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# A 2-SPECIES REDFISH MODEL

by

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## ABSTRACT

The two redfish species *Sebastes mentella* and *S. fasciatus* have different spatio-temporal distributions in the Gulf of St. Lawrence, but they are harvested and managed as though they were one species. This is an extreme example of the mixed stock fishery problem. The purpose of this paper is to present a progress report of a modelling study aimed at (i) examining the possible impacts of various spatio-temporal harvesting patterns on the long-term abundance of the two species and (ii) conducting sensitivity analyses to determine which components of the biology and distribution of the species are most critical, and are therefore most deserving of additional emphasis in data collection programmes. We present the modelling framework that will be used in future studies, as well as some simulation results for illustration of the model.



## RESUME

Bien que leurs répartitions spatio-temporelles dans le golfe du Saint-Laurent soient différentes, les deux espèces de sébaste Sebastes mentella et S. fasciatus sont récoltées et gérées comme une seule et même espèce. Leurs cas offre un exemple extrême du problème que pose l'exploitation d'un stock mixte. Le présent document constitue un rapport d'étape sur une étude de modélisation visant (i) à examiner les répercussions possibles de divers régimes spatio-temporels de récolte sur l'abondance à long terme des deux espèces et (ii) à réaliser des analyses de sensibilité afin de déterminer quels aspects de la biologie et de la distribution des espèces sont les plus importants et méritent par conséquent plus d'attention dans les programmes de récolte de données. On y présente la structure de modélisation qui servira aux études futures, ainsi que certains résultats de simulation illustrante le fonctionnement du modèle.

## INTRODUCTION

It is well recognised that problems may arise from the practice of harvesting and managing two or more fish populations (stocks) in combination. The problems fall into two categories. First, if the stocks differ substantially in population parameters such as fecundity or growth rate, then the calculated optimal harvest levels will be incorrect. Second, and potentially more serious, are the possible consequences when the stocks are very isolated in space and/or time, such that interchange of fish between the stocks is rare. If two or more isolated stocks are managed in combination, the same overall harvesting level can lead to very different longterm population dynamics, depending on the spatial and temporal distribution of the fishing. In the extreme, if all the fishing is concentrated on a subset of the stocks, and some are fished to extinction, it may take many generations for these stocks to be replaced because of the low rate of interchange. The consequences for the longterm survival of the fishery are obvious.

The problems associated with concurrent exploitation of multiple stocks can be extreme if the "stocks" are actually separate species. In this case the ecological requirements of the two species are likely to be different, and it is less likely that one species can "replace" another if the first has been overfished.

Redfish are an important component of the fishery in the Gulf of St. Lawrence and off southern Newfoundland. An overview of the species biology and the fishery is given in Atkinson (1987). There are three species, Sebastes marinus, S. mentella, and S. fasciatus. S. marinus is easily distinguished from the other two species, but it comprises an insignificant portion of the fishery. S. mentella and S. fasciatus, on the other hand, are both important components of the fishery. However, they are indistinguishable without disection and inspection of the gas bladder musculature. Therefore, they are managed and harvested as though they were one species. There is some evidence that the spatial and temporal distributions of these two species are not completely congruent (Ni 1982). Figure 1 summarizes the current understanding of the distributions of the two species in the Gulf of St. Lawrence and the waters off southern Newfoundland (NAFO divisions 3Psn4RSTV). For the purpses of this description we refer to 4ST and the northern portion of 4R as the "upper gulf" and 3Pns4v and the southern portion of 4R as the "lower gulf". It is generally believed that in the summer, S. mentella is found in deeper waters (below 250 m) in the whole gulf, as well as in shallower waters in the upper gulf. S. fasciatus, on the other hand, is found mainly in the lower gulf in both deep and shallow water, and to a much lesser extent in the shallow waters in the upper gulf. In the winter both species appear to move to the deeper waters in the lower gulf.

The overall purpose of this work is to examine the potential consequences of the combined management of these two redfish species. It is not possible to build a predictive model to study this question, because there is very little quantitative information about the distributions of the species. However, it is possible to build an exploratory simulation model to examine the range of possible dynamics of the redfish fishery under combined management. Our approach was to build a simple model that incorporates the main components of our current understanding of the spatio-temporal dynamics of the species. Simulation experiments will then be conducted with the following two goals: (i) to examine possible impacts of various spatio-temporal harvesting patterns on the long-term abundance of the two species and (ii) to conduct sensitivity analyses to determine which components of the biology and distribution of the species are most critical, and are therefore most deserving of additional emphasis in data collection programmes. This paper is a progress report in which we describe the model. We illustrate the model with the results of some preliminary simulations.

## THE MODEL

The model (Figure 2) is a stochastic simulation model; parameter values are chosen from Normal distributions, with coefficients of variation 10% of the mean (except recruitment; see below). In the model, "space" is divided into two regions that can be thought of as corresponding to the upper and lower gulf areas. Each of these is divided into two depth zones corresponding to depths above and below 250 m. The time step is 0.5 year, to incorporate the winter/summer differences in the spatial patterns of the redfish.

### Recruitment

Recruitment of redfish to the fishery occurs at about age 6. Recruitment is thought to be bimodal; most years only a small number of fish enters the fishery, but occasionally recruitment is unusually high. We plotted a frequency histogram of recruitment levels for the past 16 years for redfish in 3Ps (Figure 3). Recruitment does appear to be bimodel with values in the low recruitment years at about 1,000,000 and in the high years at approximately 4,000,000. The relative frequencies of high years is about 0.3. The coefficient of variation about these values is approximately 0.3. This information was used to build a stochastic recruitment routine in the model that mimics this pattern. It is unknown whether high recruitment occurs synchronously for both S. mentella and S. fasciatus, perhaps due to oceanographic conditions, or whether the recruitment levels of the species are independent. Therefore, the recruitment routine in the model includes a parameter termed "synchrony" which determines whether or not recruitment is synchronous. Finally, we do not assume any functionsl relationship between recruitment and stock size, but we impose an arbitrary lower limit of 1000 individuals below which recruitment is assumed to be negligible.

### Movement

The two redfish species are assumed to be distributed as described above, by depth, region and season. Fish move around in each season according to the rates given in Table 1 (with stochastic variability applied). There are no actual estimates for these values, but they correspond roughly with the understanding of the spatio-temporal distributions of the species described above (Figure 1).

## Natural Mortality

The population models of the two species are not age-structured, but we do assume that the maximum lifespan of a redfish is about 30 years. This is done by calculating the survival rate per year such that only 1% of the recruited individuals (age 6) would be present 25 years later (age 30) if there were no fishing:

$$m = 1 - e^{(1/25)\ln(0.01)},$$

where $m$ is the annual mortality rate. This results in an average annual mortality rate of about 17%; stochastic variability is then applied to this rate.

## Fishing

Fishing is included in the simulations by allowing a certain fraction of the redfish to be harvested. The fishery is assumed to be able to find the fish in the highest concentrations and to exploit these areas first. The catch is applied according to Pope's approximation to the Gulland catch equations (Figure 2).

# PRELIMINARY SIMULATIONS

To gain an initial impression of the behaviour of the model we ran a series of preliminary simulations. The aspects of the model that we examined were (i) the seasonality of the fishery (summer only, winter only, or both summer and winter), (ii) the distribution of the fishery between upper and lower gulf regions (upper gulf only, lower gulf only, both upper and lower gulf), (iii) the synchrony of recruitment for the two species (asynchronous or synchronous), and (iv) the overall level of fishing (20% or 60%). All 36 possible combinations of these factors were simulated. A particular run type is identified by a four-digit number. For example, run type 3221 had fishing in both seasons (possibility #3 for seasonality), fishing in the lower gulf only (possibility #2 for fishery distribution), synchronous recruitment between the two species (possibility #2 for asynchrony/synchrony) and exploitation rate 20% (possibility #1 for exploitation rate).

Since stochastic effects are included in the model, it was also important to look at the level of uncertainty in a single model run. We therefore conducted 3 replicate runs of each run type; each ran for 50 years.

## Preliminary Results

The results of the simulations are shown in Table 2. Figures 4 to 10 show the output for some of the runs. The most notable result is the high level of variability in the time series. This is mainly due to the bimodal probability distribution for recruitment, in which recruitment can take on either a low or a high value. This is best seen by comparing the results of the three replicate simulations for any individual run type (Table 2). Because of the extreme variability in the time series it is difficult to see the effects of the 4 factors varied in the simulations. To elucidate these it will be necessary to conduct a large number of replicate simulations (e.g., 100) for each run type, and then compare the run types by statistical analyses of the output. However, at this point some tentative conclusions can be drawn:

1. Restricting the fishing to one season or the other does not have a large effect as long as fishing is allowed in both the upper and lower gulf areas (e.g., compare run types 1321, 2321 and 3321: Figures 4, 5 and 6 and Table 2), although fishing only in summer appears to result in slightly larger population sizes (2321).

2. The largest effect of area-restricted fishing appears to occur when fishing is restricted to the upper gulf (e.g., compare run types 3121 and 3221: Figures 7 and 8 and Table 2). In this case the fishery takes a disproportionate amount of S. mentella relative to S. fasciatus.

3. The assumption of asynchronous recruitment (between the two species) appears to result in larger populations and higher catch rates than the assumption of synchrony (e.g., compare run types 3311 and 3321: Figures 9 and 6 and Table 2). Also, synchrony results in higher variability in catch rates than asynchrony (compare catch C.V.'s in Table 2).

4. The level of fishing has a large impact on the overall survival probability (e.g., compare run types 3322 and 3321: Figures 10 and 6 and Table 2).

## CONCLUSIONS AND FUTURE PLANS

The results described above are presented to illustrate the type of simulation experiments that could be conducted with this model. As stated above, the model is strictly an "exploratory" model; it can not be used to produce quantitative predictions about the population dynamics of redfish because of the large number of unknown aspects important for making such predictions. These include:
(i) the levels of variability in the parameters
(ii) the question of the degree of synchrony in recruitment of the two species,
(iii) the relationship between stock size and recruitment,
(iv) the actual abundances of the two species by area, depth and season, and the movement rates between the areas,
(v) the degree to which the species are ecologically isolated.
This final point is of crucial importance for two reasons. First, from the point of view of the fishery, it is important to know whether if one species is fished down, the other one

will expand its spatio-temporal distribution to include that of the first. If so, it is also important to know at what rate this will happen. Secondly, although for the fishery a high replacement rate may be considered advantageous, this could also have the negative ecological effect of encouraging the extinction of the second species. We plan to continue simulation studies using this model to (i) examine the possible range of dynamics of the redfish species in the Gulf and (ii) identify types of data that would be most useful.


## ACKNOWLEDGEMENTS

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## REFERENCES


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Ni, I-H. 1982. Meristic variation in beaked redfishes, *Sebastes mentella* and *S. fasciatus*, in the northwest Atlantic. Canadian Journal of Fisheries and Aquatic Sciences 39: 1664-1685.

Table 1. Movement rates of redfish. Rates are fractions of populations from other areas moving into the area indicated at the start of the season indicated.

| | Summer | | Winter | |
|---|---|---|---|---|
| | *S. m.* | *S. f.* | *S. m.* | *S. f.* |
| upper gulf, <250 m | 0.35 | 0.10 | 0.00 | 0.00 |
| upper gulf, >250 m | 0.35 | 0.00 | 0.00 | 0.00 |
| lower gulf, <250 m | 0.00 | 0.40 | 0.00 | 0.00 |
| lower gulf, >250 m | 0.30 | 0.40 | 1.00 | 1.00 |

Table 2. Simulation results.
"Param" refers to the parameter values used for the run: each of the 36 possible combinations is identified by a four-digit number. The four digits represent, respectively, fishery timing, fishery distribution, recruitment (a)synchrony and fishing level. For example, run 3221 had fishing in both seasons (possibility #3 for seasonality), fishing in the lower gulf only (possibility #2 for fishery distribution), synchronous recruitment between the two species (possibility #2 for asynchrony/synchrony) and exploitation rate 20% (possibility #1 for exploitation rate).
"Rep" is the replicate number.
<u>S. m.</u> is <u>Sebastes mentella</u> and <u>S. f.</u> is <u>S. fasciatus</u>.
Mean and C.V. values are calculated for the final 30 years of each 50-year simulation.

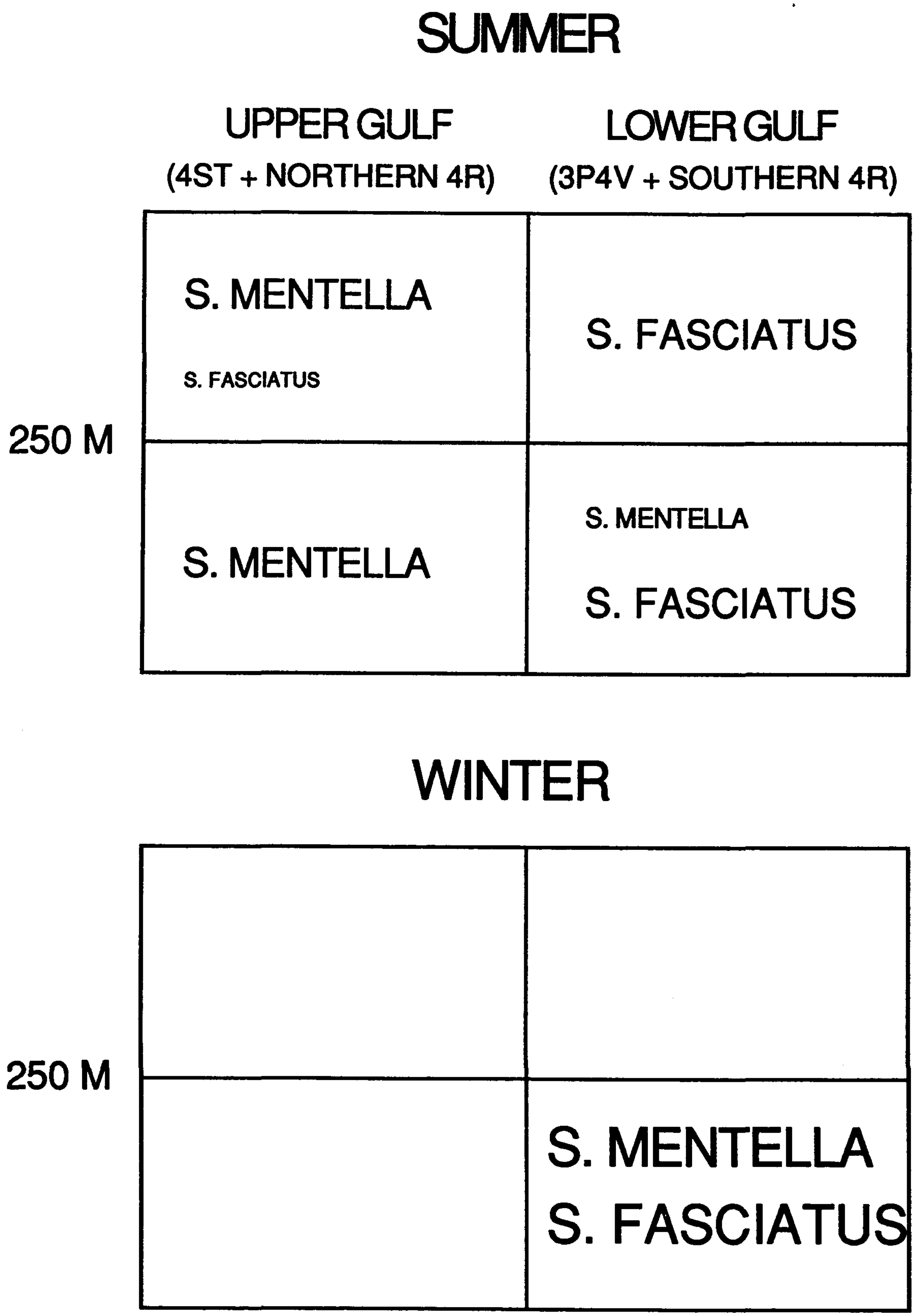
| Param | Rep | Mean Abund <u>S. m.</u> | C.V. <u>S. m.</u> | Mean Abund <u>S. f.</u> | C.V. <u>S.f.</u> | Mean Total Catch | C.V. Total Catch |
|---|---|---|---|---|---|---|---|
| 1111 | 1 | 82.93 | 74.87 | 119.78 | 30.58 | 38.14 | 35.41 |
| 1111 | 2 | 78.76 | 56.21 | 149.53 | 34.68 | 44.81 | 36.91 |
| 1111 | 3 | 45.25 | 106.38 | 150.43 | 35.95 | 34.02 | 51.01 |
| 1112 | 1 | 21.00 | 67.36 | 112.55 | 39.38 | 23.89 | 42.38 |
| 1112 | 2 | 19.93 | 69.93 | 83.95 | 51.02 | 20.28 | 49.93 |
| 1112 | 3 | 23.03 | 66.88 | 137.21 | 41.87 | 26.51 | 42.83 |
| 1121 | 1 | 81.13 | 55.88 | 120.82 | 34.49 | 40.39 | 38.87 |
| 1121 | 2 | 84.77 | 63.83 | 174.40 | 35.89 | 51.70 | 40.31 |
| 1121 | 3 | 72.96 | 77.23 | 143.24 | 37.28 | 42.85 | 50.43 |
| 1122 | 1 | 21.38 | 62.68 | 109.28 | 40.61 | 23.85 | 47.52 |
| 1122 | 2 | 23.33 | 66.30 | 113.92 | 32.55 | 25.49 | 44.53 |
| 1122 | 3 | 17.38 | 59.74 | 91.45 | 27.81 | 19.85 | 46.06 |
| 1211 | 1 | 149.55 | 45.83 | 88.39 | 44.06 | 47.59 | 36.53 |
| 1211 | 2 | 111.69 | 41.36 | 118.57 | 54.29 | 46.05 | 37.67 |
| 1211 | 3 | 119.05 | 36.49 | 91.61 | 53.16 | 42.13 | 34.49 |
| 1212 | 1 | 75.63 | 47.14 | 17.99 | 72.94 | 36.03 | 37.28 |
| 1212 | 2 | 67.33 | 49.29 | 19.10 | 89.28 | 34.35 | 49.17 |
| 1212 | 3 | 66.31 | 43.43 | 17.57 | 71.54 | 33.52 | 40.26 |
| 1221 | 1 | 135.62 | 50.82 | 100.74 | 45.53 | 47.27 | 43.61 |
| 1221 | 2 | 164.75 | 47.94 | 108.45 | 38.88 | 54.64 | 40.32 |
| 1221 | 3 | 115.67 | 49.44 | 91.52 | 55.71 | 41.44 | 49.71 |
| 1222 | 1 | 74.35 | 41.36 | 21.46 | 76.79 | 39.33 | 53.48 |
| 1222 | 2 | 68.58 | 49.53 | 18.01 | 67.91 | 33.26 | 57.25 |
| 1222 | 3 | 74.69 | 61.34 | 16.03 | 83.93 | 34.30 | 69.35 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1311 | 1 | 104.41 | 40.52 | 104.12 | 41.10 | 41.71 | 30.50 |
| 1311 | 2 | 141.39 | 36.51 | 106.34 | 45.25 | 49.55 | 30.57 |
| 1311 | 3 | 109.91 | 34.69 | 132.21 | 46.72 | 48.42 | 27.24 |
| 1312 | 1 | 88.35 | 58.10 | 75.13 | 57.47 | 98.09 | 38.24 |
| 1312 | 2 | 74.51 | 52.85 | 64.34 | 61.69 | 83.31 | 31.62 |
| 1312 | 3 | 76.63 | 64.66 | 53.38 | 71.84 | 78.01 | 49.09 |
| 1321 | 1 | 135.56 | 39.49 | 116.95 | 41.80 | 50.50 | 37.09 |
| 1321 | 2 | 120.84 | 35.66 | 120.03 | 55.21 | 48.17 | 43.49 |
| 1321 | 3 | 103.04 | 43.94 | 92.17 | 39.15 | 39.04 | 39.38 |
| 1322 | 1 | 71.41 | 57.85 | 73.39 | 67.59 | 86.87 | 61.66 |
| 1322 | 2 | 66.95 | 61.98 | 73.20 | 72.20 | 84.09 | 63.59 |
| 1322 | 3 | 72.55 | 64.55 | 72.68 | 62.73 | 87.14 | 59.59 |
| 2111 | 1 | 187.17 | 32.45 | 144.91 | 32.28 | 7.16 | 93.43 |
| 2111 | 2 | 194.14 | 32.94 | 192.14 | 29.65 | 8.14 | 91.00 |
| 2111 | 3 | 154.04 | 49.29 | 205.32 | 30.36 | 7.05 | 79.94 |
| 2112 | 1 | 195.44 | 43.36 | 167.95 | 28.24 | 5.79 | 106.39 |
| 2112 | 2 | 217.16 | 29.45 | 207.10 | 28.72 | 7.68 | 71.36 |
| 2112 | 3 | 140.95 | 48.70 | 161.21 | 36.92 | 6.21 | 73.29 |
| 2121 | 1 | 146.47 | 31.98 | 167.42 | 32.90 | 7.31 | 78.80 |
| 2121 | 2 | 165.79 | 34.74 | 167.27 | 29.15 | 5.61 | 99.96 |
| 2121 | 3 | 154.95 | 37.58 | 183.12 | 40.57 | 5.66 | 116.95 |
| 2122 | 1 | 176.57 | 34.07 | 132.06 | 21.66 | 7.67 | 102.37 |
| 2122 | 2 | 160.38 | 32.98 | 171.02 | 26.21 | 5.22 | 89.55 |
| 2122 | 3 | 189.87 | 33.84 | 209.76 | 38.09 | 7.32 | 80.70 |
| 2211 | 1 | 113.90 | 49.96 | 125.20 | 47.01 | 47.82 | 37.08 |
| 2211 | 2 | 111.00 | 40.07 | 88.84 | 38.67 | 39.97 | 28.60 |
| 2211 | 3 | 99.23 | 51.04 | 113.96 | 30.19 | 42.64 | 32.71 |
| 2212 | 1 | 54.96 | 58.83 | 67.14 | 62.03 | 73.26 | 54.79 |
| 2212 | 2 | 55.82 | 57.05 | 50.89 | 64.65 | 64.02 | 44.73 |
| 2212 | 3 | 72.50 | 60.79 | 51.38 | 50.34 | 74.33 | 36.81 |
| 2221 | 1 | 119.88 | 32.69 | 93.27 | 30.28 | 42.63 | 29.85 |
| 2221 | 2 | 82.64 | 37.33 | 119.37 | 37.00 | 40.40 | 34.80 |
| 2221 | 3 | 107.73 | 50.62 | 116.82 | 52.51 | 44.91 | 50.09 |
| 2222 | 1 | 68.94 | 54.34 | 65.05 | 66.83 | 80.39 | 58.95 |
| 2222 | 2 | 62.98 | 56.44 | 76.80 | 58.66 | 83.87 | 56.27 |
| 2222 | 3 | 64.63 | 65.51 | 51.68 | 79.98 | 69.79 | 68.45 |
| 2311 | 1 | 111.78 | 43.94 | 146.76 | 39.78 | 55.31 | 47.26 |
| 2311 | 2 | 126.22 | 37.56 | 121.36 | 40.00 | 52.11 | 38.63 |
| 2311 | 3 | 87.30 | 41.99 | 128.19 | 36.68 | 47.22 | 59.56 |
| 2312 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2312 | 2 | 3.74 | 421.85 | 3.37 | 411.36 | 5.54 | 382.65 |
| 2312 | 3 | 60.61 | 56.71 | 42.99 | 68.50 | 70.99 | 56.13 |
| 2321 | 1 | 125.60 | 50.79 | 106.67 | 41.61 | 49.63 | 53.81 |
| 2321 | 2 | 137.48 | 51.43 | 113.97 | 48.09 | 51.66 | 44.83 |
| 2321 | 3 | 119.75 | 49.77 | 98.19 | 33.47 | 50.35 | 51.28 |
| 2322 | 1 | 6.92 | 368.59 | 8.90 | 405.40 | 13.22 | 428.40 |
| 2322 | 2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2322 | 3 | 49.07 | 106.29 | 46.29 | 104.98 | 65.02 | 125.96 |
| 3111 | 1 | 106.60 | 44.88 | 117.91 | 28.95 | 25.84 | 30.00 |
| 3111 | 2 | 123.08 | 42.74 | 146.37 | 33.10 | 30.67 | 38.40 |
| 3111 | 3 | 148.91 | 37.58 | 166.94 | 32.54 | 37.57 | 27.61 |
| 3112 | 1 | 22.98 | 75.47 | 91.79 | 40.94 | 23.28 | 51.82 |
| 3112 | 2 | 19.70 | 50.98 | 89.20 | 40.74 | 20.79 | 36.95 |
| 3112 | 3 | 34.24 | 84.23 | 144.45 | 43.78 | 33.21 | 38.01 |
| 3121 | 1 | 142.91 | 56.59 | 192.17 | 31.89 | 39.41 | 45.58 |
| 3121 | 2 | 135.70 | 34.67 | 202.95 | 20.32 | 38.02 | 23.76 |
| 3121 | 3 | 151.70 | 49.17 | 169.34 | 42.00 | 35.53 | 40.99 |
| 3122 | 1 | 26.15 | 60.74 | 110.26 | 39.19 | 26.87 | 48.13 |
| 3122 | 2 | 19.88 | 62.15 | 85.60 | 34.86 | 20.19 | 44.68 |
| 3122 | 3 | 20.59 | 60.14 | 92.22 | 28.50 | 21.89 | 48.09 |
| 3211 | 1 | 107.76 | 38.96 | 111.79 | 45.02 | 43.91 | 28.17 |
| 3211 | 2 | 101.72 | 44.19 | 87.58 | 40.30 | 37.86 | 33.39 |
| 3211 | 3 | 121.57 | 35.65 | 99.15 | 53.27 | 44.14 | 29.67 |
| 3212 | 1 | 65.82 | 65.28 | 54.97 | 57.11 | 72.48 | 49.88 |
| 3212 | 2 | 71.83 | 50.42 | 67.37 | 64.82 | 83.52 | 43.65 |
| 3212 | 3 | 67.07 | 59.93 | 65.37 | 65.59 | 79.46 | 54.78 |
| 3221 | 1 | 98.50 | 39.53 | 87.76 | 42.36 | 37.25 | 35.48 |
| 3221 | 2 | 111.62 | 36.78 | 112.62 | 45.37 | 44.85 | 38.89 |
| 3221 | 3 | 152.74 | 31.76 | 134.76 | 41.24 | 57.50 | 34.51 |
| 3222 | 1 | 65.11 | 57.75 | 55.83 | 68.82 | 72.56 | 60.02 |
| 3222 | 2 | 71.44 | 62.59 | 53.56 | 73.93 | 75.00 | 63.29 |
| 3222 | 3 | 58.36 | 55.28 | 49.40 | 69.58 | 64.66 | 58.80 |
| 3311 | 1 | 86.48 | 48.02 | 132.12 | 36.71 | 45.49 | 38.43 |
| 3311 | 2 | 99.47 | 40.04 | 127.49 | 27.83 | 46.46 | 18.60 |
| 3311 | 3 | 132.74 | 37.80 | 116.66 | 41.70 | 56.11 | 47.69 |
| 3312 | 1 | 66.90 | 55.37 | 64.83 | 65.00 | 80.65 | 40.80 |
| 3312 | 2 | 66.28 | 57.09 | 76.26 | 76.88 | 85.52 | 51.04 |
| 3312 | 3 | 66.60 | 60.81 | 62.41 | 57.94 | 77.40 | 45.53 |
| 3321 | 1 | 97.29 | 50.47 | 117.25 | 55.18 | 47.13 | 55.26 |
| 3321 | 2 | 98.58 | 30.08 | 100.10 | 38.38 | 39.73 | 30.92 |
| 3321 | 3 | 86.26 | 38.44 | 77.75 | 34.29 | 33.56 | 32.01 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3322 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3322 | 2 | 66.95 | 57.95 | 64.48 | 66.29 | 78.85 | 56.99 |
| 3322 | 3 | 63.87 | 63.35 | 61.75 | 72.09 | 75.37 | 65.41 |

Figure 1. Spatial and temporal distribution of two redfish species. Size of lettering indicates roughly the relative amount of each species in the area indicated.



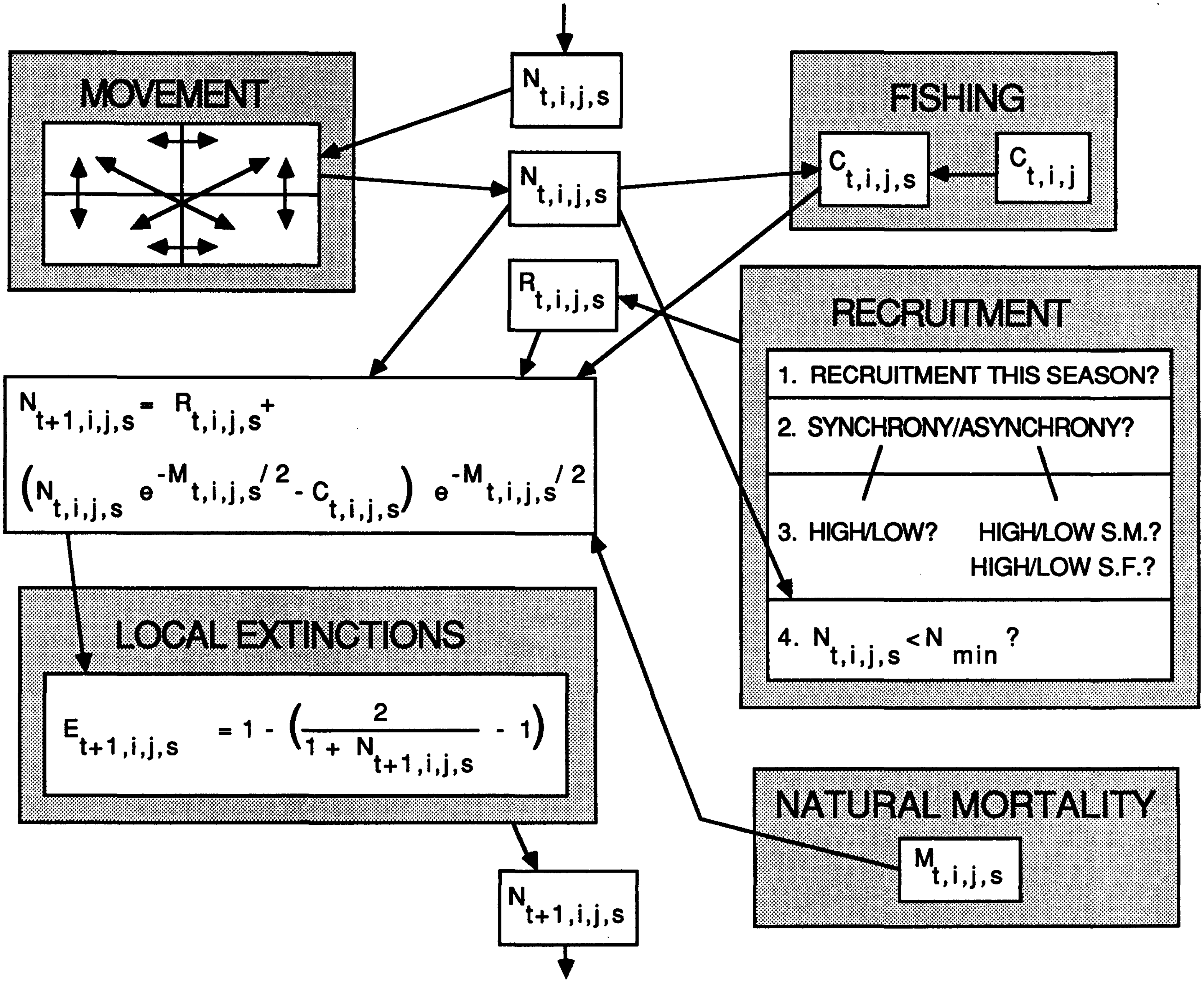



Figure 2. Schematic representation of the model of two redfish species. N=number of fish, R=number of 6-year-olds (recruitment), C=catch, E=extinction probability of local populations, M=natural mortality rate, t=time step, i=region (upper or lower gulf), j=depth, s=species. Time runs from top to bottom of diagram.

**Figure 3. Frequency distribution of recruitment (number of 6-year-olds) in 3Ps redfish for 16 years.**

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FREQUENCY

5 +              *****
  |              *****
  |              *****
  |              *****
  |              *****
4 +              *****
  |              *****
  |              *****
  |              *****
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3 +  *****  *****  *****                              *****
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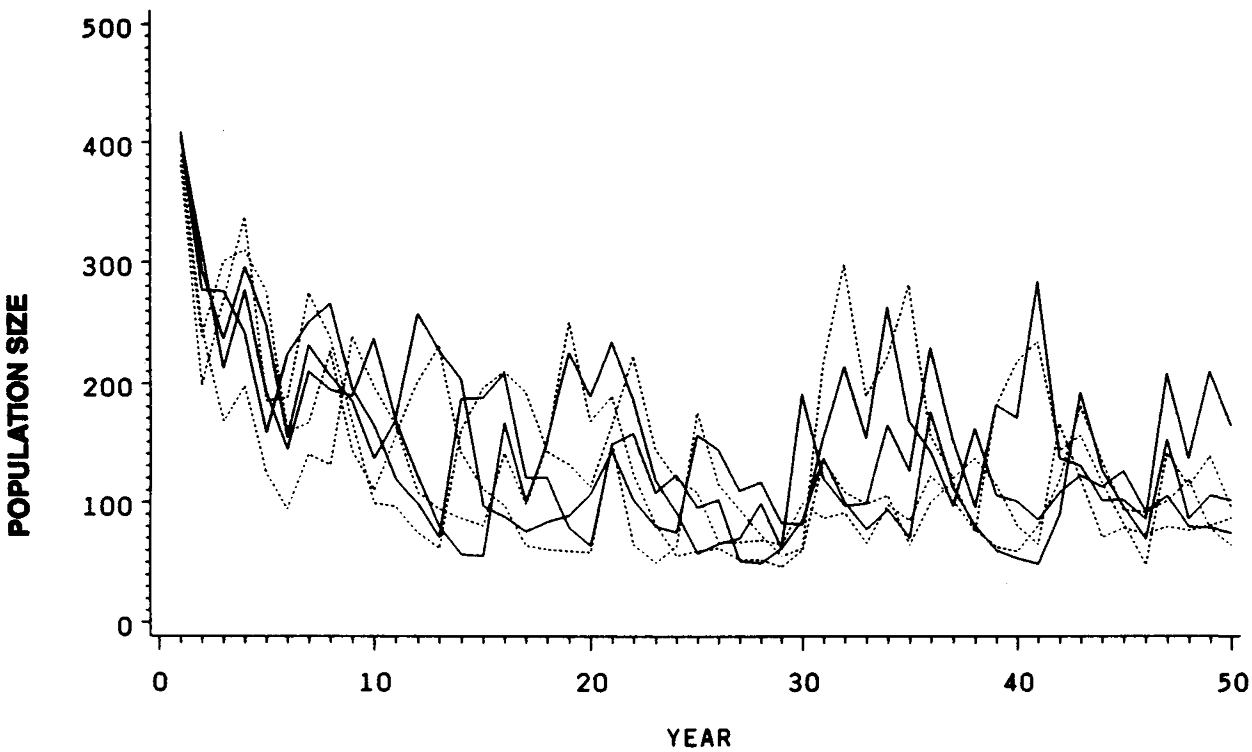
  |  *****  *****  *****                              *****
  |  *****  *****  *****                              *****
  |  *****  *****  *****                              *****
2 +  *****  *****  *****                              *****
  |  *****  *****  *****                              *****
  |  *****  *****  *****                              *****
  |  *****  *****  *****                              *****
  |  *****  *****  *****                              *****
1 +  *****  *****  *****                 *****        *****        *****
  |  *****  *****  *****                 *****        *****        *****
  |  *****  *****  *****                 *****        *****        *****
  |  *****  *****  *****                 *****        *****        *****
  |  *****  *****  *****                 *****        *****        *****
  ----------------------------------------------------------------------
              1      1      2      2      3      3      4      4      5
       5      0      5      0      5      0      5      0      5      0
       0      0      0      0      0      0      0      0      0      0
       0      0      0      0      0      0      0      0      0      0
       0      0      0      0      0      0      0      0      0      0
       0      0      0      0      0      0      0      0      0      0
       0      0      0      0      0      0      0      0      0      0
       0      0      0      0      0      0      0      0      0      0

                 3Ps RECRUITMENT (NO. OF 6-YEAR-OLDS)
```

Figure 4. Simulation results for parameters 1321: fishing in winter only, fishing in both upper and lower gulf, synchronous recruitment, exploitation rate = 0.2. Upper panel is the total population size for the two species, for three separate runs; solid lines are *Sebastes mentella* and dotted lines are *S. fasciatus*. Lower panel is total catch for the three runs.



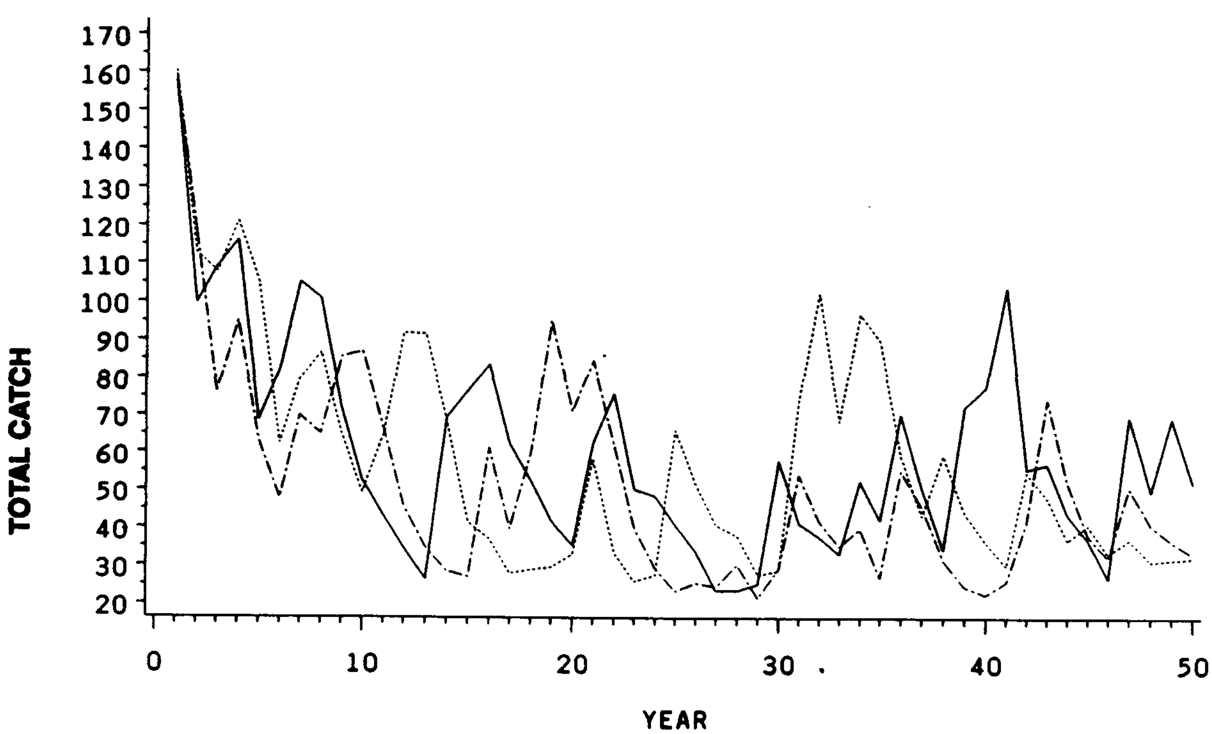



Figure 5. Simulation results for parameters 2321: fishing in summer only, fishing in both upper and lower gulf, synchronous recruitment, exploitation rate = 0.2. Upper panel is the total population size for the two species, for three separate runs; solid lines are *Sebastes mentella* and dotted lines are *S. fasciatus*. Lower panel is total catch for the three runs.

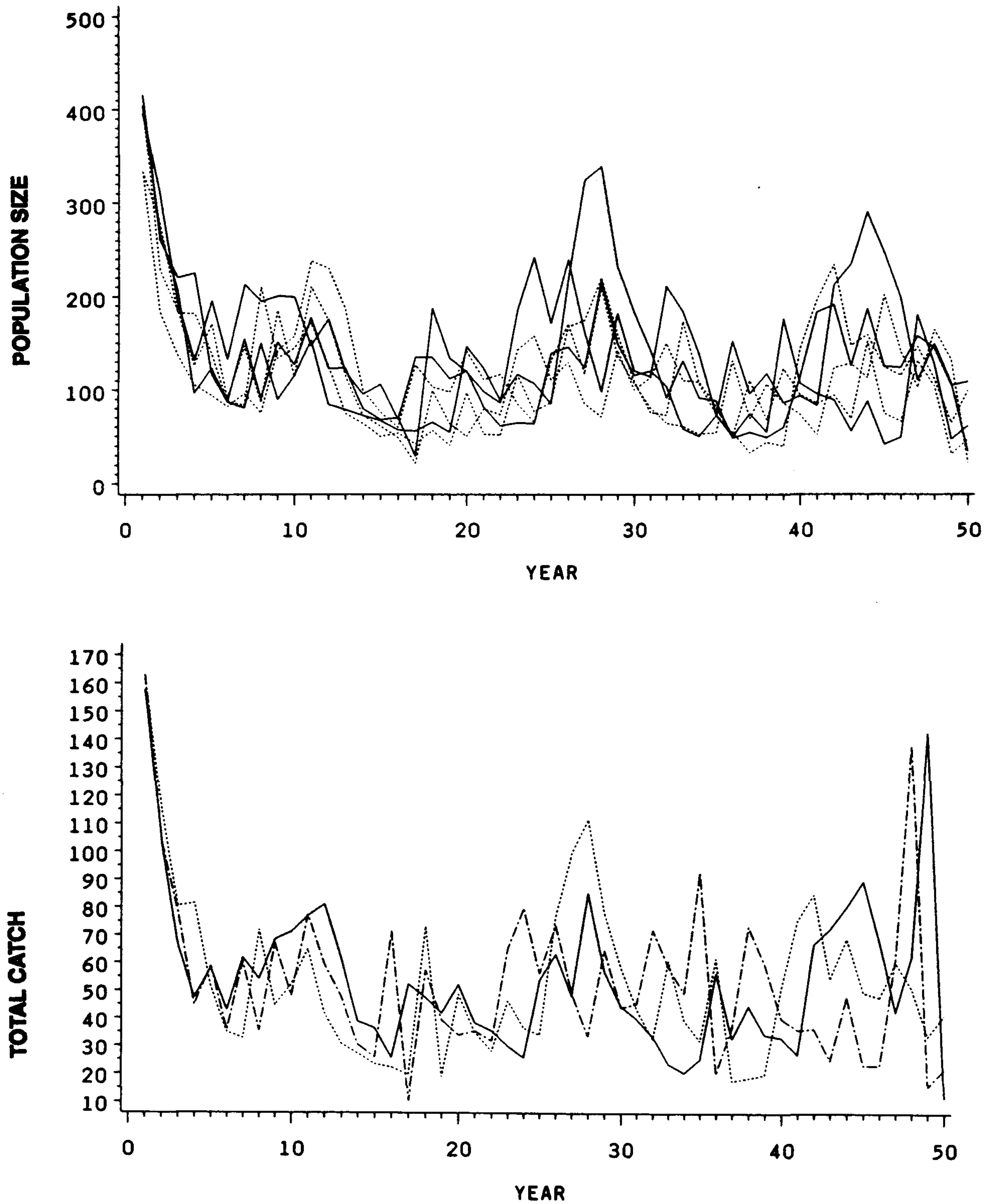


Figure 6. Simulation results for parameters 3321: fishing in summer and winter, fishing in both upper and lower gulf, synchronous recruitment, exploitation rate = 0.2. Upper panel is the total population size for the two species, for three separate runs; solid lines are *Sebastes mentella* and dotted lines are *S. fasciatus*. Lower panel is total catch for the three runs.

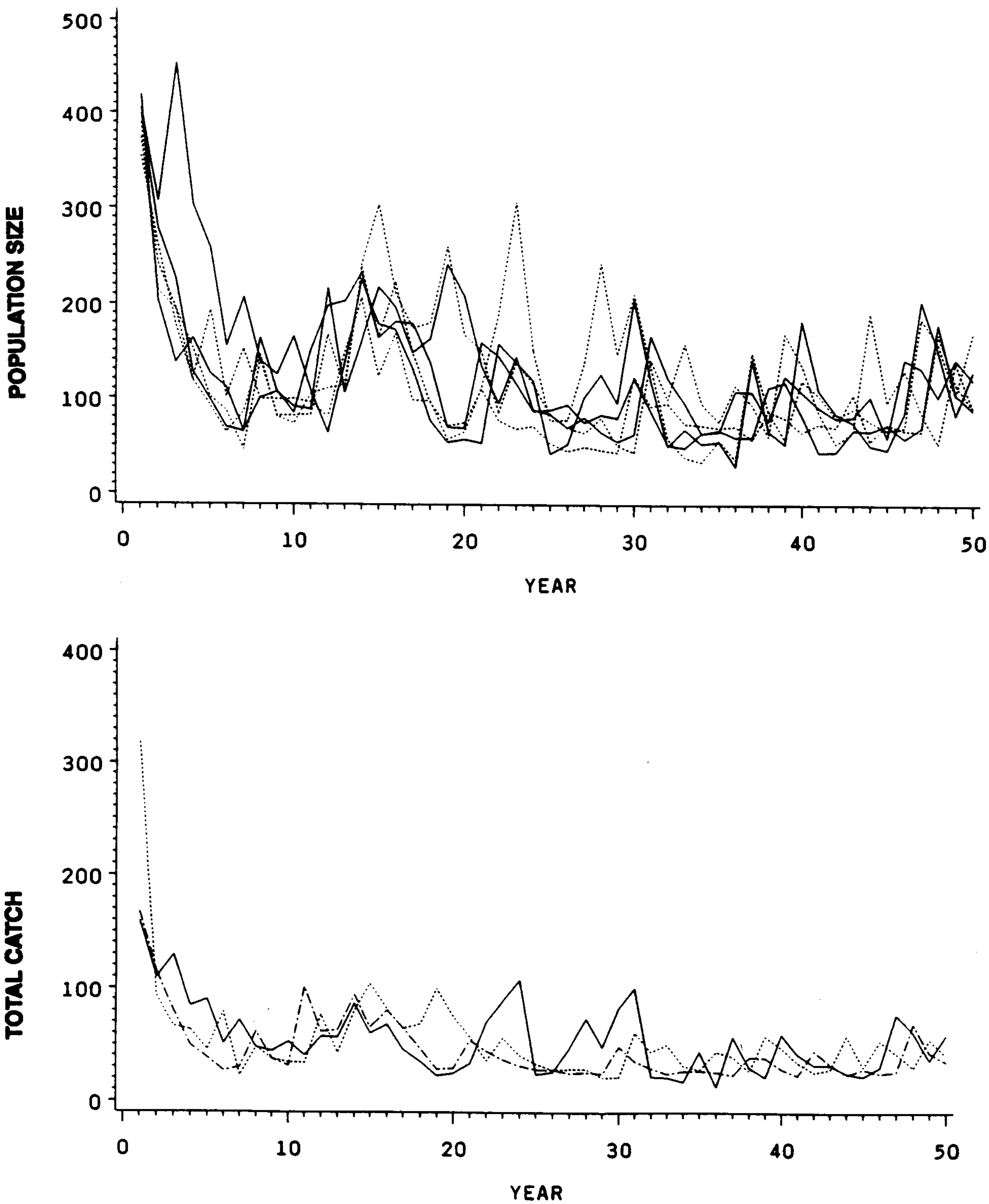


Figure 7. Simulation results for parameters 3121: fishing in summer and winter, fishing in upper gulf only, synchronous recruitment, exploitation rate = 0.2. Upper panel is the total population size for the two species, for three separate runs; solid lines are *Sebastes mentella* and dotted lines are *S. fasciatus*. Lower panel is total catch for the three runs.

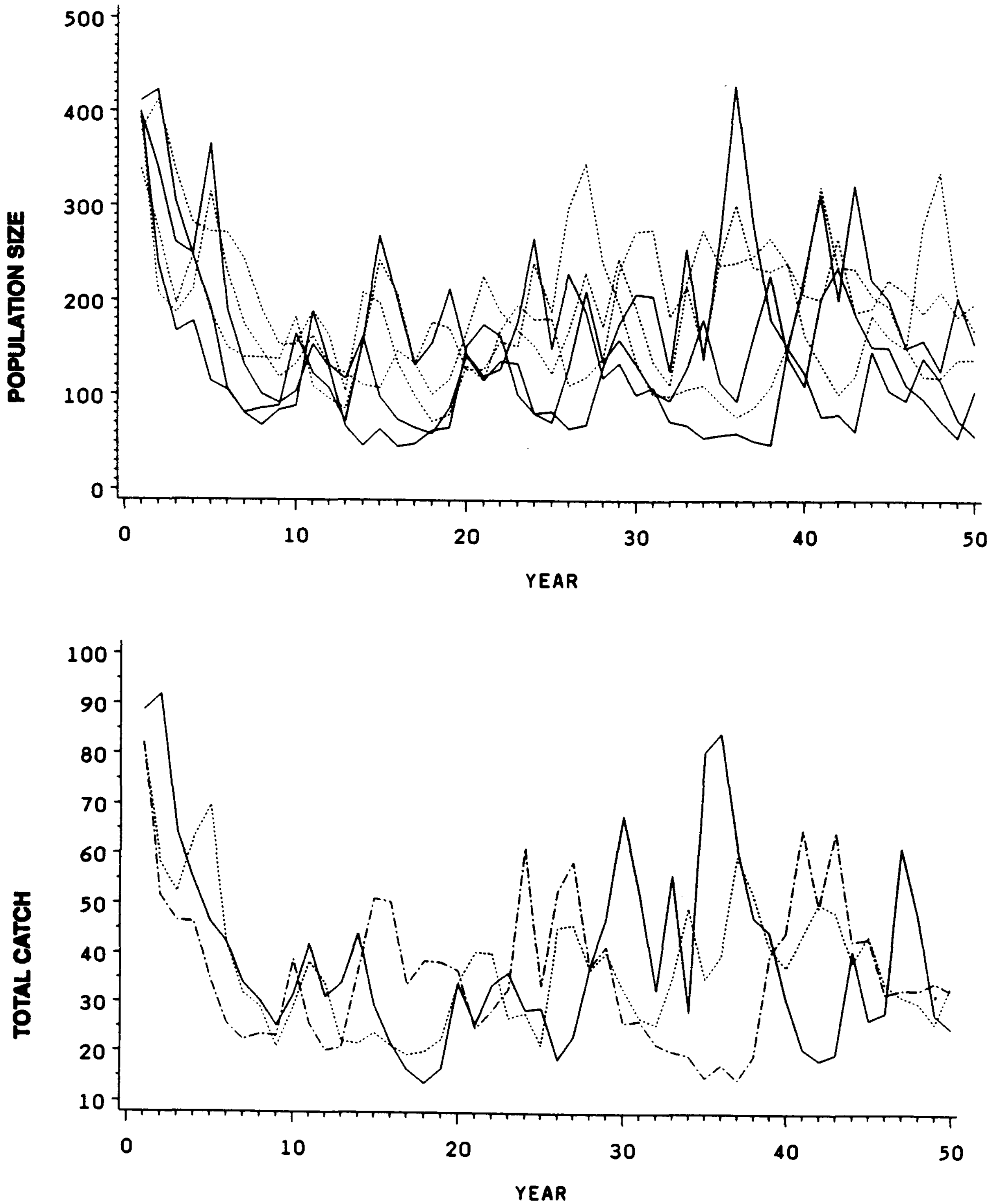
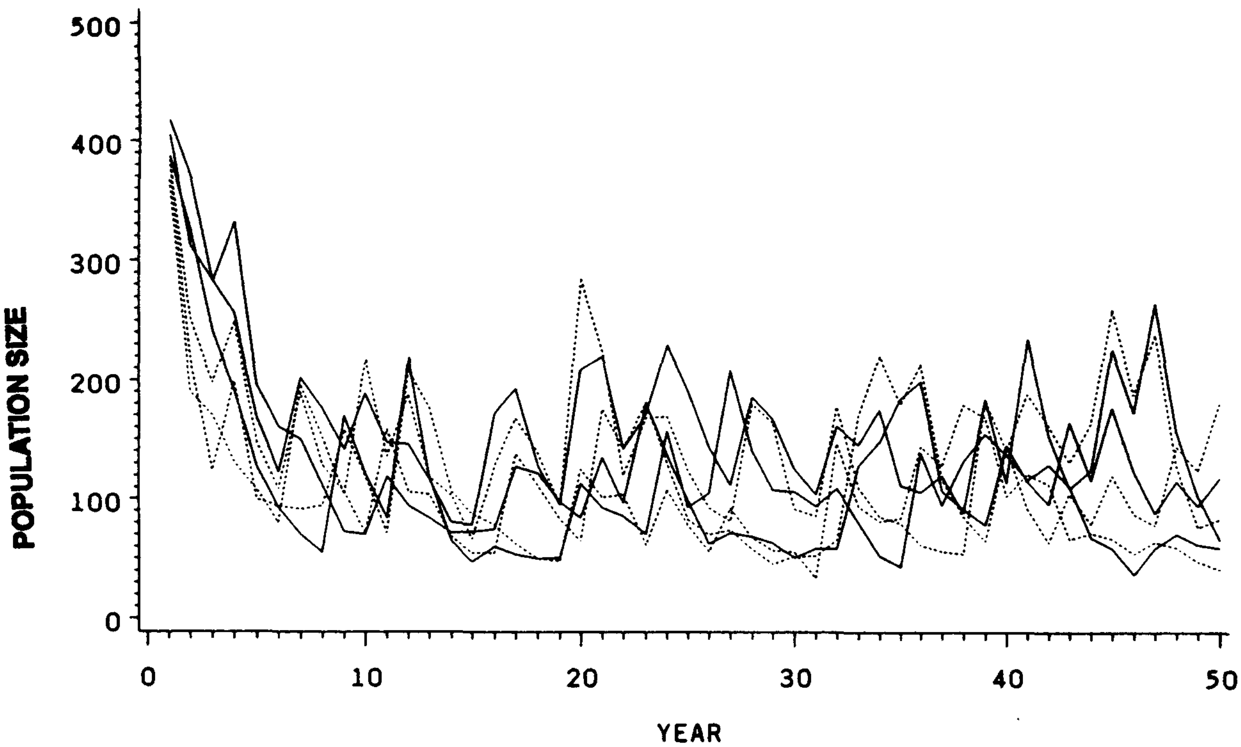


Figure 8. Simulation results for parameters 3221: fishing in summer and winter, fishing in lower gulf only, synchronous recruitment, exploitation rate = 0.2. Upper panel is the total population size for the two species, for three separate runs; solid lines are *Sebastes mentella* and dotted lines are *S. fasciatus*. Lower panel is total catch for the three runs.



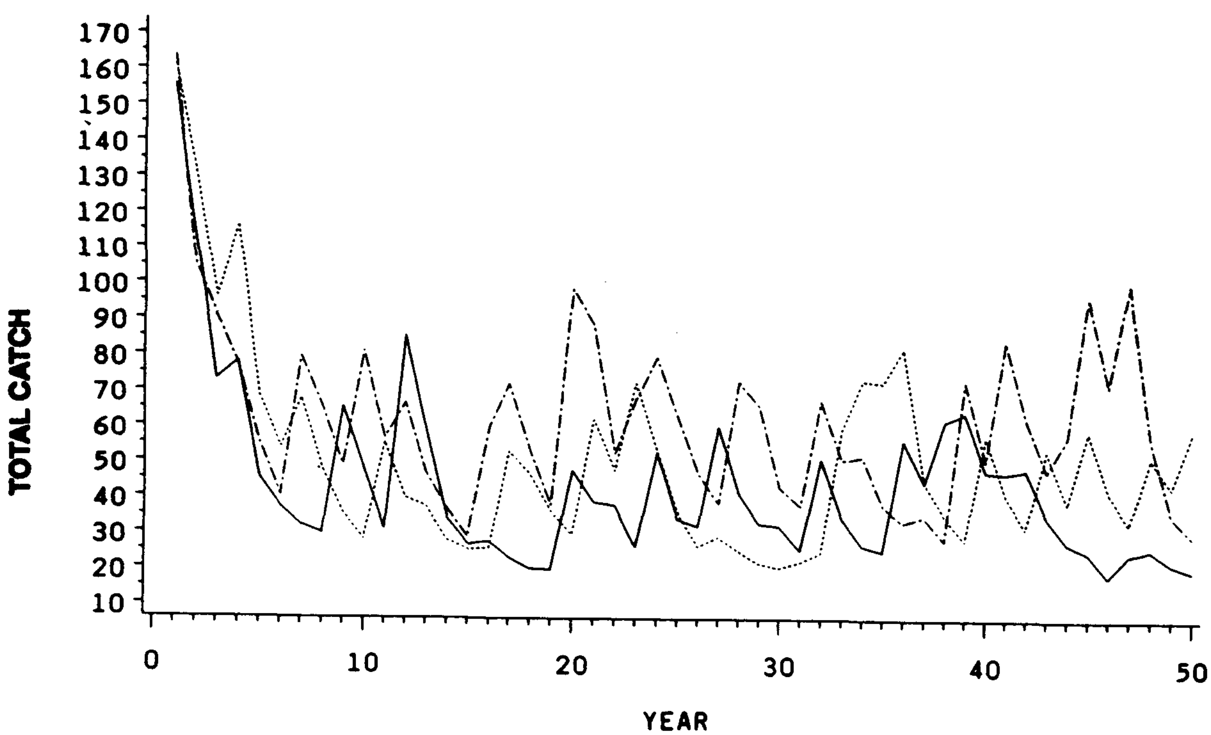



Figure 9. Simulation results for parameters 3311: fishing in summer and winter, fishing in both upper and lower gulf, asynchronous recruitment, exploitation rate = 0.2. Upper panel is the total population size for the two species, for three separate runs; solid lines are *Sebastes mentella* and dotted lines are *S. fasciatus*. Lower panel is total catch for the three runs.

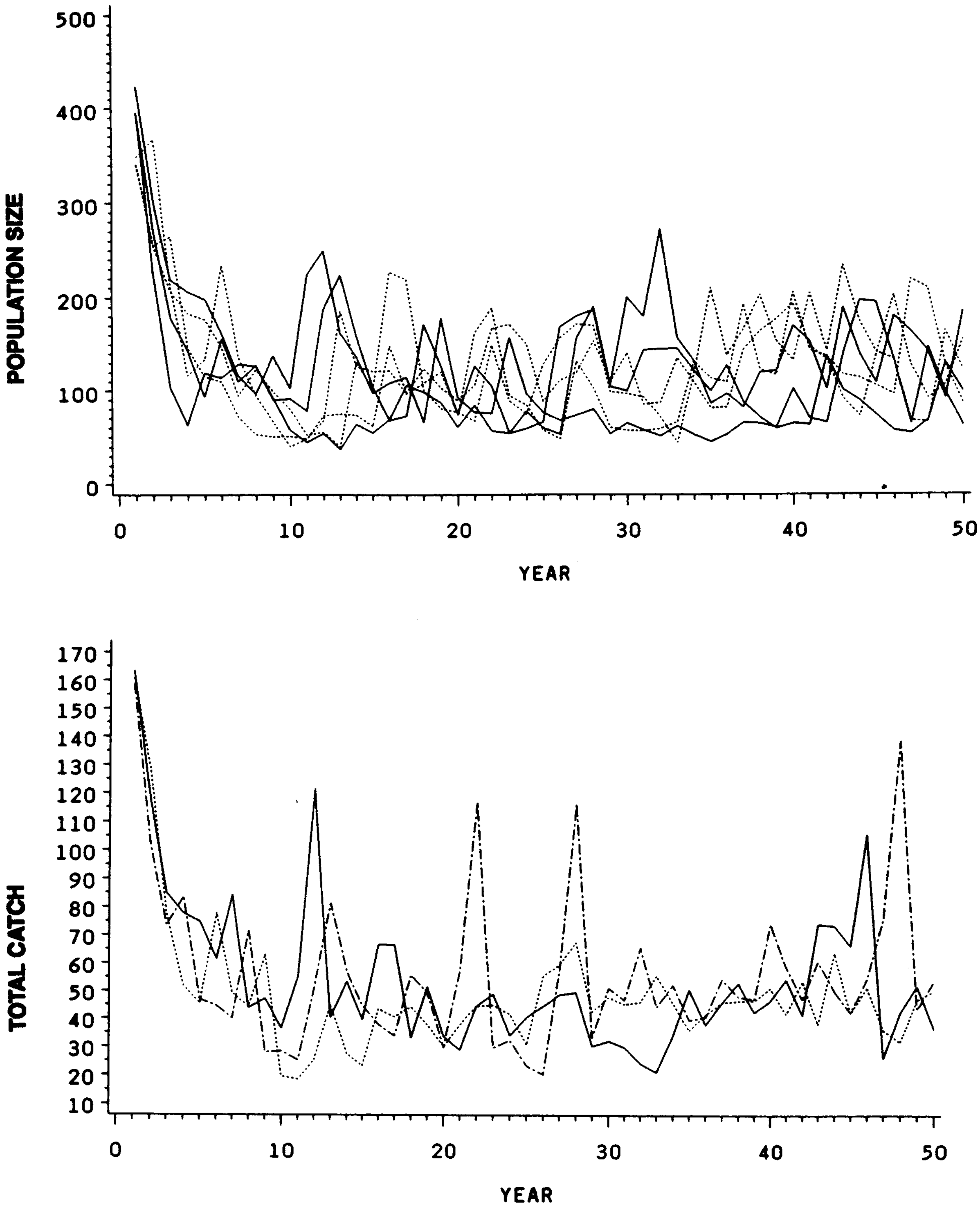


Figure 10. Simulation results for parameters 3322: fishing in summer and winter, fishing in both upper and lower gulf, synchronous recruitment, exploitation rate = 0.6. Upper panel is the total population size for the two species, for three separate runs; solid lines are *Sebastes mentella* and dotted lines are *S. fasciatus*. Lower panel is total catch for the three runs.