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Uncertainty in a Mixed Stock Fishery: a Redfish Simulation Study

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Abstract

The redfish fisheries in the Gulf of St. Lawrence and off the southern coast of Newfoundland harvest two species, *Sebastes mentella* and *S. fasciatus*, which are fished and managed as though they were one. There is evidence that the two species have different distributions over the region, and between winter and summer. The consequences of uncertainty in the relative abundance and the recruitment synchrony of the two species are examined, for different spatial and temporal patterns of fishing and an attempt is made to identify fishing patterns that would be particularly risky in terms of the survival probability of the two species. A simulation model was constructed of the redfish population dynamics where the region was divided into upper and lower areas and the year was divided into summer and winter. Simulation experiments gave the following main results: (i) fishing only in winter is generally less risky than fishing only in summer or in both seasons; (ii) spreading the catch over the whole region is generally less risky than restricting the catch to either the upper or lower area; (iii) if fishing is carried out in both seasons or summer only, and the relative abundance of *S. mentella* is low, it is important to fish in the lower area or in both the upper and lower areas, but not in the upper area only; and (iv) if fishing is carried out in both seasons or summer only, and the relative abundance of *S. mentella* is high, fishing should be spread over the entire region.

Introduction

It is well recognized that problems may arise from the practice of harvesting and managing two or more fish populations (stocks) in combination (Hilborn, 1985). The problems fall into two categories. First, is if the stocks differ substantially in population parameters such as fecundity or growth rates, the calculated optimal catch levels will be incorrect. Second, and potentially more serious, is if the stocks are isolated in space and/or time, such that interchange of fish between the stocks is rare. The possible consequence if two or more isolated stocks are managed in combination, is that the same overall harvesting level can lead to very different long-term population dynamics, depending on the spatial and temporal distribution of the fishing. In an extreme case, if all the fishing is concentrated on a subset of the stocks, and some stocks are fished to extinction, it may take many generations for these stocks to be replaced because of the low rate of interchange. The long-term survival of the fishery is consequently affected. The problems associated with mixed stock fisheries can be extreme if the "stocks" are actually separate species. In such a 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 fisheries in the Gulf of St. Lawrence and off southern Newfoundland (Fig. 1). An overview of the species biology and the fishery is given by 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

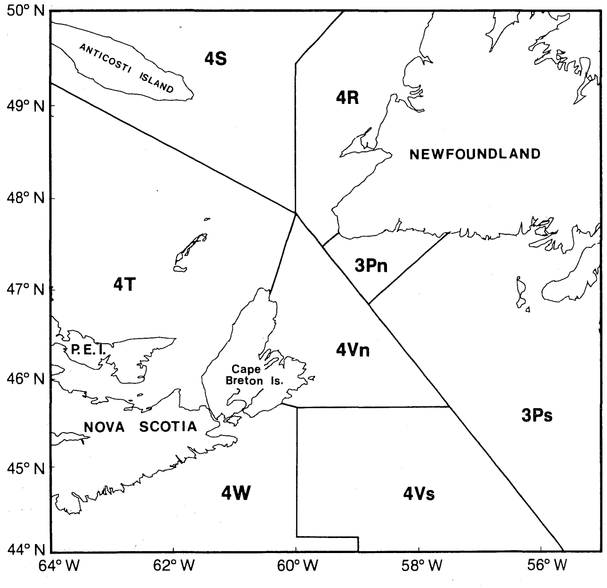

Fig. 1. NAFO Divisions and Subdivisions in the Gulf of St. Lawrence off southern Newfoundland, where redfish are an important component of the fisheries.

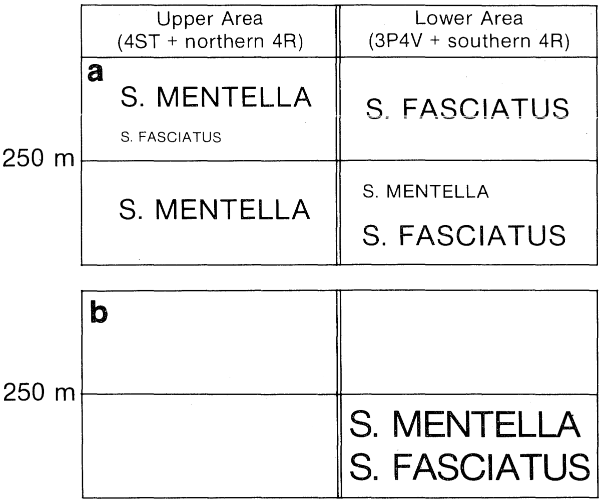

Fig. 2. Spatial and temporal distributions of two redfish species in (**a**) summer and (**b**) winter. Size of lettering indicates roughly the relative amount of each species in the area.

the other hand, are both important components of the fishery and are indistinguishable without dissection 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 congruent (Ni, 1982). Figure 2 summarizes the current understanding of the distributions of the two species in the Gulf of St. Lawrence and the waters off southern Newfoundland (in Subdiv. 3Ps+Pn and Div. 4RSTV). For the purposes of this description we refer to Div. 4ST and the northern portion of Div. 4R as the "upper area" and Subdiv. 3Pn+Ps, and Div. 4V and the southern portion of Div. 4R as the "lower area". It is generally believed that in the summer, *S. mentella* is found in deeper water (below 250 m) in the whole region, as well as in shallower waters in the upper area. *S. fasciatus* is found mainly in the lower area in both deep and shallow water, and to a much lesser extent in the shallow waters in the upper area. In the winter both species appear to move to the deeper waters in the lower area.

Uncertainty concerning the populations

Because the two main species are difficult to distinguish, there is much that remains unknown concerning the differences between their biologies and distributions. Perhaps the most basic area of uncertainty is that of their relative abundance in the region. Research surveys have been conducted to aid in assessment of the populations (Atkinson and Power, MS 1989, Laberge and Hurtubise, MS 1989), but only a small number of the fish are identified to species. Information from the commercial fishery is not available at the species level. There is therefore currently no estimate available of their relative abundances.

A second potentially important area of uncertainty is that of recruitment synchrony. As with most fish populations, recruitment in redfish is highly variable from year to year. It is not known whether years of good recruitment are years in which both species have high recruitment (perhaps due to environmental conditions), or whether the recruitment levels of the two species are independent over time.

The purpose of this work was to examine the consequences of different spatial and temporal patterns of fishing on the two redfish populations. We were particularly interested in investigating the potential consequences of the relative abundance and recruitment synchrony. It is not possible to build a predictive model of redfish dynamics, because of the lack of quantitative information, 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 incorporated the main components of our current understanding of the spatio-temporal dynamics of the species. Simulation experiments were then conducted to examine the possible impact of (a) different levels of relative abundances of the two species and (b) synchronous *vs* asynchronous recruitment, on long-term catches, species abundance and species risk levels (see Simulation Experiments section below for definition). These simulations were conducted under a range of levels of variability in parameter values, to compare effects of the uncertainty to effects of intrinsic variability in population parameters. The simulations were conducted for different spatial and temporal patterns of fishing to identify fishing patterns that might be most harmful to the redfish populations.

The Model

The model is a stochastic simulation model. "Space" is divided into two regions that can be thought of as corresponding to the upper and lower 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 distributions of the redfish. The model does not explicitly follow age-classes; this means that only numbers of fish can be calculated, not biomass, since weights have to be applied separately to each age-class.

Recruitment. Recruitment of redfish to the fishery occurs at about age 6. No functional relationship was assumed between recruitment and total stock size. To simulate a realistic temporal pattern of recruitment, the 16 years of recorded recruitment for Subdiv. 3Ps redfish was used (D. Power, Northwest Atlantic Fisheries

Centre, St. John's, Newfoundland, pers. comm.). Expected recruitment for a particular year in the simulation was chosen at random from this series. The recruitment routine in the model included a parameter termed "synchrony" which determined whether or not recruitment in the two species was synchronous. For simulations in which recruitment was assumed to be synchronous, only one recruitment value was chosen for each year. For simulations in which recruitment was assumed to be asynchronous, separate recruitment values were chosen for each species each year. In both cases, the recruitment value selected for a species was then multiplied by the relative abundance of the species in the parent stock (i.e. the stock 6 years previous).

Movement. The two redfish species were assumed to be distributed as described in the Introduction (Fig. 2), by depth, region and season. Fish move around in each season according to the rates given in Table 1 (with stochastic variability applied). There were no estimates for these values, but they corresponded roughly with the understanding of the spatio-temporal distributions of the species.

Natural mortality. The population models of the two species were not age-structured, but the maximum lifespan of a redfish was assumed to be about 50 years. This was done using the following model by calculating the survival rate per year such that only 1% of the recruited individuals (age 6) would be present 44 years later (age 50) if there was no fishing;

$$m = e^{\left(\frac{1}{44}\right)^{\ln(0.01)}}$$

where *m* is the annual mortality rate. This resulted in an average annual mortality rate of about 10%; stochastic variability was then applied to this rate.

Fishing. An annual exploitation rate of 0.1 was allowed. Depending on the simulation, fishing may be permitted in only the winter, only the summer, or both winter and summer. If fishing was permitted in winter and summer it was assumed that fishing would be concentrated first in the winter and then continued into the summer only if the quota had not been filled in the winter. Also depending on the simulation, fishing may be permitted in the upper area only, the lower area only, or both the upper and lower areas. The fishery was assumed to be able to find the fish in the highest concentration and to exploit those areas first.

Simulation Experiment I

Equal relative abundance, no parameter variability, synchronous recruitment. The goal of the first simulation experiment was to examine the effects of different spatial and temporal patterns of fishing in the absence of parameter variability and under the assumption of equal relative abundance of the two species. Synchronous recruitment was also assumed. Each simulation was run for 100 years to get an idea of the long-term consequences of different fishing patterns. Output were analyzed for the final 50 years. Table 1 gives a list of the parameter values used in the simulations.

Results. The simulation results are shown in Table 2. Output is expressed in terms of five variables: mean annual catch, mean abundance of *S. mentella* and *S. fasciatus*, and percent of years in which the abundance of each species was less than 20% of the mean unexploited abundance, which we call the "risk level". The 20% rule was used as a threshold below which recruitment declines might be expected to occur (Beddington and Cooke, 1983). A sample time series is shown in Fig. 3.

TABLE 1. Values used in simulations.

Total starting population size (Both species, all areas)	400
Years in simulation	100
Annual exploitation rate	0.1
Recruitment values (millions)	3,3,5,8,10,11,13,14,14,17,17,32,38,40,42,49
Lifespan of both species	50 years
Age at recruitment ot the fishery	6 years

Movement rates between areas: movement into the area indicated

	Summer		Winter	
	S. mentella	*S. fasciatus*	*S. mentella*	*S.* fasciatus
Shallow upper area	0.35	0.10	0.00	0.00
Deep upper area	0.35	0.00	0.00	0.00
Shallow lower area	0.00	0.50	0.00	0.00
Deep lower area	0.30	0.40	1.00	1.00

TABLE 2. Results of Simulation Experiment I.

Fishing pattern	Mean annual catch	Mean abundance		Risk level	
		S. mentella	*S. fasciatus*	*S. mentella*	*S. fasciatus*
Both seasons, whole region	33.09	161.30	161.30	0.00	0.00
Both seasons, upper area	37.23	0.24	370.72	1.00	0.00
Both seasons, lower area	32.51	158.51	158.51	0.02	0.02
Winter, whole region	30.01	146.32	146.32	0.00	0.00
Winter, upper area	0.00	300.08	300.08	0.00	0.00
Winter, lower area	30.43	148.35	148.35	0.00	0.00
Summer, whole region	32.70	210.39	108.46	0.00	0.16
Summer, upper area	32.28	0.18	321.52	1.00	0.00
Summer, lower area	29.90	216.74	74.78	0.00	0.56

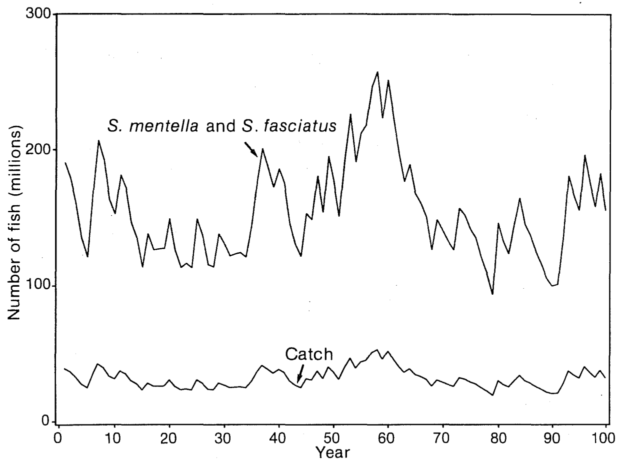

Fig. 3. Sample run from Simulation Experiment I: Fishing in winter and summer and in whole area.

The variability in the time series was due to the random selection of recruitment from the observed values for Subdiv. 3Ps (Table 1).

The results (Table 2) indicate that all spatial and temporal distributions of fishing produced approximately the same level of long-term catches, except when fishing was restricted to the upper area in winter. In this latter case there was no harvest because there were no fish there (Fig. 2). Although the different spatial and temporal distributions of fishing resulted in similar catches, their impacts on the two species were markedly different. When fishing occurred in both winter and summer and fishing was allowed to take place in either the whole region or the lower area only, most or all of the harvest occurred in winter because the fishing season begins in winter (see model description). In this case the two species were equally exploited (Fig. 2), so their long-term abundance were identical. However, if fishing was restricted to the upper area and occurred either in both seasons or only in the summer (these are equivalent, see Fig. 2) then the pressure was much greater on *S. mentella* than on *S. fasciatus* (Fig. 2), so *S. mentella* had a much lower long-term abundance. On the other hand, when fishing was restricted to the lower area in summer then the fishing pressure on *S. fasciatus* was greater than on *S. mentella* and the abundance of *S. fasciatus* was lower. The effect was not as great as in the case of the upper area because in the summer the relative amount of *S. mentella* in the upper area (0.88) was greater than that of *S. fasciatus* in the lower area (0.75) (Table 1).

Simulation Experiment II

Unequal relative abundance, synchronous and asynchronous recruitment and parameter variability. As described earlier, two of the main aspects of uncertainty in the redfish populations are the current relative abundance of the two species, and whether recruitment levels in the two species are synchronous or asynchronous. In conducting simulations to examine the consequences of these uncertainties, we felt it was important to compare the potential impacts of the uncertainty to the impact of the inter-annual variability in population parameters. Since we do not know the actual level of this variability, we conducted simulations over a range of values. Therefore, the goal of the second simulation experiment was to examine the consequences of different spatial and temporal patterns of fishing, with different values for the relative abundances of the two species, synchronous *vs* asynchronous recruitment, and different levels of inter-annual variability in the parameters controlling population dynamics and movement in the model. The parameter variability was applied by selecting the survival rates, recruitment rates, and between-area movement rates from normal distributions; the variability was modified by modifying the coefficient of variation (CV). The same CV was used for all random variables within a simulation. The design of the simulation experiment is shown in Table 3. A total of 1,800 runs was conducted. This included 100 runs, each with different randomly chosen values of relative abundance of *S. mentella* (relative to *S. fasciatus*) ranging from 0 to 1, and CV ranging from 0 to 0.5, for each of the 18 combinations of temporal fishing patterns, spatial fishing patterns and recruitment synchrony (Table 3). As in experiment I,

TABLE 3. Design of Simulation Experiment II.

Fishing season	1. Both seasons (winter and summer) 2. Winter only 3. Summer only
Fishing area	1. Whole region (upper and lower) 2. Upper area only 3. Lower area only
Recruitment	1. Asynchronous 2. Synchronous
Relative abundance of *S. mentella*	Random number between 0 and 1 for 100 runs
CV of parameters — recruitment, mortality, movement	Random number between 0 and 0.5 for 100 runs

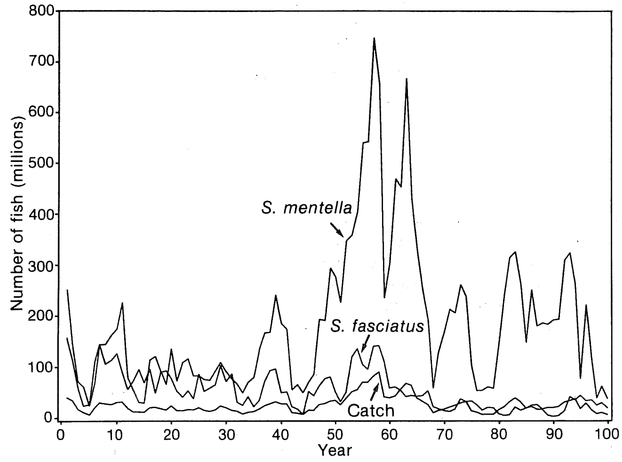

Fig. 4. Sample run from Simulation Experiment II: Fishing in winter and summer and in whole area, CV of parameters = 0.3.

each simulation was conducted for 100 years and the final 50 years' output were analyzed. A sample time series is shown in Fig. 4.

Analyses. The results of the simulations were analyzed in terms of five output values; mean annual catch, mean abundance of each species, and percent of years in which the abundance of each species was less than 20% of the unexploited abundance (risk level). The goal of the analysis was to quantify the relative effects of temporal fishing pattern, spatial fishing pattern, relative abundance, recruitment synchrony/asynchrony, and CV on the output values. A discussion of the general approach to analyses of this type of simulated data is in Fahrig (1991). The first step in the analysis was to replace the two quantitative input parameters, relative abundance and CV, with new parameters that reflect the shapes of the underlying curves relating the input parameters to the output values. These new parameters were determined by conducting stepwise polynomial regressions (using procedure GLM in SAS, 1985a) for each of the output values on each of relative abundance and CV. The polynomial equations are shown in Table 4. The second step of the analysis was to conduct an analysis of variance (using procedure GLM in SAS, 1985a) in which the effects of the new parameters (i.e. the polynomial equations for relative abundance and CV) and the class variables recruitment synchrony/asynchrony, spatial fishing pattern and temporal fishing pattern are included in the same analysis. A separate analysis was conducted for each of the output values.

Results. The results of the analyses are shown in Table 5. Temporal fishing pattern, spatial fishing pattern, CV and relative abundance had significant effects on all five output values. Recruitment synchrony/asynchrony did not have a significant effect on any of the output values. The most important parameter affecting long-term catches in this system was the amount of variability in the parameters controlling the population dynamics and movement (CV). In general, the larger the CV, the lower the expected catch rate. CV was also extremely important in determining the risk levels for both species; the higher the CV, the higher the risk level. Although both spatial and temporal patterns of fishing affected the output values, in all cases the spatial distribution of fishing had a larger effect than the temporal distribution. In fact, for the risk level of *S. mentella*, the spatial distribution of fishing had the largest impact of all independent variables. The largest factor affecting the long-term population levels of the two species was the relative abundance of that species at the start of the simulation.

The relationships between the output values of mean catch and risk levels, and the input parameters CV and relative abundance, were plotted as surface plots for all nine spatio-temporal patterns of fishing (i.e. 27 plots, Fig. 5–13). The following observations can be made from the plots:

i) Mean annual catch is relatively insensitive to changes in relative abundance (e.g. Fig. 6a, 7a, 10a, 11a).

ii) In general catch decreases with increasing CV (e.g. Fig. 7a, 8a, 10a, 13a). An exception to this is

TABLE 4. Polynomial equations relating independent and dependent variables: separate equation for each pair of variables.

Dependent variable	Independent variable	Polynomial equation
Mean annual catch (*H*)	Relative abundance *S. mentella* (*RA*)	$H = 22.6 + 2.27RA$
	Parameter CV (*CV*)	$H = 29.1 - 21.0CV$
Mean abundance of *S. mentella* (*NSM*)	Relative abundance *S. mentella* (*RA*)	$NSM = 166 - 282RA + 2.27RA^2$
	Parameter CV (*CV*)	$NSM = 23.0 + 450CV - 904CV^2 + 678CV^3$
Mean abundance of *S. fasciatus* (*NSF*)	Relative abundance *S. mentella* (*RA*)	$NSF = 187 - 159RA$
	Parameter CV (*CV*)	$NSF = 228 - 383CV + 777CV^2 - 593CV$
Risk level for *S. mentella* (*RSM*)	Relative abundance *S. mentella* (*RA*)	$RSM = 0.243 + 0.895RA$
	Parameter CV (*CV*)	$RSM = 0.435 - 0.586CV + 2.48CV^2 - 2.00CV^3$
Risk level for *S. fasciatus* (*RSF*)	Relative abundance *S. mentella* (*RA*)	$RSF = 0.131 + 0.972RA$
	Parameter CV (*CV*)	$RSF = 0.428 + 0.445CV - 1.73RA^2 + 1.20RA^3$

TABLE 5. Analyses of variance of results of Simulation Experiment II. *SEAS* = seasonal fishing pattern (winter, summer or both seasons). *AREA* = regional fishing pattern (upper area, lower area or whole region). *SYN* = recruitment synchrony/asynchrony in the two species. *RA* = polynomial value relating the dependent variable to relative abundance of *S. mentella* (see Table 4). *CV* = polynomial value relating the dependent variable to the CV value used for parameter variability (see Table 4).

Source	Degree freedom	Type III SS	Mean square	F value	Prob.>F
		1. Dependent variable: mean annual catch			
SEAS	2	11,300.00	5,630.00	146.6	0.0001
AREA	2	19,400.00	9,676.03	251.7	0.0001
SYN	1	8.68	8.68	0.2	0.6348
RA	1	600.00	600.00	15.6	0.0001
CV	1	17,800.00	17,800.00	462.8	0.0001
		2. Dependent variable: mean abundance of *S. mentella*			
SEAS	2	496,000.00	248,000.00	41.5	0.0001
AREA	2	3,020,000.00	1,510,000.0	253.0	0.0001
SYN	1	2,390.00	2,390.00	0.4	0.5273
RA	1	3,940,000.00	3,940,000.00	659.2	0.0001
CV	1	651,000.00	651,000.00	109.0	0.0001
		3. Dependent variable: mean abundance of *S. fasciatus*			
SEAS	2	257,000.00	128,000.00	22.9	0.0001
AREA	2	6,530,000.00	3,260,000.00	582.0	0.0001
SYN	1	5.58	5.58	0.00	0.9748
RA	1	3,640,000.00	3,640,000.00	649.6	0.0001
CV	1	1,120,000.00	1,120,000.00	200.7	0.0001
		4. Dependent variable: risk level for *S. mentella*			
SEAS	2	8.39	4.20	48.8	0.0001
AREA	2	94.3	47.1	548.2	0.0001
SYN	1	0.02	0.02	0.2	0.6527
RA	1	4.28	4.28	49.8	0.0001
CV	1	29.24	29.24	340.1	0.0001
		5. Dependent variable: risk level for *S. fasciatus*			
SEAS	2	5.64	2.82	33.8	0.0001
AREA	2	42.42	21.21	253.9	0.0001
SYN	1	0.12	0.12	1.4	0.2379
RA	1	3.03	3.03	36.2	0.0001
CV	1	33.52	33.52	401.2	0.0001

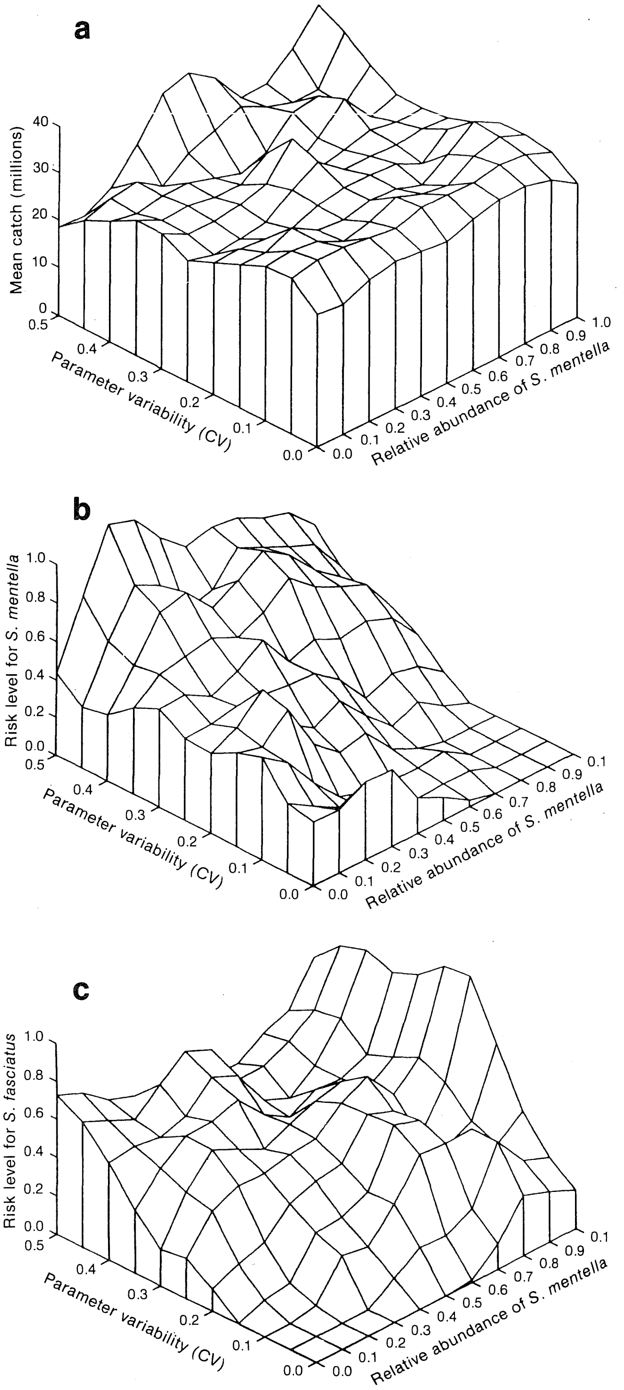

Fig. 5. Output from Simulation Experiment II, where fishing patterns are winter and summer, and over whole region. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

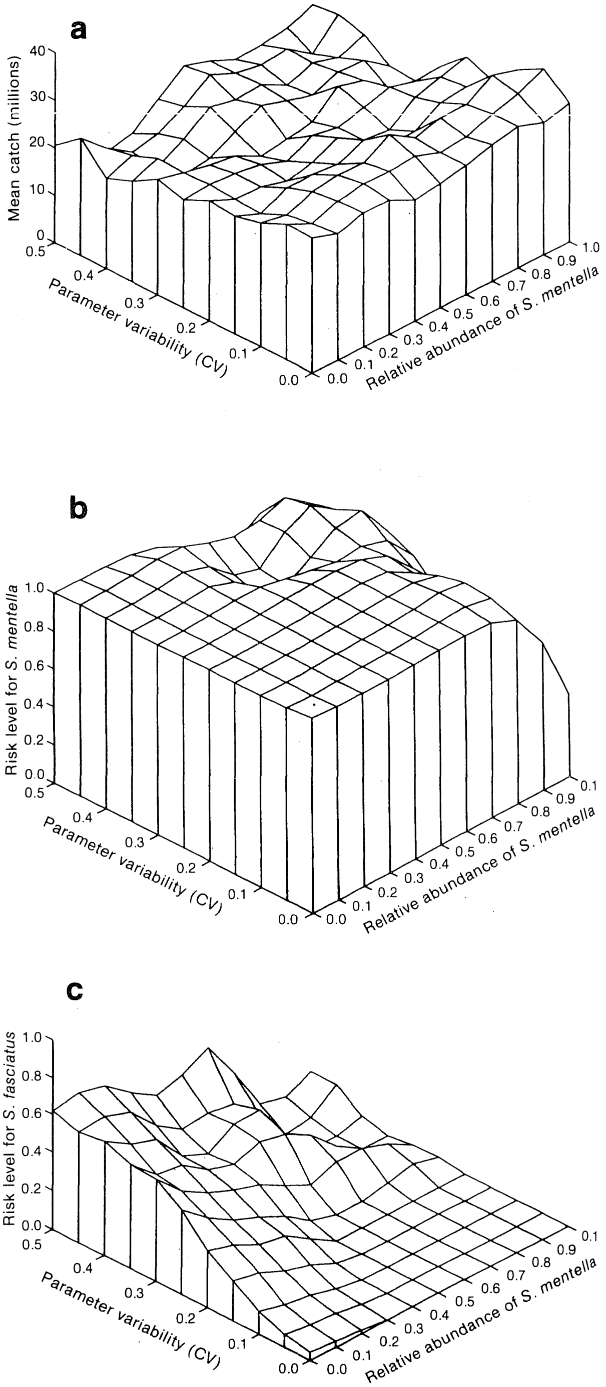

Fig. 6. Output from Simulation Experiment II, where fishing patterns are winter and summer, and over upper area only. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

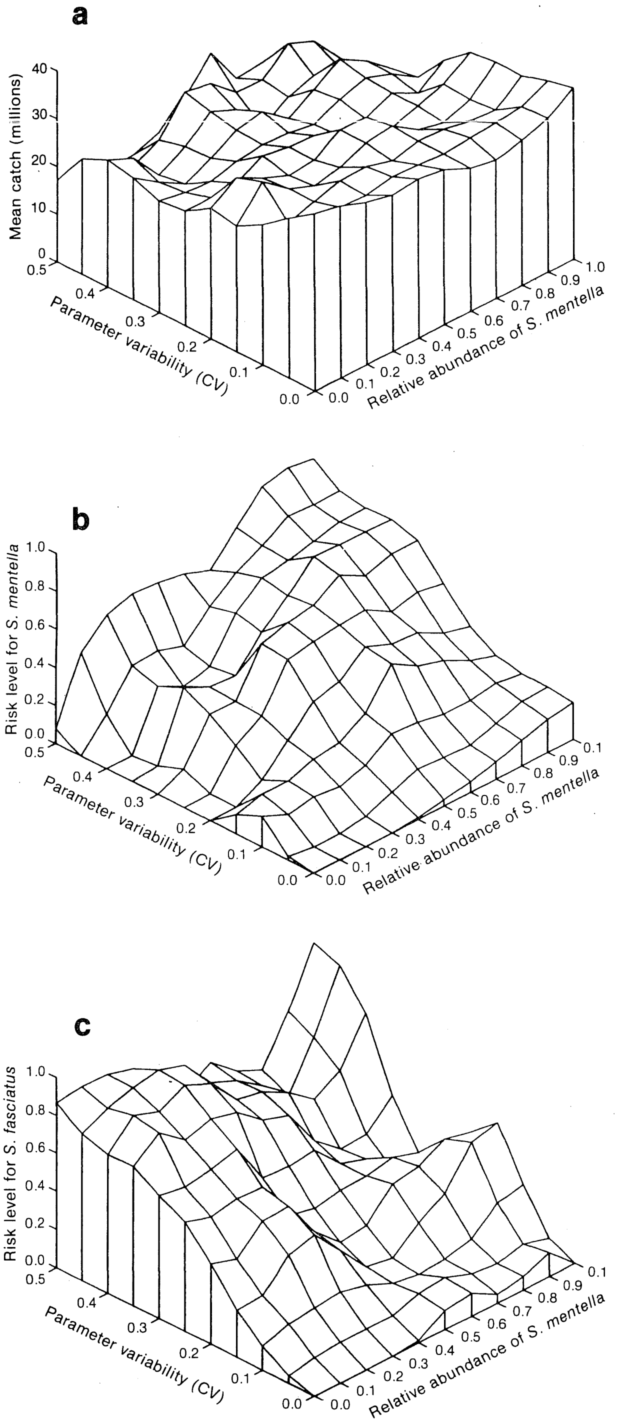

Fig. 7. Output from Simulation Experiment II, where fishing patterns are winter and summer, and over lower area only. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

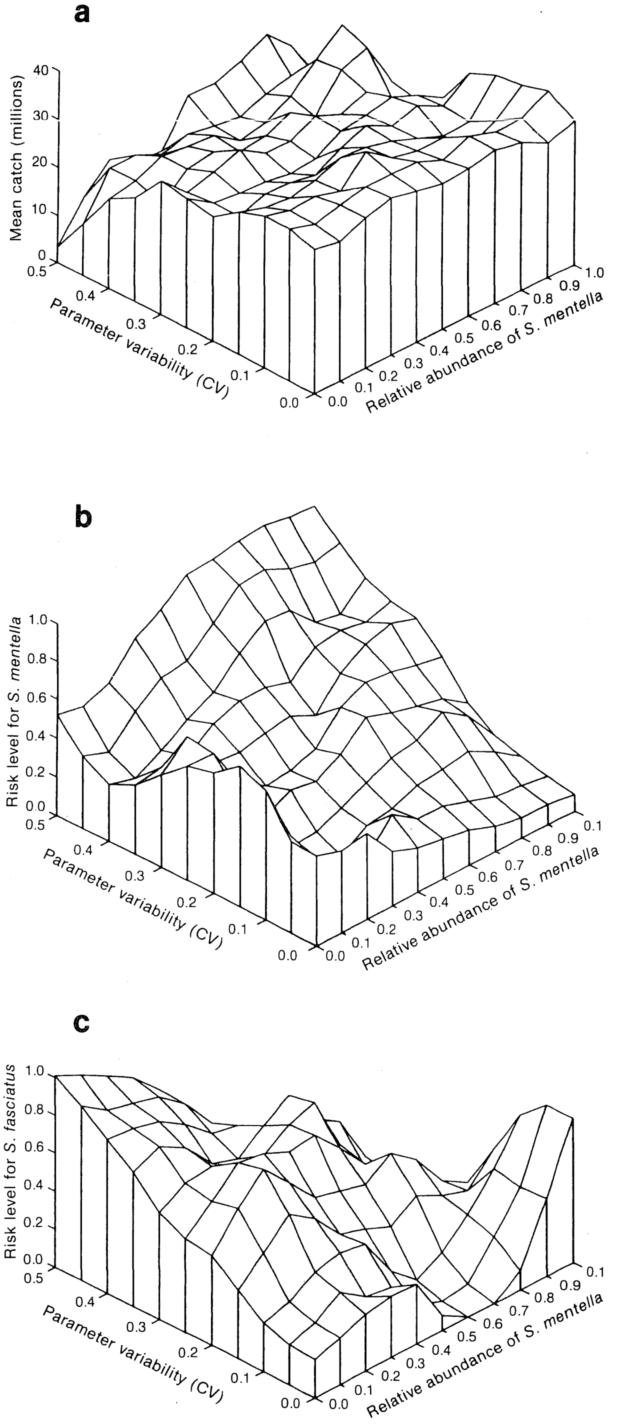

Fig. 8. Output from Simulation Experiment II, where fishing patterns are winter only, and over whole region. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

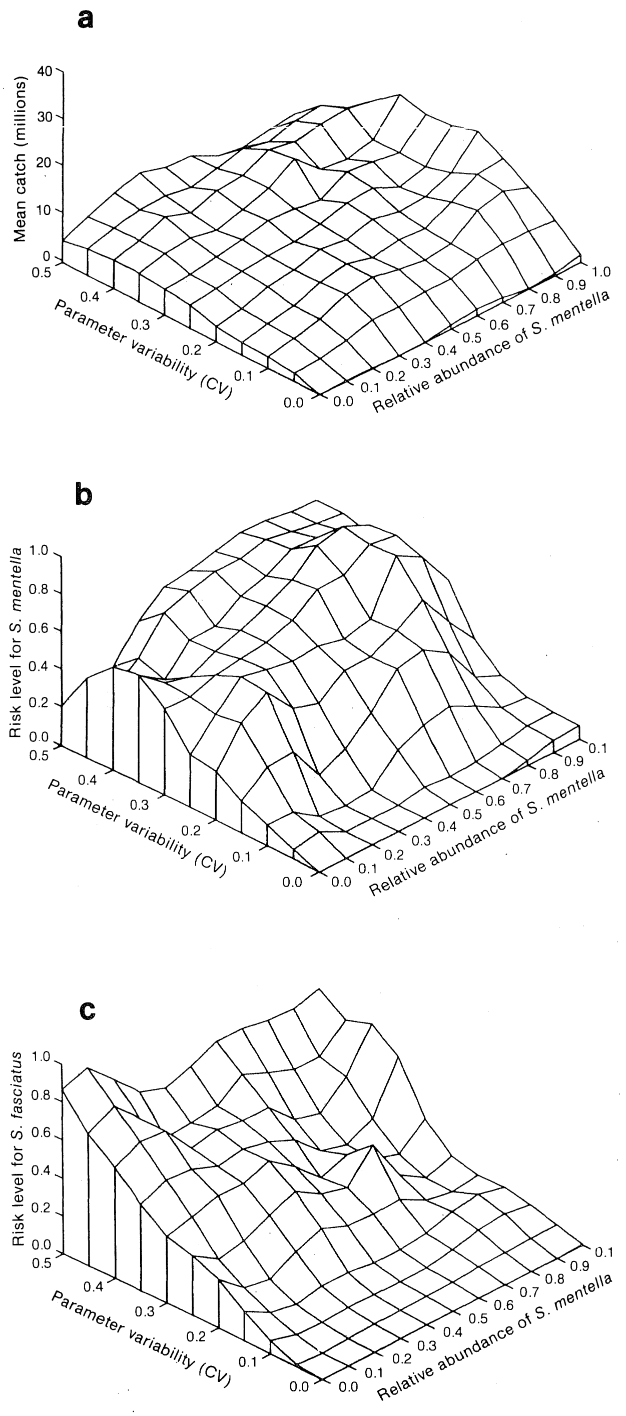

Fig. 9. Output from Simulation Experiment II, where fishing patterns are winter only, and over upper area only. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*, frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

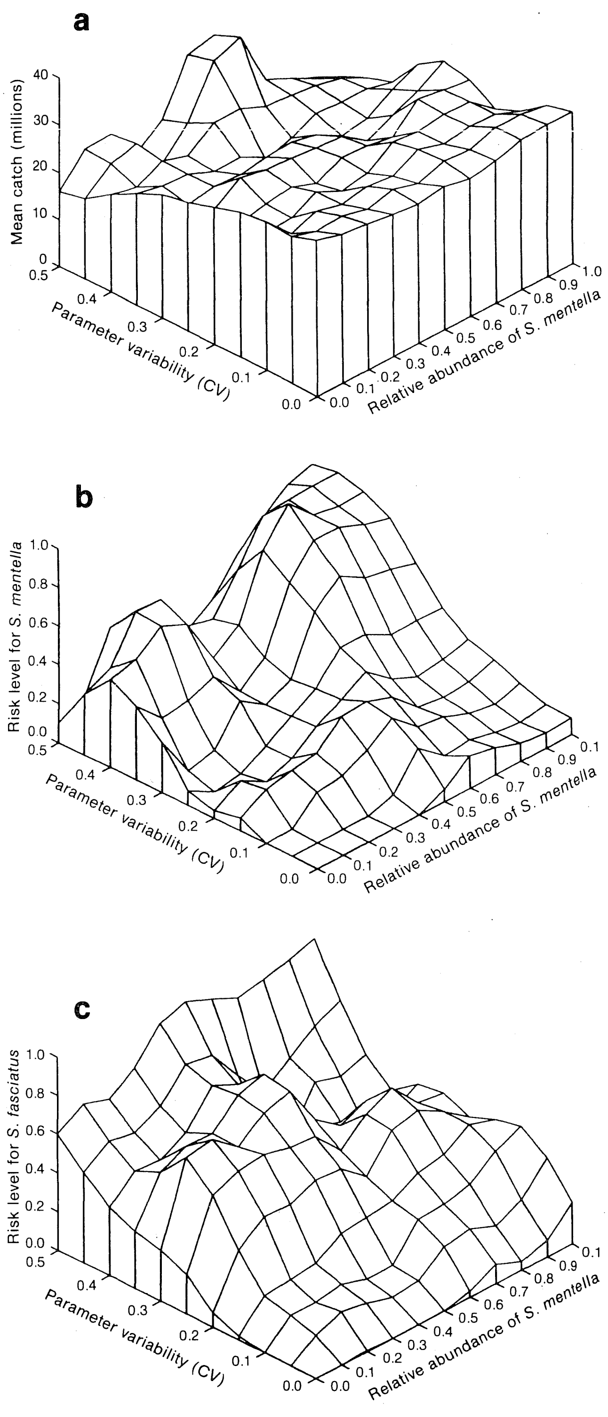

Fig. 10. Output from Simulation Experiment II, where fishing patterns are winter only, and over lower area only. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

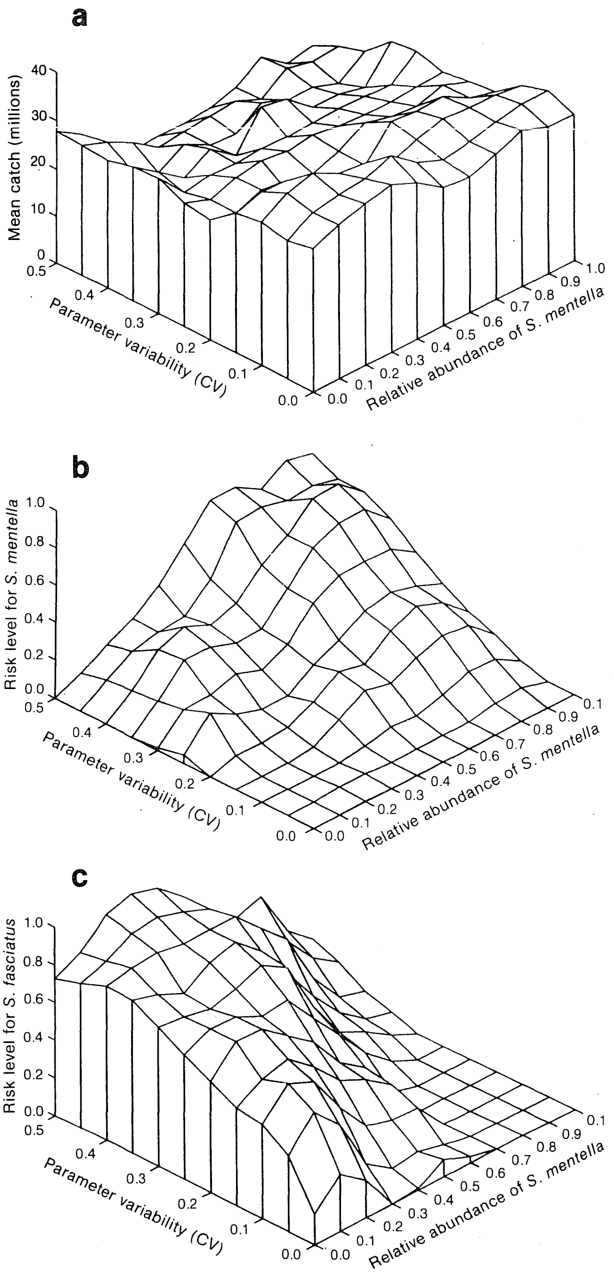

Fig. 11. Output from Simulation Experiment II, where fishing patterns are summer only, and over whole region. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

when fishing is permitted only in the upper area in the winter (Fig. 9a). In this case, the only fish available to the fishery are due to random spill-over of fish from the lower area. The amount of spill-over generally increases with increasing variability in movement rates (i.e. increasing CV).

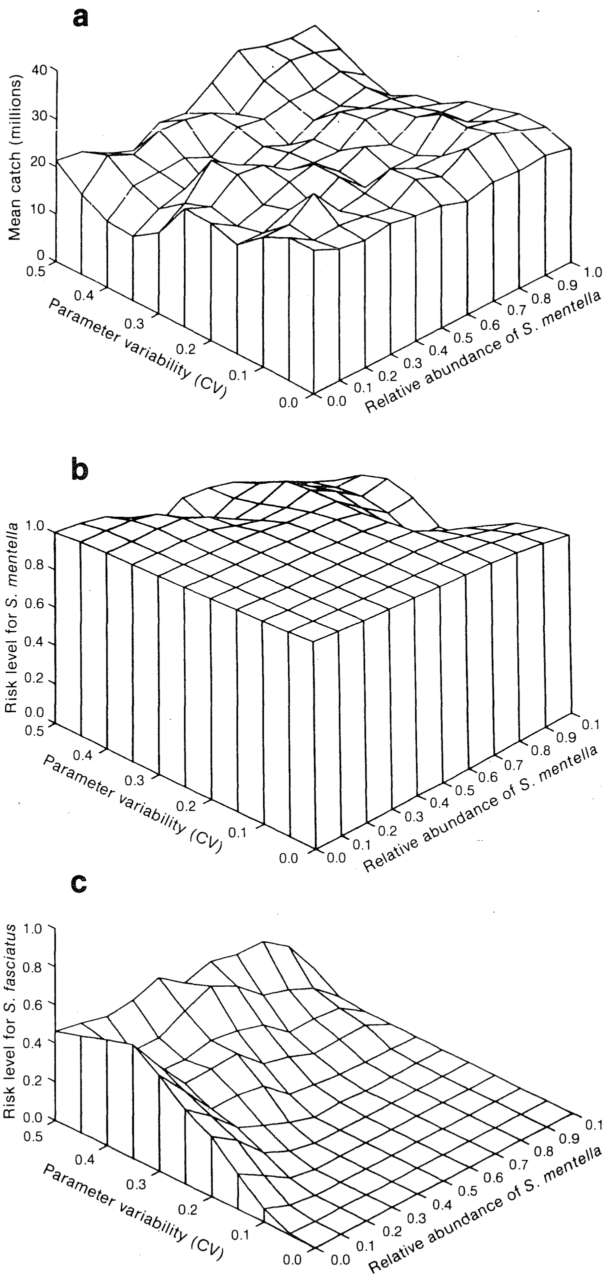

Fig. 12. Output from Simulation Experiment II, where fishing patterns are summer only, and over upper area only. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

iii) Risk levels for the two species increase with increasing CV (e.g. Fig. 5b,c, 6c, 7b,c, 10b,c, 11b,c, 12c, 13b,c), with the following exception:

When fishing is predominantly on *S. mentella* and the relative abundance of *S. mentella* is high, the

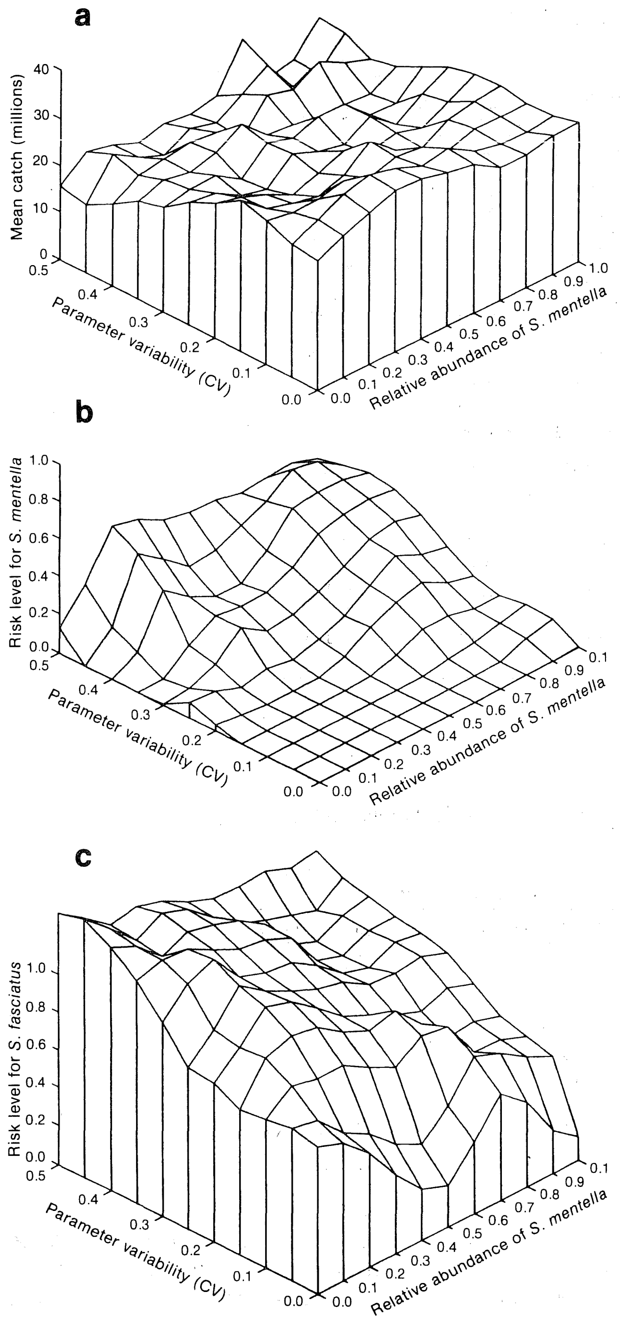

Fig. 13. Output from Simulation Experiment II, where fishing patterns are summer only, and over lower area only. The independent variables are parameter variability (CV) and relative abundance of *S. mentella*. The dependent variables are: frame (**a**) mean catch in millions of fish; frame (**b**) risk level for *S. mentella*; frame (**c**) risk level for *S. fasciatus*. Risk level is as defined in the text.

risk level for *S. mentella* decreases with increasing CV. This is the case for fishing distributions of summer only, upper area only (Fig. 12b) and winter and summer, upper area only (Fig. 6b). Note that these are nearly the same since there are very few fish in the upper area in winter.

iv) As the relative abundance of *S. mentella* increases, the risk level for *S. mentella* also increases (Fig. 7b, 8b, 9b, 10b, 11b, 13b), with the following exception:

When fishing is predominantly on *S. mentella*, the risk level for *S. mentella* decreases with increasing relative abundance of *S. mentella*. This is the case for fishing distributions of summer only, upper area only (Fig. 12b), winter and summer, upper area only (Fig. 6b). Again, these are almost the same since there are very few fish in the upper area in winter.

v) As the relative abundance of *S. mentella* increases, the risk level for *S. fasciatus* decreases (Fig. 6c, 11c, 12c, 13c).

The final stage in the analysis was aimed at identifying fishing patterns that would result in the least risk to the two species. To compare the nine patterns two scenarios were chosen, one with high relative abundance of *S. fasciatus* (relative abundance of *S. mentella* at 0.1) and the other with high relative abundance of *S. mentella* (0.9). Using the gridded values output from the G3GRID procedure (SAS, 1985b), the risk levels were averaged across CV values. The results are shown in Table 6. Note that the fifth pattern, when fishing was only in the winter in the upper area, was not a realistic option because in this case the catches were extremely low because there were almost no fish present.

The lowest risk fishing pattern was one that had the lowest annual probability that at least one species goes below the 20% level. These values are shown in Table 7 for the two scenarios of high and low relative abundance of *S. mentella*. The results suggest:

i) Fishing only in winter is generally less risky than fishing only in summer or in both seasons.

ii) Spreading the catch over the whole region is generally less risky than restricting the catch to either the upper or lower area.

iii) If fishing is carried out in both seasons or summer only, and the relative abundance of *S. mentella* is low, it is important to fish in the lower area or in both the upper and lower areas, but not in the upper area only.

iv) If fishing is carried out in both seasons or summer only, and the relative abundance of *S. mentella* is high, fishing should be spread over the entire region.

Discussion

The results of these simulations indicate that the spatio-temporal distribution of fishing in the Gulf of St. Lawrence and off the south coast of Newfoundland can have a large impact on the probability of survival of *S.*

TABLE 6. Mean values of catch and risk levels at low (0.1) and high (0.9) relative abundance values of *S. mentella*.

Fishing season	Fishing area	Mean catch	Risk for *S. mentella*	Risk for *S. fasciatus*
	1. Low relative abundance of *S. mentella*			
Winter and summer	Whole region	25.61	0.316	0.434
Winter and summer	Upper area	24.36	0.997	0.318
Winter and summer	Lower area	26.73	0.372	0.378
Winter	Whole region	23.91	0.479	0.305
Winter	Upper area	4.8	0.504	0.272
Winter	Lower area	24.84	0.102	0.461
Summer	Whole region	26.16	0.218	0.577
Summer	Upper area	25.07	0.990	0.150
Summer	Lower area	28.52	0.009	0.587
	2. Low relative abundance of *S. fasciatus*			
Winter and summer	Whole region	27.00	0.373	0.248
Winter and summer	Upper area	28.07	0.627	0.090
Winter and summer	Lower area	25.35	0.296	0.613
Winter	Whole region	29.34	0.298	0.439
Winter	Upper area	8.8	0.470	0.073
Winter	Lower area	24.89	0.411	0.260
Summer	Whole region	24.33	0.527	0.055
Summer	Upper area	23.89	0.890	0.000
Summer	Lower area	22.96	0.300	0.852

TABLE 7. Probability per year that at least one of the two species falls below 20% of the mean unexploited abundance (*PR*).

Fishing season	Fishing area	Relative abundance: *PR* at low *S. mentella*	Relative abundance: *PR* at high *S. mentella*
Winter and summer	Whole region	0.613	0.528
Winter and summer	Upper area	0.998	0.660
Winter and summer	Lower area	0.609	0.728
Winter	Whole region	0.638	0.607
Winter	Upper area	0.639	0.509
Winter	Lower area	0.516	0.564
Summer	Whole region	0.669	0.553
Summer	Upper area	0.991	0.890
Summer	Lower area	0.591	0.897

mentella and *S. fasciatus*, because the distributions of the two species are not congruent over the region and between seasons. In fact, the spatial distribution of fishing had the largest effect on the risk level for *S. mentella*. Any simulations that restricted fishing to the upper area had a much larger impact on *S. mentella* since most of the fish there were *S. mentella* (Fig. 2). The simulations suggest that, in our present state of uncertainty with respect to the relative abundance of the two species, the least risky fishing pattern would be to restrict fishing to the winter season when the bulk of both species is apparently in the lower area. When better information on the relative abundance of the two species is available, simulations can be run to find the best fishing pattern for the relative abundance level.

Several assumptions of the model are critical to the results. The first relates to the spatial and temporal distributions of the two species. The conclusions drawn on the effects of different fishing patterns depend to a large extent on our assumptions about the distributions of the fish themselves. To test these assumptions, estimates of the relative abundance of the two species in both winter and summer over the whole region are needed. The results also rely heavily on the assumption that the relative recruitments of the two species are proportional to the relative abundances of the parent stocks. This assumption cannot be tested at present because several years of estimates would be required of the relative abundances of the two species in the recruiting population (age 6) as well as in the whole adult population 6 years previous. Also, it was assumed that there was no relationship between absolute stock size and recruitment. This means that the simulations were probably optimistic in terms of the long-term population sizes of the two species. If there were a positive relationship between stock size and recruitment, then simulations in which there was a high risk of dipping below the 20% unexploited stock level should actually have even lower long-term abundances than those calculated.

There are also assumptions concerning the behaviour of the fishery that may be critical. First, the assumption that fishing is concentrated in the winter, even if it is permitted in both seasons, may affect the results. There is some indication that this may be a reasonable assumption for Div. 3P (Atkinson and Power, MS 1989). The assumption that the fishery concentrates in the areas with the greatest abundance of fish is also important, and here too we feel the assumption is probably realistic.

The result that the expected catch rate decreases with increasing CV is consistent with the general observation that the most probable rate of growth of a population that is subject to fluctuations is lower than that of one not subject to fluctuations. For a recent review of this idea see Harwood and Hall (1990).

We initially expected that the simulations that assumed recruitment synchrony would produce lower catch rates than those in which we used asynchronous recruitment, since synchronous recruitment means that the total recruitment of both species combined is more variable than if the two recruitment series are independent. However, this difference in variability did not show up as a significant effect on catch rates; the effect was small relative to the effect of CV in the parameters.

The simulations presented here demonstrate the importance of spatial and temporal heterogeneity in species and stock distributions for management of a mixed stock (or mixed species) fishery. This problem has long been recognized for salmon fisheries in which the fishery on a single river is often a mixed stock fishery with a different stock from each of many tributaries (Gould and Stefanson, 1985; Sprout and Kadowaki, 1987). The scale of spatio-temporal subdivision we have chosen for the redfish study is much coarser, however, it is likely that the stock structures of redfish, and indeed of many marine species, are more complex than presently recognized, possibly as complex as the structure of salmon. Development of general principles for management of mixed stock fisheries is therefore critical; these principles must be robust to the uncertainties regarding stock structure because such uncertainties are certain to persist.

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