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Proposals for redfish fishery regulation with randomized recruitment in the Flemish Cap Bank area

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Abstract

The object of the study is redfish species of the Flemish Cap Bank in NAFO Div.3M, the Northwest Atlantic statistical area. The aim of the work is to develop proposals for a management strategy for the redfish fishery allowing for the precautionary approach, based on the population dynamics model, with a random choice of the stock recruitment size.

It is shown that the main cause of stock variations in Div. 3M (along with fishery) is change in the recruitment abundance (redfish abundance at the age of 4). The redfish fishery management strategy should be based on maintaining spawning stock at the level of 35-40 x 10^3t. It is recommended to set the exploitation rate (fishing mortality) in the range of biological reference points from F_{msy} to F_{max} (0.08-0.20) depending on the recruitment abundance variation. With such exploitation, the long-term average annual catch can be from 10 to 16 x 10^3t, and the stock of redfish species will be within biological safe limits. The analysis can be used to determine the strategy for the exploitation of the redfish stock on the Flemish Cap Bank in the long term, the grounds for an increase in the TAC (total allowable catch) for 2019-2020, 10.5 x 10^3 t and the possibility of further increasing the yield to 12-16 x 10^3t .

Key words: REDFISH SPECIES, STOCK, ABUNDANCE, MODELLING, PARAMETERS, FISHING MORTALITY, FISHERY MANAGEMENT.

Introduction

Three redfish species including beaked redfish *Sebastes mentella*, golden redfish *Sebastes marinus* and *Sebastes fasciatus* are the fishery objects in the Flemish Cap area. For the purposes of fishery regulation, they are considered as a single redfish stock on the Flemish Cap Bank. According to the results of morphometric analysis, three redfish species are independent stocks. However, the difficulties of separating by appearance in the catches make us considering all three species as a single stock when estimating abundance.

Due to high external similarity of *S. mentella* and *S. fasciatus,* they are considered as the same species "beaked redfish" which dominates in the catches, accounting for more than 80% of the total catch, and therefore the stock assessment is carried out for the beaked redfish.

Intensive unregulated fishing in the 1980s and in the early 1990s (more than 30-40 x 10^3 t were caught annually) resulted in the depression of the redfish stock on the Flemish Cap Bank. From 1994 to 2004, the spawning biomass of the beaked redfish did not exceed 10 x 10^3 t. The depressive state of the stock was also caused by poor recruitment. First, a complete ban on fishing, then the establishment of low total allowable catch (TAC), as well as the appearance of strong and average abundance year-classes of 2002-2006 contributed to the recovery of the redfish stock by 2012. In recent years (2012-2017), spawning biomass of the redfish species is more than 50 x10^3 t. At the present stage, the goal of regulating the fishery is to maintain the spawning stock at the current high level.

Material and methods

Statistical data from international fisheries for redfish on the Flemish Cap Bank for 1989-2016 are derived from NAFO databases on STATLANT 21A and STATLANT 21B fishing statistics.

The biomass and abundance indices, the size and age composition of catches, the average weight of individuals by age, the maturation ogives are taken from the working papers submitted to the annual meetings of the NAFO Scientific Council, from the annual reports of the Scientific Council and the reports on the results of the bottom stratified trawl surveys of the EU.

The redfish abundance dynamics was estimated according to the XSA model (Darby, 1994) and the modified fishery management model (with optimization and forecast) (Korzhev V, Pochtar M, 2017). To estimate the abundance of the recruitment, the Beverton-Holt "stock-recruitment" relationship was used (Ricker, 1979).

To adjust the XSA method, the results of annual stratified bottom trawl surveys conducted by the EU since 1989 were used.

Results and discussion

The model of fishery optimization

Optimization (forecasting) of the stock state is carried out using the same relationships as when restoring a retrospective of the stock dynamics (Darby, 1994). In forecasting, these relationships are used to sequentially calculate the parameters of year-classes from younger to older, i.e. in the opposite direction. This allows us to estimate the changes in the abundance of year-classes, depending on the given level of fishing mortality.

The calculation of the stock in the starting year. It is assumed that at the starting point of the calculation, the population was in equilibrium. This condition is characterized by an estimate of recruitment and a population distribution by age according to the following equations:

$$N_1 = R_1, \qquad (1)$$

$$N_a = N_{a-1} \cdot \exp(-M_a),\; a = 2,3,...,m-1 \qquad (2)$$

$$N_m = \frac{N_{m-1} \cdot \exp(-M_m)}{1-\exp(-M_m)},\ \text{for}\ a = m. \qquad (3)$$

where Na is the abundance of individuals at age a,
Ma is the natural mortality rate for a.

Modelling of recruitment. The results of Russian and foreign studies carried out on the Flemish Cap Bank show that the beaked redfish is characterized by considerable variability in the year-class strength (Vaskov, 2002; Rikher and Bukatin, 2003). In the period from 1971 to 2014, in the Div.3M, strong year-classes of beaked redsfish appeared in 1969–1970, 1972–1973, 1989–1980, 1985–1986, 1989–1990, 1999–2000, and in 2001–2005. The year-classes of 2006-2010 estimated as poor, and those ones of 2011-2014 were preliminary estimated to be very poor. No specific patterns in the change of the size of recruitment for the period of research and fishing have been noticed. There is a hypothesis that the cause of fluctuations in the yield of year-classes of benthic fish on the Flemish Cap Bank is related to the circulation of water in this region. However, there were no found significant links between the strength of year-classes and certain environmental factors (temperature and salinity of water at different depths, the index of the North Atlantic Oscillation, etc.) for the beaked redfish. The use of a constant recruitment for the entire forecast period, considered earlier (Korzhev V, Pochtar M, 2017) simplifies the forecasting procedure, assuming the stock is independent from the recruitment, but it does not take into account one of the main factors of stock variation.

As a consequence, the following recruitment modelling procedure is considered. A constant recruitment equal to the average long-term value of the known recruitment values for the years 1989-2015 is set for the first three years (the age of recruitment is 4 years) of the forecast. According to estimates of the stock of the beaked redfish in 1989-2015 (calculated by XSA) the classical "stock-recruitment" relationship is set according to the Beverton – Holt equation (Ricker, 1979):

$$R_{t+3} = \frac{1}{\alpha+\beta/SSB_t}, \text{ t = 1, 2, 3, … .. (4)}$$

where Rt is the abundance of recruitment in the *t*-year, 10^3 ind.;
SSBt - spawning biomass in the *t*-year, t;
α and β are parameters.

The value of the modelled recruitment (R model) is calculated for each year of the estimated period (1989-2015), according to equation (4). Then, an array of deviations (δ) of actual recruitment from simulated one (δ = Ln (Rfact. / R model)) is formed. The value of the recruitment is determined for each forecast year, starting with the fourth (i + 3), using formula (4) per *t*-year , when randomly choosing the deviation δi from the array of deviations created δ: R = R model. * exp (δ rand.). Naturally, with such a prediction of the beaked redfish stocks 100 years ahead, the actual distribution of recruitment for these years cannot be obtained. However, given the random pattern of the choice of deviations both rich and poor recruitment will be obtained during the forecast period. In this case, using the stochastic approach, one can get a set of values of the stock parameters in each year of the forecast. With a great number of iterations, the most probable state of the stock parameters (mathematical expectation) and their confidence intervals can be estimated.

<u>Modelling the average weight of redfish by age.</u> Analysis of variation in the average weight of redfish in the catches on the Flemish Cap Bank for 1960-2016 showed that at the beginning of the fishery, when the stock of the beaked redfish was in a healthy state, the average weight of the same age redfish varied slightly, and fluctuated relative to their mean value without visible patterns. In the period of decline in the stock of the beaked redfish from 1989 to 2004, there are significant trends in the decrease in the average weight of the same age fish in time for all age classes in varying degree. The EU survey results show the same trends for the redfish average weight in the stock. After the recovery of the biomass of the beaked redfish stock, in the period 2010-2016, the average weight of the beaked redfish remains relatively stable over time. Optimization of the fishery involves maintaining the spawning stock at a stable (as far as possible), high level. Therefore, it is supposed to consider acceptable to set the weight of individual constant in each age group, equal to the mean long-term value for a period of relatively stable stock status in 2010-2016 for the forecast period .

Maturation ogive. To predict the proportion of maturation of the beaked redfish individuals by age, the maturation ogives used by the NAFO redfish experts in assessing the redfish stock for 1989-2016 were analyzed. (A, Ávila de Melo and others, 2011). In most years, maturation ogives have large differences among themselves. To analyze the maturation change of the same age individuals, the average values for the three periods of the fishery were used including 1958-2014, 1989-2014, 2003-2014 and their values were approximated by the maturation curve of the species:

$$Mat_a = \frac{b}{1+e^{-\lambda(a-a50\%)}} . \qquad (5)$$

where Mata is the proportion of mature fish at the age a;
a50% is the age of fish at which 50% of the individuals are mature;
λ and b are parameters.

The results of the approximation showed significant deviations between the averaged data for the entire period and the data for the period of the recovered stock (2003-2014). The issue of changing the rates of maturation of various year-classes of the beaked redfish on the Flemish Cap Bank is still poorly understood, therefore, when optimizing the fishery, a constant maturation period, equal to the average long-term value for 1989-2016 was used. The use of constant ogive in forecasting can lead, in our opinion, only to a change in the absolute values of the spawning stock, but it does not affect the trends in their dynamics.

The precautionary approach. The precautionary approach to sustainable fisheries is based on two concepts: the concept of sustainable development, and the precautionary principle. According to these concepts, the following tasks are solved: a) minimizing the risks associated with the possibility of damage to the exploited stock, b) taking measures in the event of a real danger to the state of the stock, c) taking into account the uncertainty (incomplete knowledge of the stock), d) restoring the exploited stocks at this level.

One of the principles of the precautionary approach is the zonal principle of fisheries regulation. The entire range of possible stock states (0, B∞) is divided into regions, for each of which a special regulation mode is established. In the paper the regulation scheme accepted in ICES is used. Three areas of stock for biomass are distinguished: a) the area of depleted stock (0, Blim), b) the area of stock recovery (Blim, Bpa), and c) the area of safe stock status (Bpa, B∞). In the area of the depleted stock, a complete cessation of fishing is assumed (fishing mortality is zero F = 0). When the stock is in the area of recovery, fishing mortality (and therefore the catch) is expected to increase in proportion to the ratio of SSB / Bpa. In the area of safe stock status, regulation is carried out by increasing fishing mortality to Fpa.

The analysis is performed on the basis of the version implemented with the help of two paired reference points: limit (Blim, Flim) and precautionary (Bpa, Fpa). The role of the biomass target serves as a precautionary reference point Bpa. The rule for managing the fishery and estimating the values of target and limiting biological reference points for the Flemish Cap redfish species are described in detail earlier (Korzhev V, Pochtar M, 2017). In this paper, the values of the biological reference points Blim and Bpa are assumed to be 20 and 40 thousand tons, respectively.

Optimization results. We will call the best fishery, in which the average spawning biomass of redfish will be maintained at the level of Bpa (40 thousand tons) and the probability of biomass reduction depending on the amount of recharge to Blim will be no more than 5% ($p < 0.05$) for a long period of time (for example, 100 years). In this case, the fishing regime (fishing mortality) should ensure the maximum possible catch. The target values of fishing mortality were several values of fishing mortality, including: FMSY = 0.08, F0.1 = 0.10, Fmax = 0.21. The optimization of the fishery was carried out in two stages.

At the first stage, the fishing mortality rates were determined, at which the greatest catch is observed. Calculations of the dynamics of the beaked redfish abundance with a fishing mortality of F equal to from 0.05 to 0.4 with a step of 0.02 were made. Moreover, despite the random selection of recruitment, calculations were performed once for each value of F. Given the uncertainty of recruitment, the results of the calculations do not represent a smooth curve, which is obtained with a constant recruitment, but a jagged curve, which is shown in Figure 1. Smoothing this moving average curve makes it possible to isolate the range of estimates of fishing mortality at which the greatest catch is obtained. In Figure 1, this is the range F 0.09–0.25. It is important to note that the curve of dependence of the catch on the fishing mortality has a flat, not clearly expressed maximum.

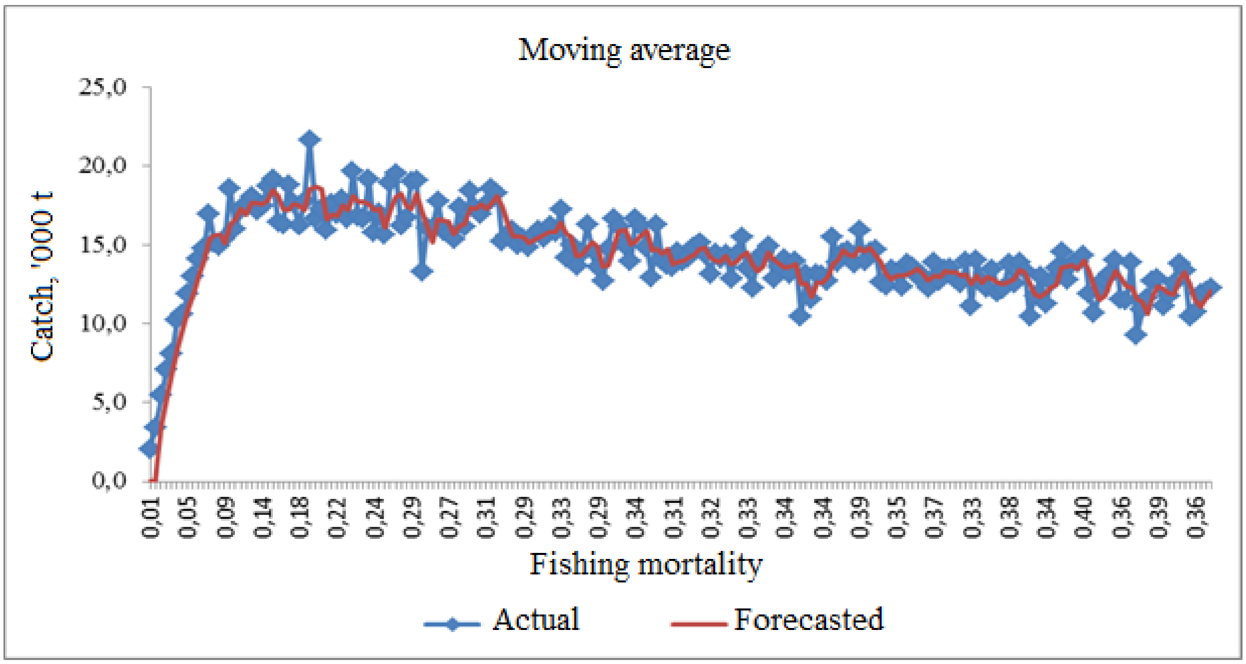

Figure 1. Dependence of redfish catch on the Flemish Cap Bank on fishing mortality with random stock recruitment

At the second stage, 100 iterations were performed with random recruitment to determine the optimal fishing mortality, the average values (mathematical expectations) and confidence intervals were calculated (percentile 0.05 and 0,95). Table 1 shows the values of the main parameters of the stock of the beaked redfish with confidence intervals.

Table 1. Changes in the basic stock parameters of the beaked redfish on the Flemish Cap Bank

Fishing mortality			Biomass, 10^3t			Spawning biomass, 10^3t			Catch, 10^3t		
L 0,05	Mean	U 0,95	L 0,05	Mean	U 0,95	L 0,05	Mean	U 0,95	L 0,05	Mean	U 0,95
0,075	0,076	0,076	210,8	240,6	273,1	107,0	126,2	145,5	13,5	15,5	17,5
0,091	0,092	0,093	197,9	219,3	253,2	96,6	110,5	130,6	14,8	16,5	19,0
0,109	0,110	0,110	174,6	202,6	229,8	81,6	97,3	112,9	15,0	17,3	19,0
0,126	0,128	0,128	165,0	192,2	216,1	72,9	88,1	101,9	15,7	18,3	20,9
0,144	0,146	0,147	152,8	174,9	198,0	64,7	76,5	20,9	16,0	18,3	20,9
0,159	0,164	0,165	138,9	160,3	181,5	55,1	66,0	77,8	15,5	18,2	20,7
0,171	**0,181**	**0,184**	**130,6**	**148,4**	**169,7**	**48,3**	**58,0**	**68,9**	**15,7**	**18,2**	**20,8**
0,142	**0,216**	**0,227**	**121,6**	**133,9**	**197,8**	**37,8**	**42,9**	**85,2**	**17,3**	**19,1**	**20,3**
0,240	0,252	0,265	111,4	116,1	121,8	31,7	33,0	34,5	17,1	18,4	19,9
0,285	0,298	0,313	91,7	96,1	101,0	21,9	22,8	23,8	15,8	17,0	18,5

The average recruitment values in all variants were 104-122 10^6 ind., and the confidence intervals - 97-140 x 10^6 ind. These recruitment values are much higher than the geometric mean recruitment value for 1989-2015 (86 x 10^6 ind.), which caused relatively large average catches. The most preferable option, in our opinion, is fishing with a fishing mortality F from the range of 0.18-0.22, that is, with fishing mortality close to Fmax. In all variants, average catches differ little from each other. Considering that the instantaneous fishing mortality rate is directly proportional to the magnitude of the effective fishing effort E: F = qE, where q is the catchability coefficient (q = const), it is recommended to adopt the optimal fishing with the average multi-year F equal to 0.18. Slightly losing in catch (compared with F = 0.22) it is possible to significantly reduce the amount of fishing efforts.

The results in Table 1 show the average biomass, yield, fishing mortality and recruitment values over the period of 100 years. During the forecast period (100 years), the values of these parameters significantly changed over the years depending on the change in the recruitment. A detailed consideration of the change in the parameters of the population over time, depending on the size of the recruitment, makes it possible to give some recommendations on the regulation of the fishing of beaked redfish on the Flemish Cap Bank.

One of the optimal fishing options with a fishing mortality of 0.18 during the 100-year fishing is presented in Figure 2. Spawning biomass, recruitment, fishing mortality and catch (for clarity of presentation) were normalized by the mean and variance: (Xnormiri = (Xi -¯X) / S, where Xi is the i-th value of the population parameter, X is the average value of this parameter, S is the standard deviation.

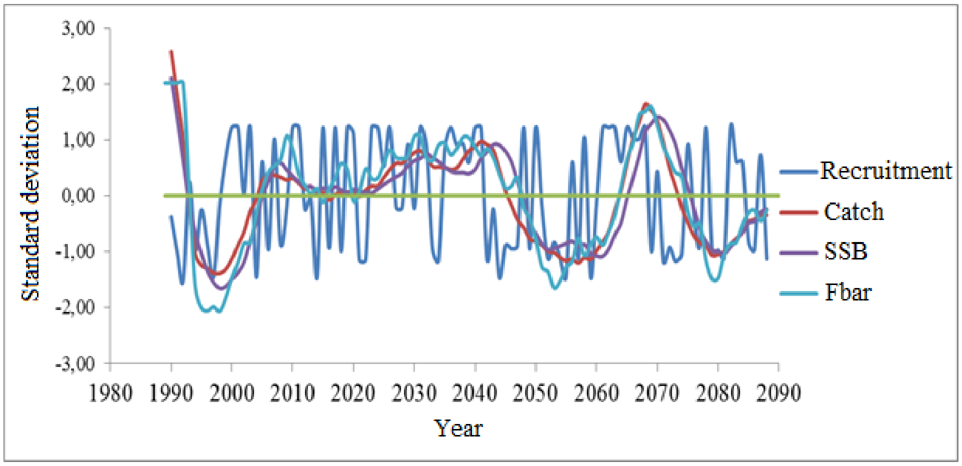

Figure 2. Changes in normalized deviations of recruitment, spawning biomass, fishing mortality and catch of redfish on the Flemish Cap Bank with 100-year forecasting

It should be noted that in this example only the amount of recruitment is random. All other parameters are dependent on changes in recruitment. The average values of the reserve parameters in this example are: recruitment - 112.5 million ind., spawning biomass - 31.0 x 10^3 t, fishing mortality - 0.18, catch – 13 x 10^3 t . To have a more simple visual interpretation of changes in their parameters values are presented as shares with respect to the total average value of this parameter for the entire period, which is presented in Table 2.

In the example above, there are several periods of change in the fishery. From 1992 to 1998, there was a decrease in catch from 1.5 to 0.55 of the total average value over the surveyed interval of 100 years (see Fig. 2 and Table 2). During this period, there are 2 medium and 5 weak recruitment, the average value of which was 48% of the total average. Fishing mortality fell to 0.71 total average.

In the subsequent period of 1999-2005, the average value of recruitment increased to 1.31 of the total average due to the appearance of 4 strong and 1 average number of recruitment. Therefore, the catch and fishing mortality during this period increased, and the catch by the end of the period was 1.09 mean values.

Table 2. Ranges of changes in the shares of catch and fishing mortality, the average value of the recruitment relative to their total average values over the periods of the fishery in the optimal fishing for beaked redfish on the Flemish Cap Bank over 100 years

Period	Catch		Recruitment		Fishing mortality
	Pattern of changes	Range of changes (portion from average)	Average value (portion from average)	Strength of year-classes	Range of changes (portion from average)
1992 - 1998	Decrease	1,5 – 0,55	0,48	2 average, 5 weak	1,29 -0,71
1999 - 2005	Increase	0,55 – 1,09	1,31	4 strong, 1 average, 1 weak	0,71 – 1,06
2006 - 2014	Decrease	1,12-1,01	0,98	3 strong, 3 average, 3 weak	1,06 – 1,02
2015 - 2022	Stable	1,01 – 1,02	1,04	4 strong, 4 weak	1,00 -1,02
2023 - 2032	Increase	1,03 – 1,23	1,42	6 strong, 4 average	1,02 – 1,10
2033 - 2036	Stable	1,23 – 1,15	0,99	1 strong, 1 average, 1 weak	1,10 – 1,11
2037 - 2041	Increase	1,15 – 1,31	1,63	5 strong	1,11 – 1,12
2042 - 2059	Decrease	1,31 – 0,63	0,65	3 strong, 3 average, 12 weak	1,12 – 0,87
2060 - 2068	Increase	0,63 – 1,53	1,61	6 strong, 3 average	0,87 – 1,22
2069 - 2080	Decrease	1,53 – 0,66	0,69	2 strong, 2 average, 8 weak	1,22 – 0,80
2081 - 2088	Increase	0,66 – 0,84	0,93	1 strong, 3 average, 4 weak	0,80 – 0,96

In the next four periods (2006–2014; 2015–2022; 2023–2032 and 2033–2036), the model predicts a relatively stable state of the population, caused by a relatively stable average recruitment, which was 0.98–1.04 of the total average. In the years 2023-2032, there is a slight increase in the biomass of the stock, and, consequently, the catch by 2030 to 1.23 and then its slight decrease. During this period, recruitment increased to 1.42 of the total average. During these periods, predicted mainly average recruitment, and the weak year-classes were compensated by the strong ones.

The appearance of 5 strong year-classes to commercial stock (average value 1.63) will increase the stock size by 2,041 and the catch - by 16% (from 1.15 to 1.31), which is presented in Table 2. 1 average and 12 weak year-classes, replacing them, will lead to a significant decrease in the abundance of beaked redfish in 2042–2059, and to a forced decrease in catch to 0.63 by the end of this period. Over the next 9 years (2060–2068), 6 strong and 3 medium-sized recruitment will be observed (average - 1.61), which will sharply increase the size of the beaked redfish stock and lead to an increase in catch to 1.53.

The alternation of strong and weak recruitment in the next two periods of 2069–2080 and 2081–2088 (average values, respectively, 0.69 and 0.93) will first lead to a sharp decrease in the biomass of the stock, and, consequently, the catch to 0.69, and then its increase to close to the average value (0.93).

The given example is one of the many options for random changes in recruitment. Naturally, using this example, it is impossible to form a complete management strategy for beaked redfish fishing on the Flemish Cap Bank. In our opinion, additional detailed analysis of various situations is required (which may be a continuation of the work begun on defining a strategy). However, the analysis carried out makes it possible to give certain recommendations on the management of redfish fisheries.

1. The recommended range of changes in fishing mortality for beaked redfish on the Flemish Cap Bank from Fmsy to Fmax (0.08-0.21).

2. In the starting year of the forecast, the average value of the recruitment for the last 4-6 years is estimated. If it is close to the average for the 1989-2016 fishing period, then the TAC for the next two after the starting year (short-term forecast) is estimated at the level of the average yield of the status quo (Fstatusquo).

3. If preliminary estimates of recruitment for 2-3 years ahead increase or decrease the average value of recruitment for the last 4-6 years by 30-40%, then the catch can be respectively increased or reduced by 13-20% compared to the current, with SSB close to 40 thousand tons.

4. The maximum value of F must not exceed Fmax = 0.21.

5. It is recommended to carry out short-term forecasts up to 5-10 years ahead and estimate average values of stock parameters taking into account the precautionary approach.

Conclusion

The analysis showed the dependence of the stock and catch of redfish species on the Flemish Cap Bank on the recruitment value with a slight delay of 1-2 years. Calculations of the field with a random choice of the recruitment value showed that the fishery with a fishing mortality of 0.16-0.18 and a catch of 16-18 thousand tons can be considered optimal. It is necessary to take into account that the average value of recruitment in the presented calculations was high (more than 100 million individuals). An analysis of one of the options for a specific change in the parameters of the stock of redfish species allowed to develop some recommendations for regulating their fishing on the Flemish Cap Bank.

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