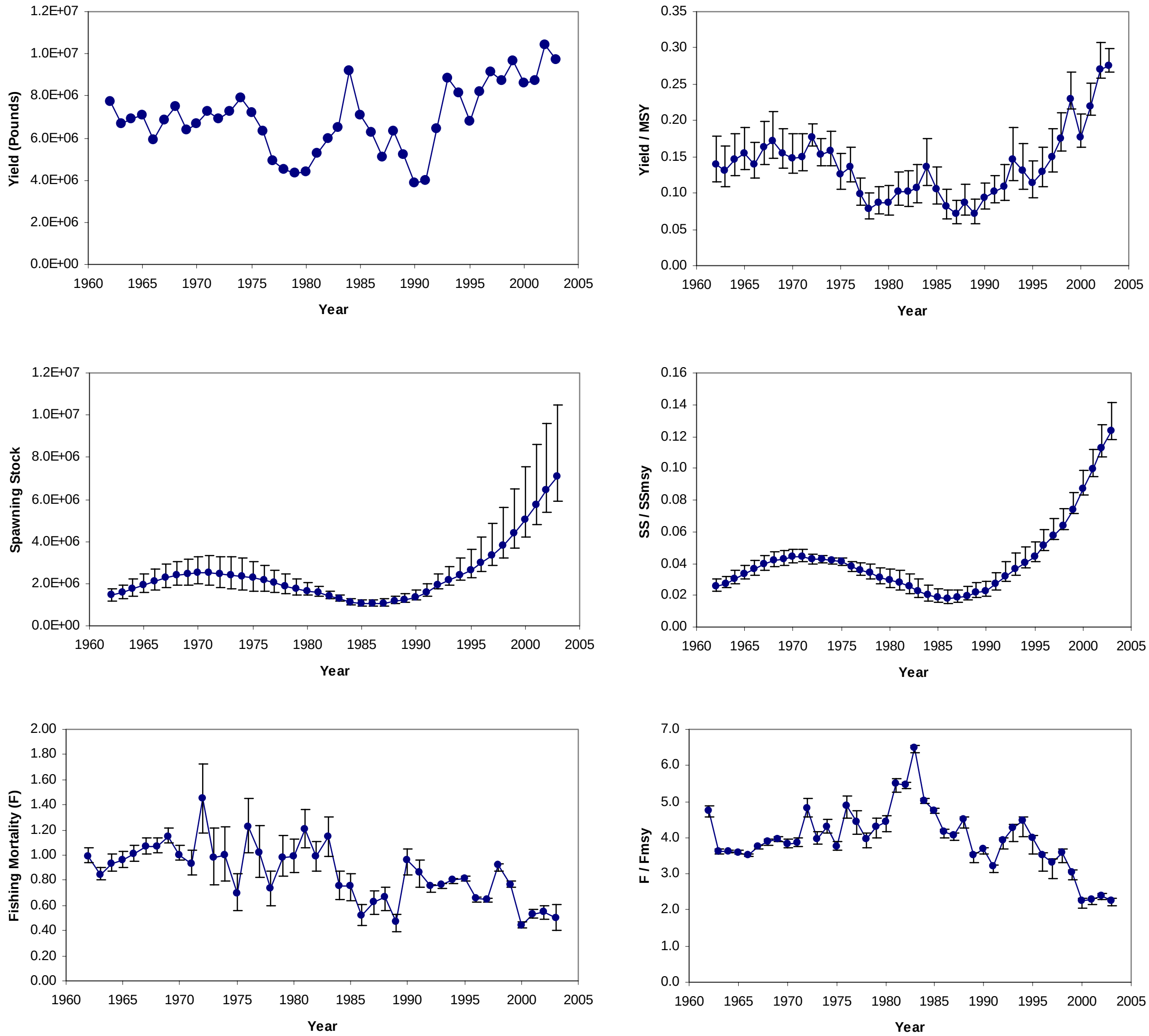



**Figure 15**. Trajectories for steepness 0.95. (A) yield, (B) ratio of yield to MSY, (C) spawning stock biomass, (D) ratio of SS to $SS_{MSY}$, (E) fishing mortality, (F) ratio of F to $F_{MSY}$. LINKED CASE.

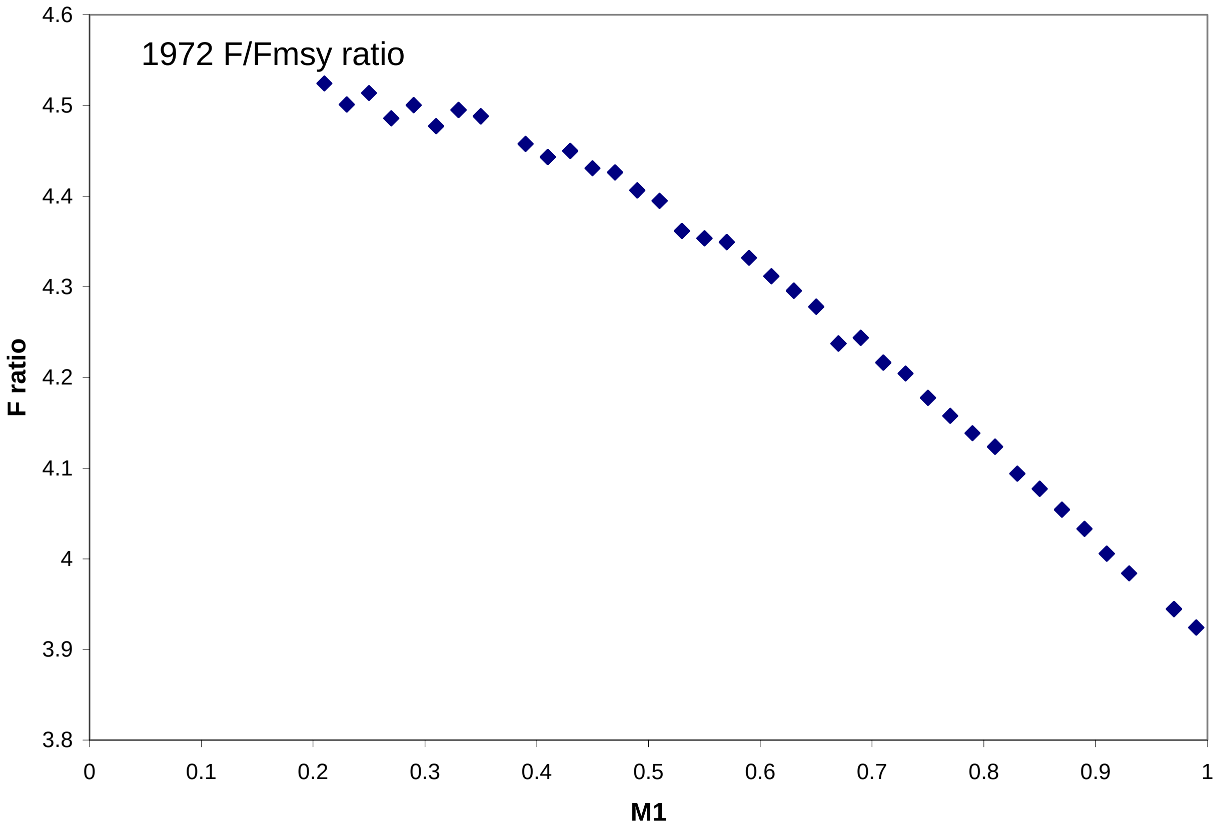



**Figure 16**. Sensitivity of the MSY parameters in 1972 when natural mortality rates for 0- and 1-year olds are relatively low ($M_1 < 0.35$, $M_0 < 0.5833$) shown here for steepness of 0.81 (other steepnesses showed similar but not quite so extreme behavior). Similar spikes were noted in $SS_{MSY}$ and $F_{MSY}$ values, as evidenced in Figs. 9-11. LINKED CASE.

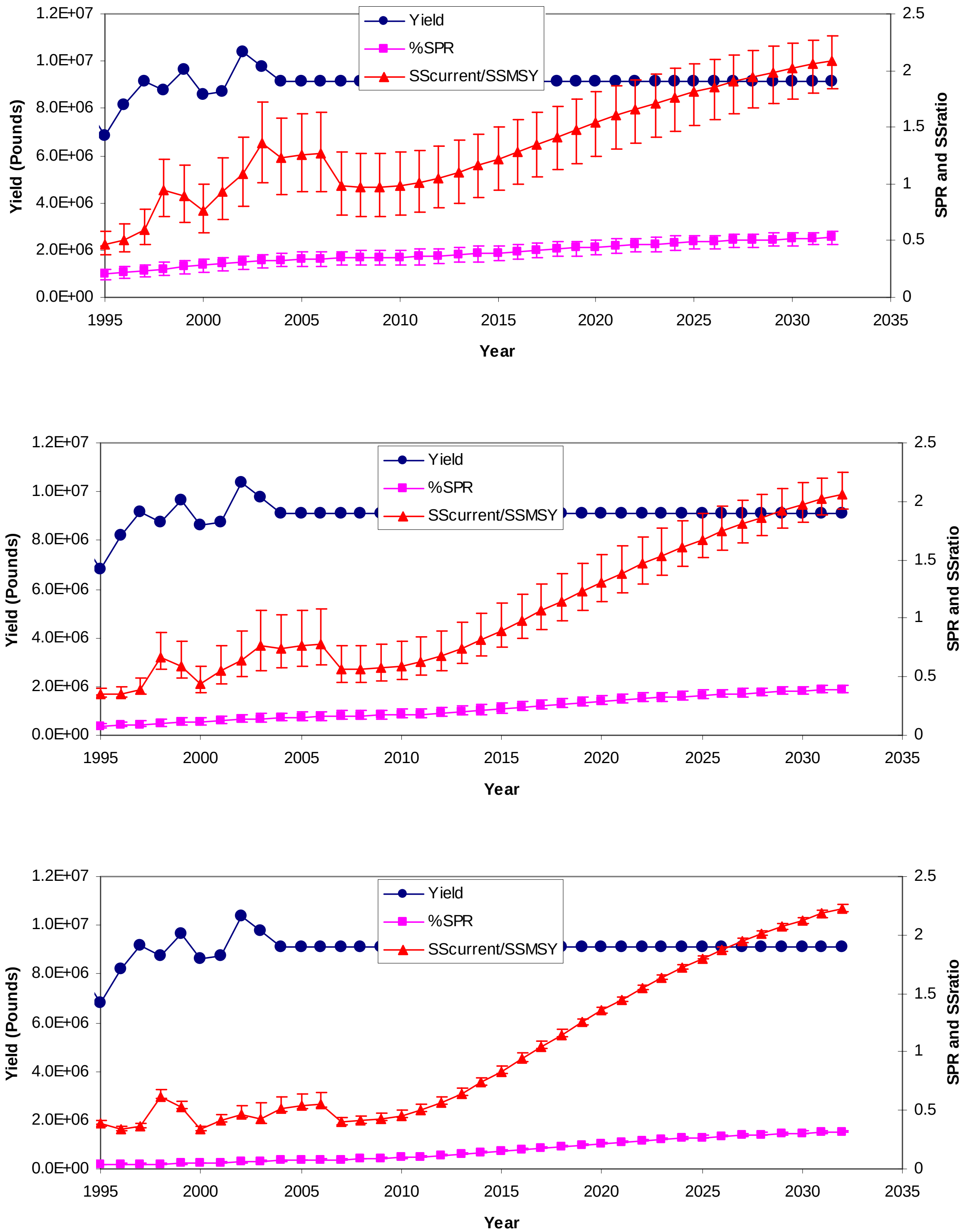
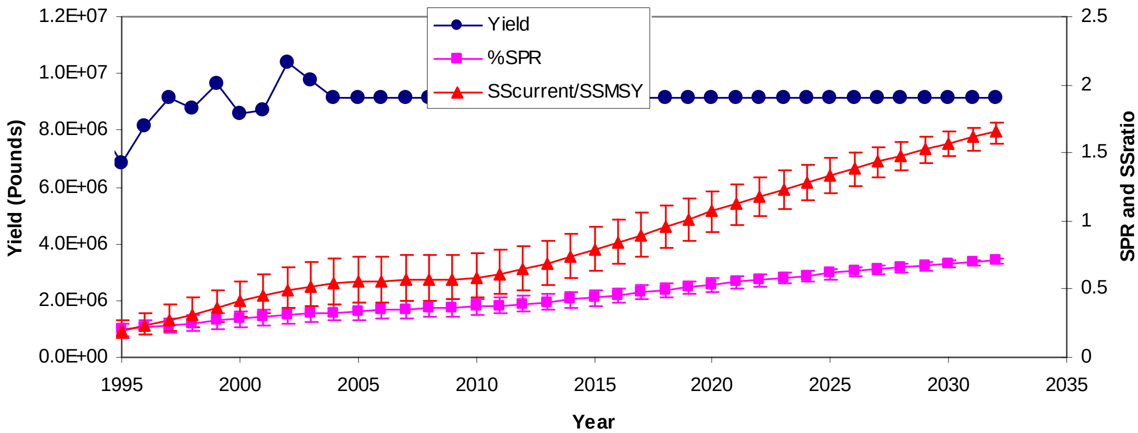
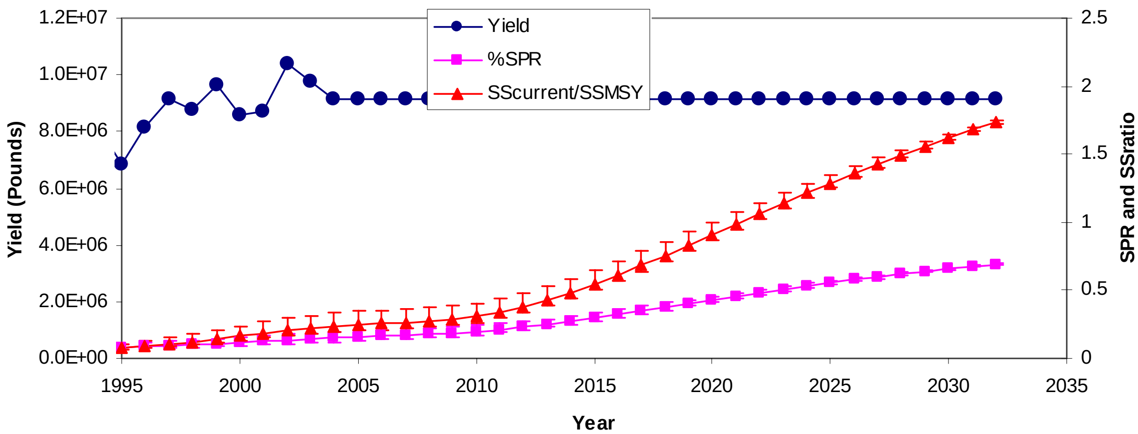



**Figure 17**. Projection of yield, %SPR, and spawning stock ratio (relative to $SS_{MSY}$) for steepness (A) 0.81, (B) 0.9, and (C) 0.95. UNLINKED CASE.



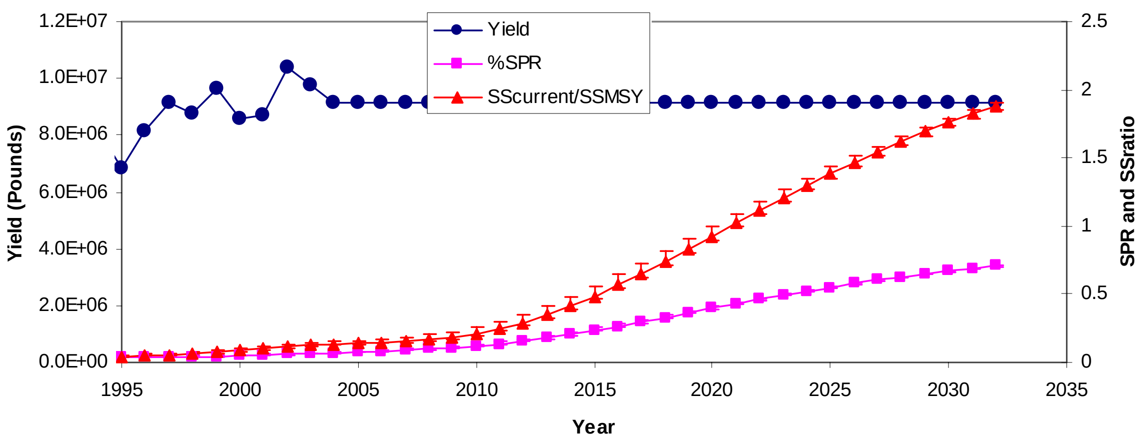




**Figure 18**. Projection of yield, %SPR, and spawning stock ratio (relative to $SS_{MSY}$) for steepness (A) 0.81, (B) 0.9, and (C) 0.95. LINKED CASE.

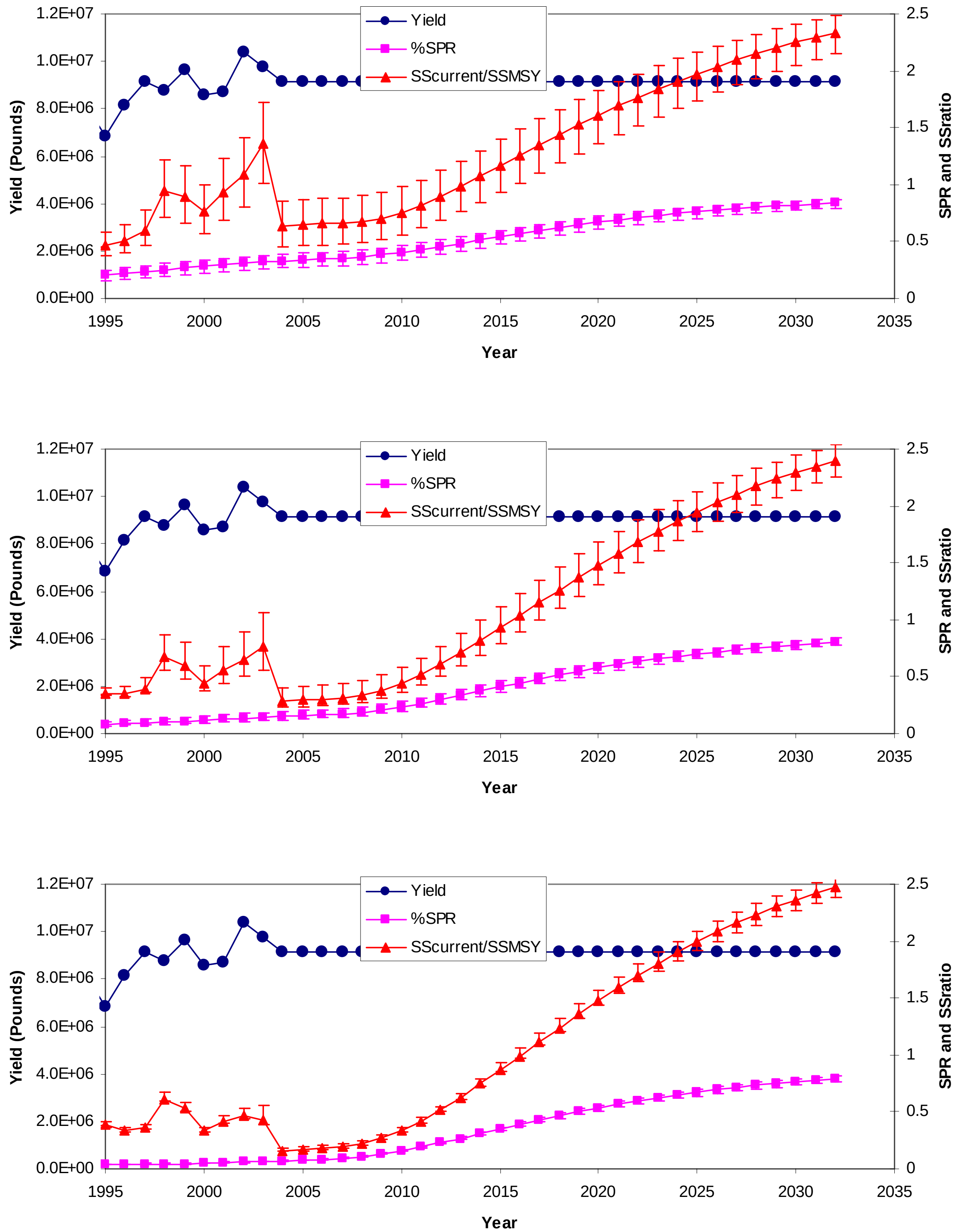



**Figure 19**. Projection of yield, %SPR, and spawning stock ratio (relative to $SS_{MSY}$) for steepness (A) 0.81, (B) 0.9, and (C) 0.95. NO BYCATCH CASE.

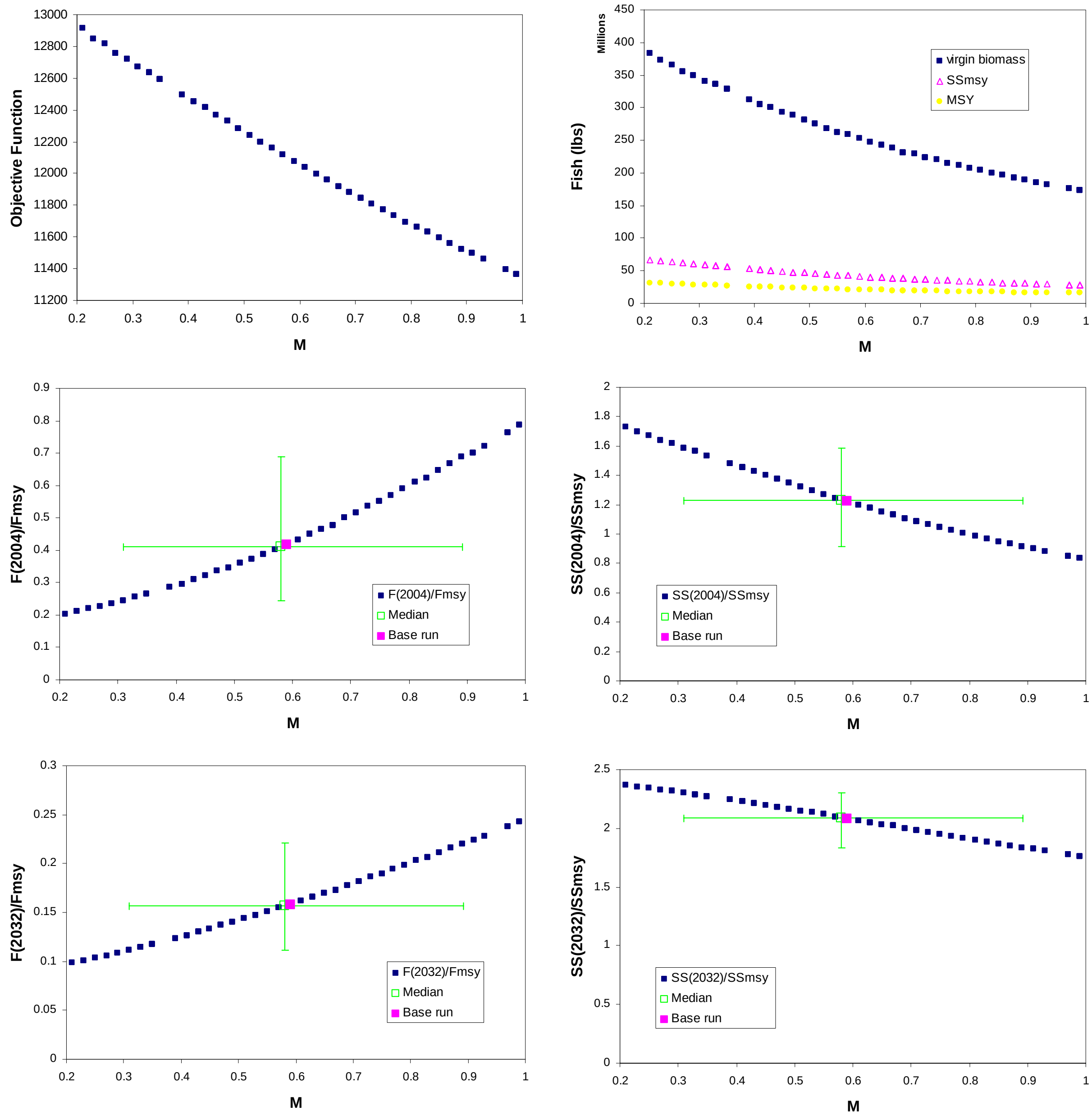



**Figure 20**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.81. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. UNLINKED CASE.

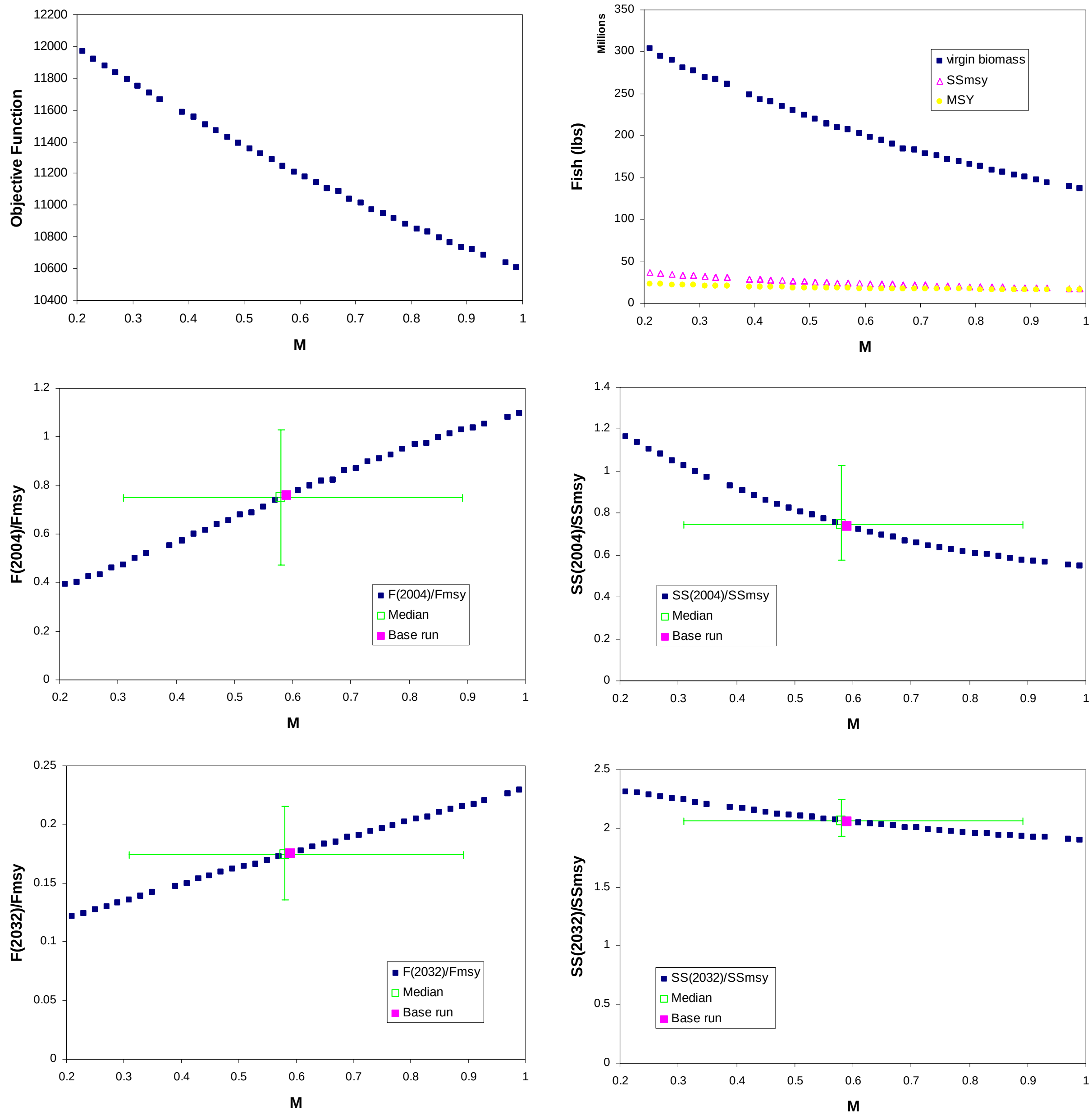



**Figure 21**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.9. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. UNLINKED CASE.

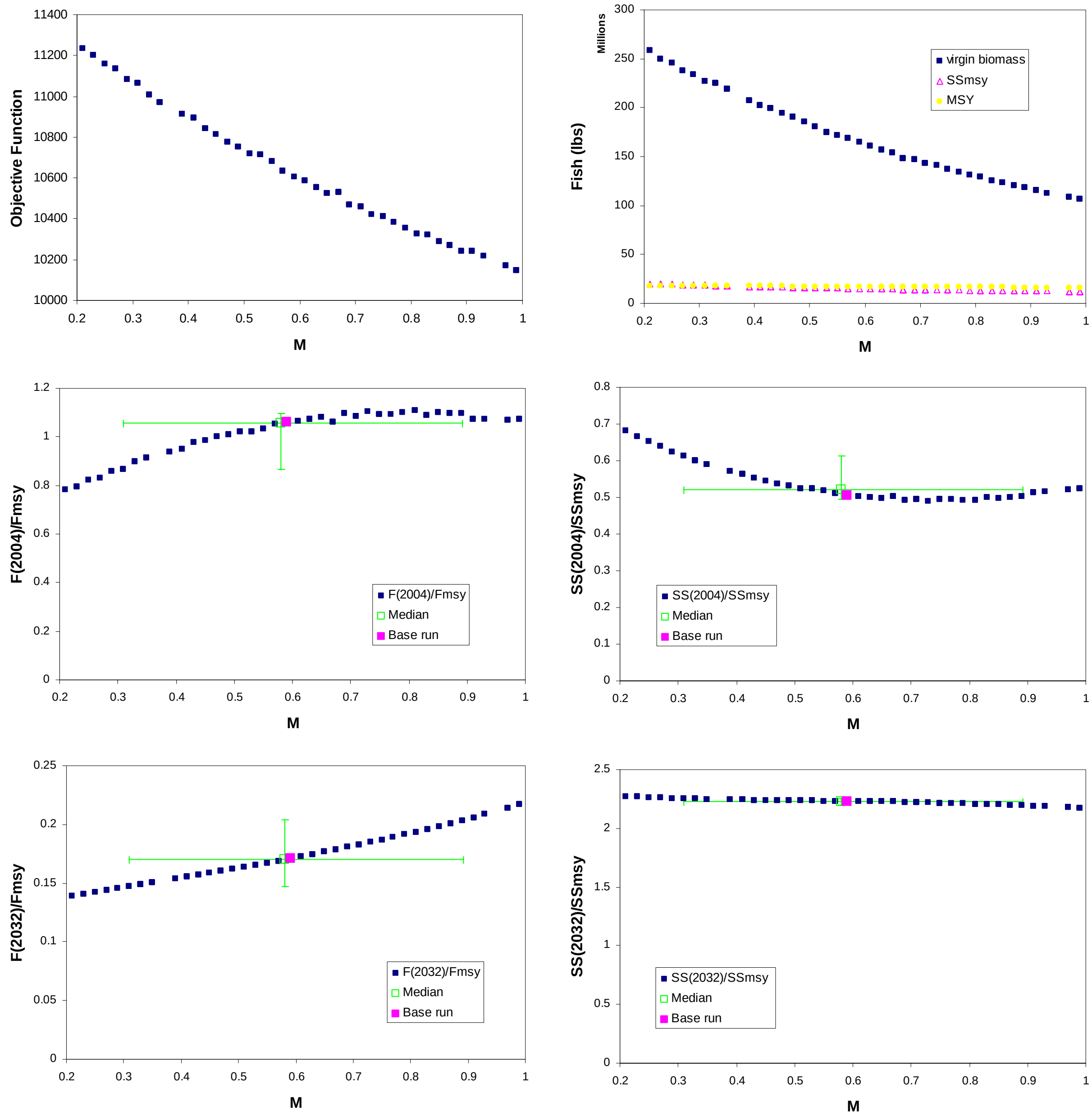



**Figure 22**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.95. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. UNLINKED CASE.

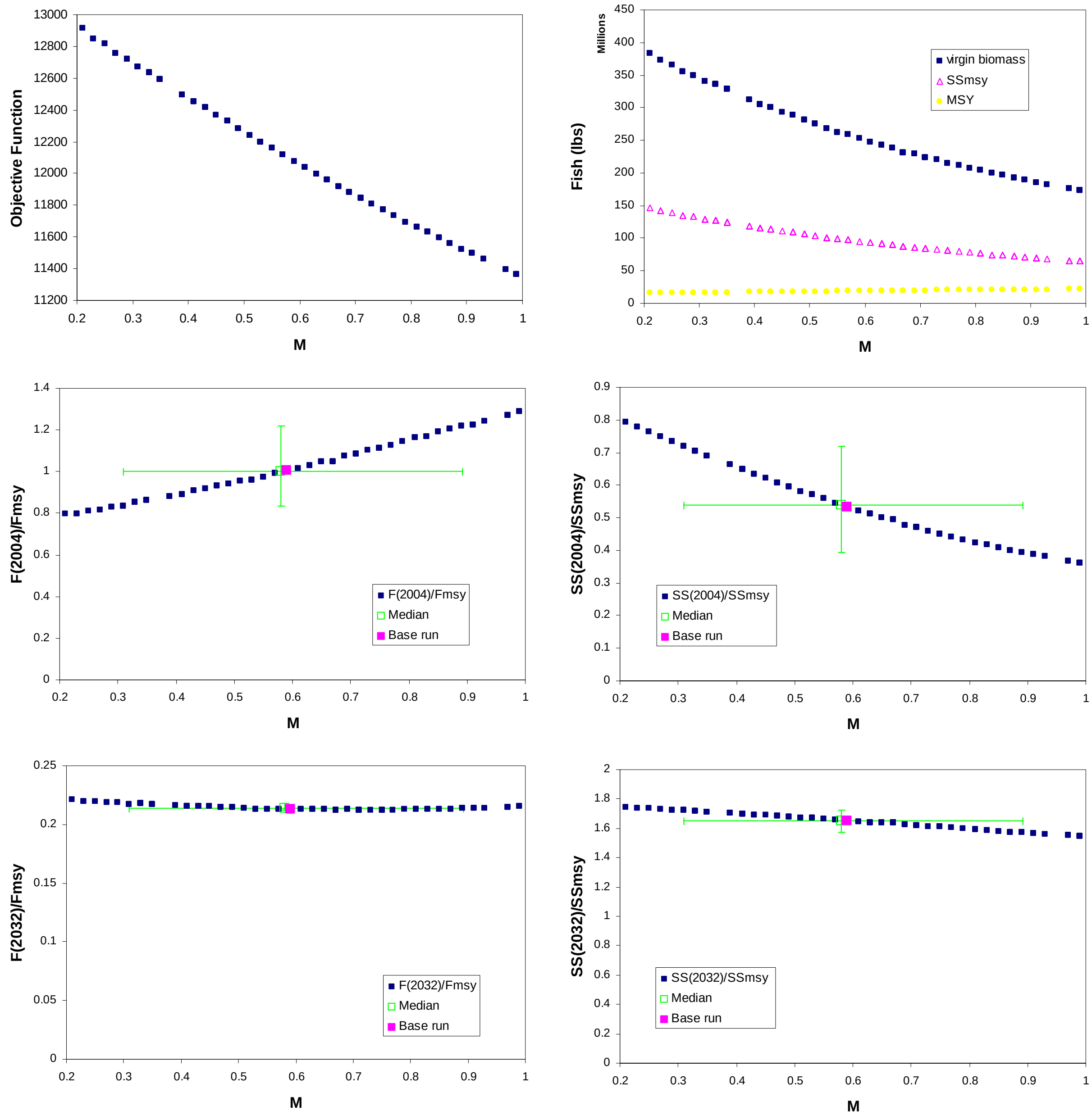



**Figure 23**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.81. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. LINKED CASE.

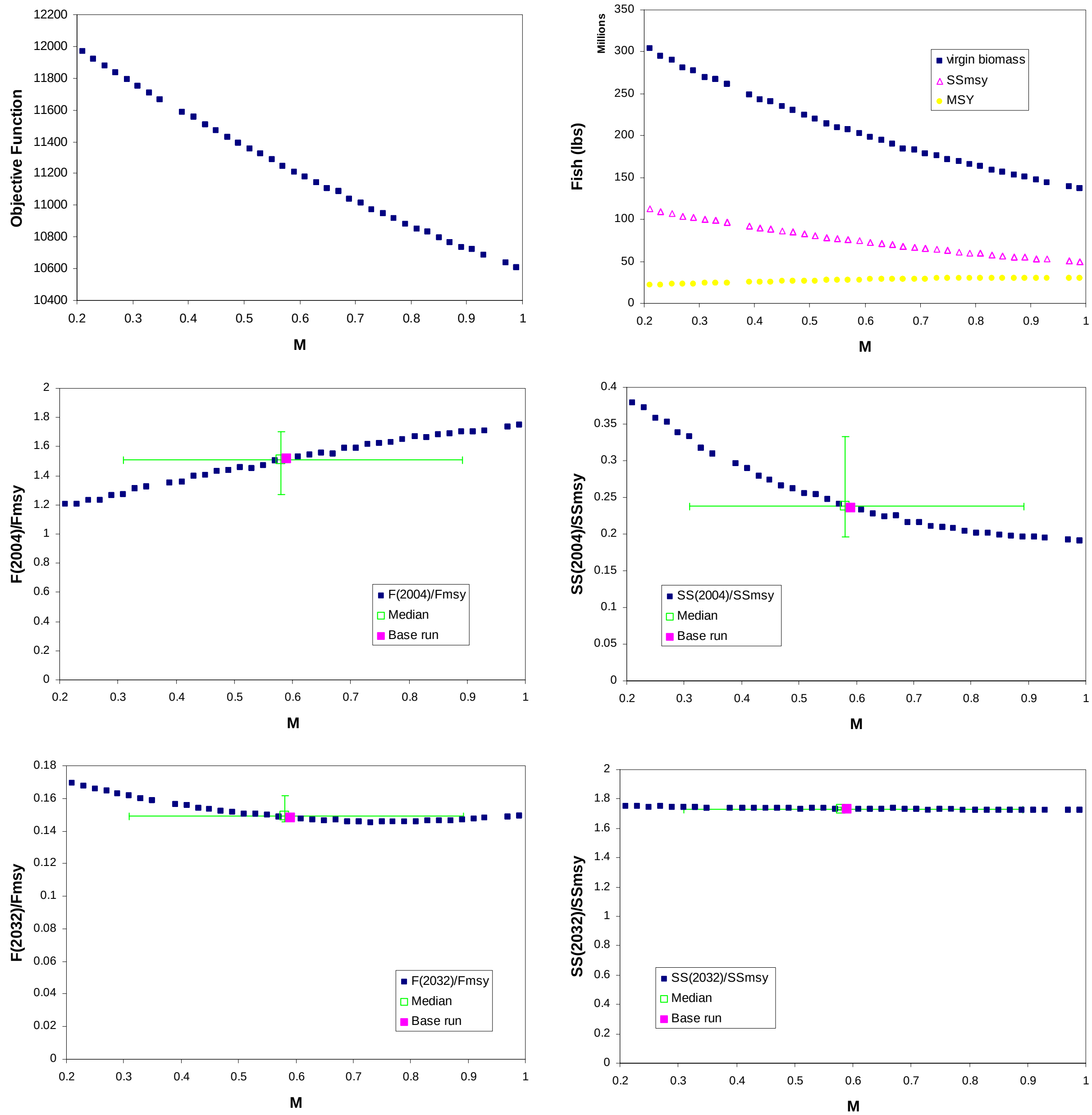



**Figure 24**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.9. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. LINKED CASE.

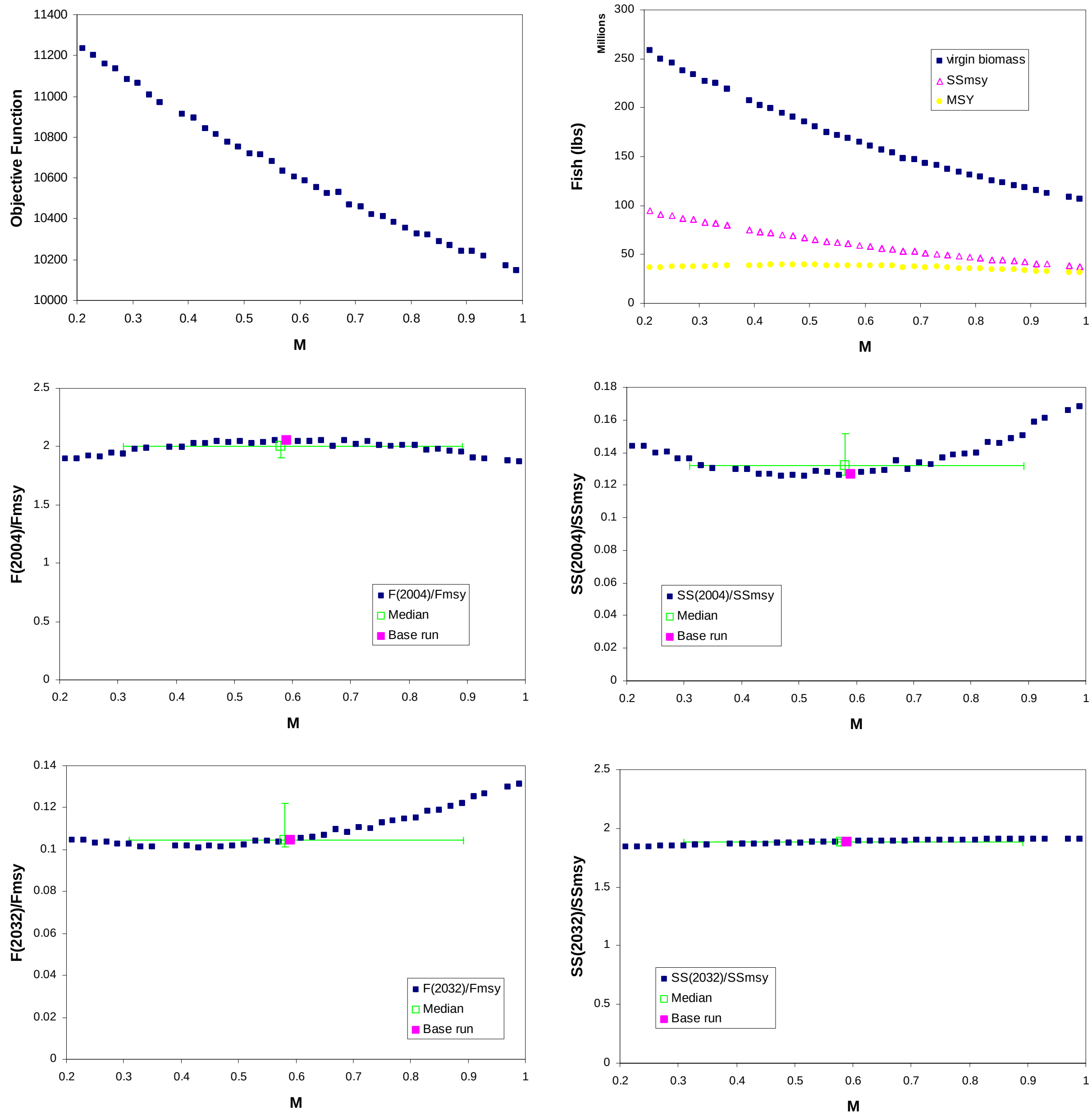



**Figure 25**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.95. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. LINKED CASE.

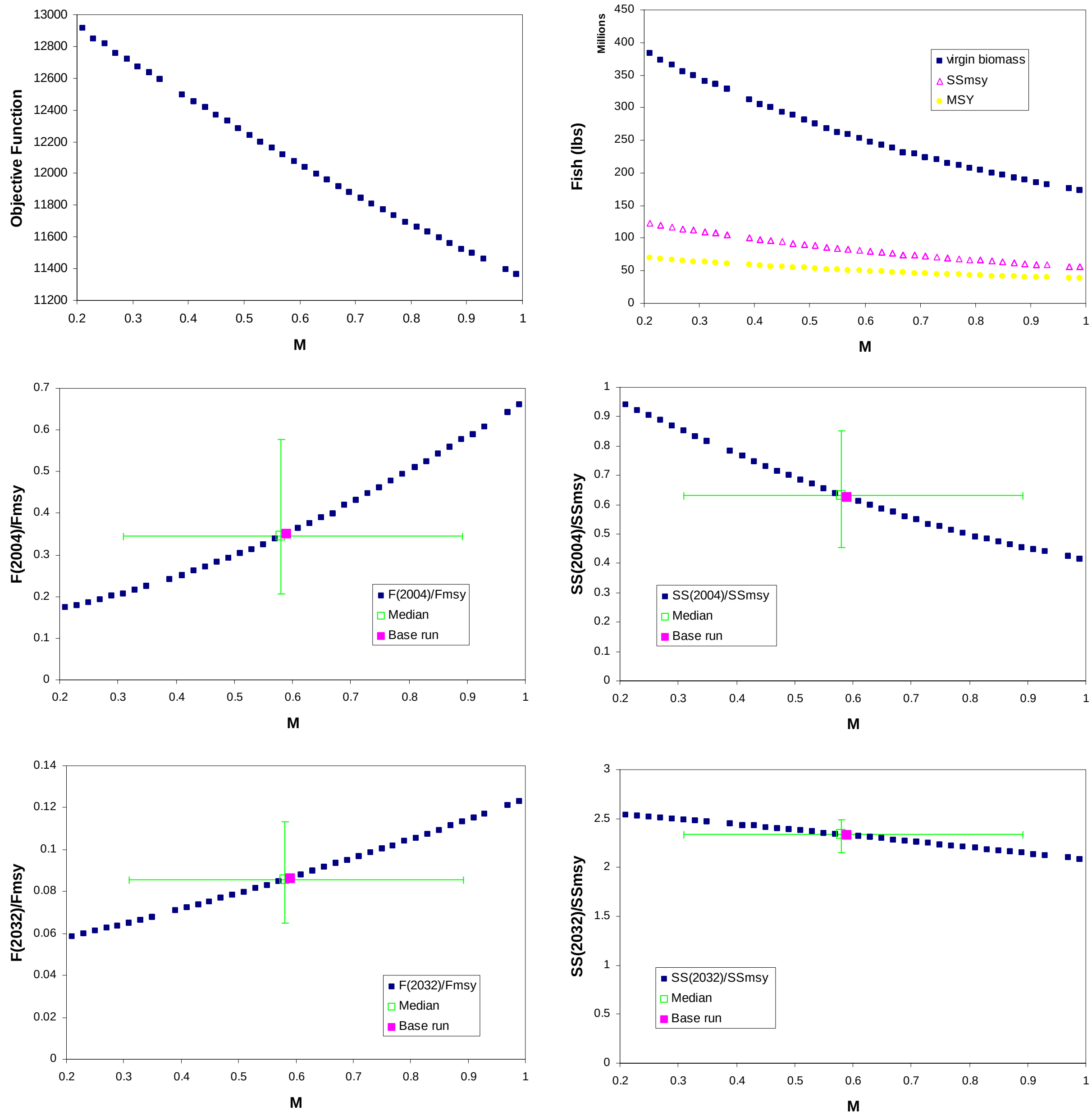



**Figure 26**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.81. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. NO BYCATCH CASE.

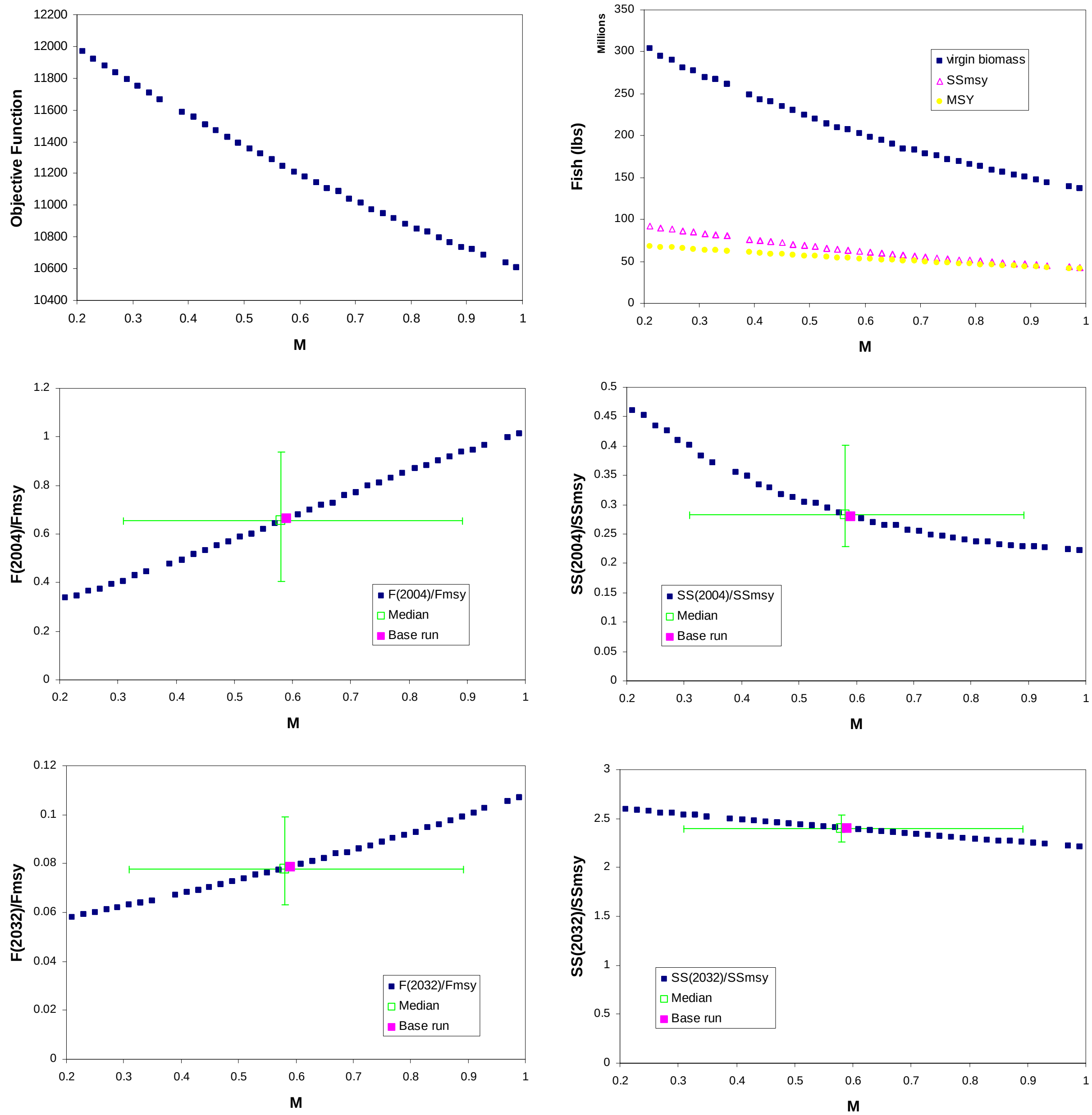



**Figure 27**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.9. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. NO BYCATCH CASE.

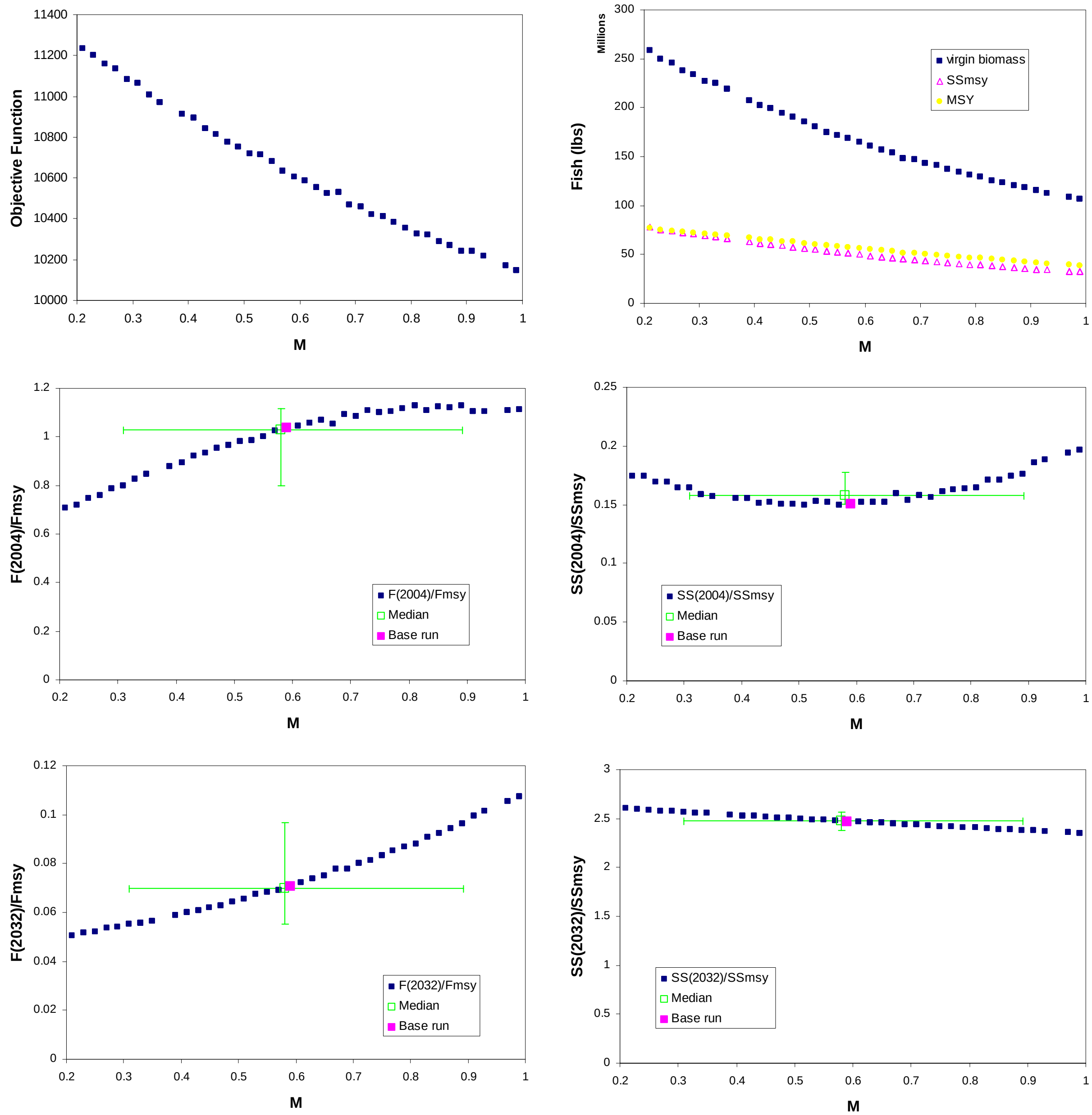



**Figure 28**. Influence of $M_1$ (and linked $M_0$) values, steepness 0.95. (A) objective function fits at various $M_1$ levels (lower is better), (B) biomass and yield reference points, (C) fishing mortality rate in 2004 relative to $F_{MSY}$, (D) spawning stock biomass in 2004 relative to $SS_{MSY}$, (E) fishing mortality rate in 2032 relative to $F_{MSY}$, (F) spawning stock biomass in 2032 relative to $SS_{MSY}$. NO BYCATCH CASE.