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Proposals for the exploitation strategy of the Flemish Cap redfish stock

by

V. Korzhev and M. Pochtar

Polar Research Institute of Marine Fisheries and Oceanography (PINRO)
6 Knipovich Street, Murmansk, 183038 Russia, e-mail: inter@pinro.ru

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 based on the population dynamics model using the dependence of model parameters on environmental factors.

The procedures for modelling the average weight and recruitment of redfish are developed depending on the change in the size of the stock and individual environmental factors using the multiple stepwise regression methods. The estimation of the optimum yield of the redfishes and the exploitation rate in the long-term aspect was carried out, while maintaining the spawning stock in the safe biological limits with the use of a precautionary approach with different values of the predicted recruitment.

It is shown that the main strategy for managing fishery of redfish species is to maintain the spawning stock at a level of 30-40 x 10^3t. The exploitation rate (fishing mortality) should be set in the range of F_{msy}-F_{max} (0.08-0.21), depending on the average recruitment abundance for the last 6 years. With this exploitation, the long-term average annual catch can be 10-16 x 10^3t, and the stock of redfish will be in the biological safe limits. The analysis made can be used to determine the strategy for exploiting the Flemish Cap Bank redfish stock, the grounds for establishing the TAC for 2019-2020, 10.5 x 10^3t, 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 norvegicus* and *Sebastes fasciatus* are considered as a single redfish stock on the Flemish Cap Bank.

The primary information to assess the status of the redfish stock in Div.3M is obtained from the annual stratified bottom trawl surveys conducted by the European Union (EU) since 1989. Since the late 1990s, the Scientific Council of NAFO annually considers the results of the assessment of the redfish stock by various mathematical models (mainly, by the XSA method).

The paper presents the results of modelling the change in the average weight and recruitment of redfishes, depending on changes in the stock size and environmental factors. Using earlier assessments of the biological reference points of the precautionary approach by biomass and fishing exploitation, with the aid of the previously developed and modified model of fishing optimization the recommendations on a management strategy for the fishery of redfish species depending on the variable recruitment are given.

Material and methods

Statistical data from domestic and international fisheries for redfish on the Flemish Cap Bank for 1989-2016 are derived from the database on vessel daily reports of PINRO, as well as from the 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 series of data on temperature and salinity are taken from NAFO working papers [1-4]. The NAO indices are freely available on the NOAA (National Oceanic and Atmospheric Administration) website (http://www.cpc.ncep.noaa.gov).

The redfish abundance dynamics was estimated according to the XSA model [5] (in retrospect) and the modified fishery management model (with optimization and forecast) [6]. To estimate the abundance of the recruitment, Ricker's "stock-recruitment" relationships [7] were used. The average weight was simulated using the stepwise multiple regression method from the Statistica software.

The model of fishery optimization

Studies to develop proposals for a management strategy for the fishery of redfishes were carried out using a modified fishing optimization model. The algorithm of the optimization model had been described in detail earlier [6]. Optimization (forecasting) of the stock state is carried out using the same relationships as when restoring a retrospective of the stock dynamics. 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. At each step, the recommended fishing mortality (F) is estimated according to the previously adopted regulatory rule in accordance with the previously obtained estimate of the spawning stock biomass at the beginning of the forecast year. Modification of the model included the development of new approaches to modelling the average weight of individuals in the stock and recruitment.

Modelling the average weight of redfish by age. When modelling the average weight of redfish by age the stepwise multiple regression was applied. A large number of predictors characterizing the temperature and salinity of water at various sections and depths of the Flemish Cap area, as well as the North Atlantic Oscillation Index, were considered. In actual values of the average weight of redfishes by age, there were individual deviations, which raised doubts about the reliability. Therefore, using the stepwise multiple regression, removing the outliers detected by the program, for fish aged 4-19 years, multiple regression equations with a regression coefficient> 0.75, including the most significant factors (Table 1), were obtained. This minimum value of the regression coefficient could be taken as an allowable threshold when using equations for forecasting. With the historical data of 1989-2015, the new average weight model in the stock basically shows a more accurate approximation of the observed data compared with the previous approach, based on the Bertalanffy growth dependence (Table 2). The sum of the squares of the deviations for the regression model is smaller than when modelling the weight using the Bertalanffy dependence. The exceptions are 2005, 2007 and 2009 (in Table 2 they are highlighted in yellow). However, in these years, the anomalous values (outliers) of the average weight of individuals at some ages in the observed data were recorded.

Table 1. Predictors and their values in the multiple regression equations for modelling the average weight of the redfish species in the stock on the Flemish Cap Bank by age

Age, years	Intercept term	Variables-predictors in the multiple regression equation						Correlation coefficient
		Biomass	SSB	SST	T bottom	T50	NAO J-M	R
4	0,087086	-	5,654E-07	-0,01143	0,008556	-	-	0,78
5	0,128774	-4,558E-08	8,775E-07	-	-	-	-	0,81
6	0,186549	-4,965E-08	4,291E-07	-	-	-0,011222	-	0,80
7	0,254665	-1,935E-08	-4,794E-07	-0,01143	0,00899	-	-	0,78
8	-3,01125	-	-1,063E-06	-0,48465	-0,02585	-	-	0,82
9	0,376894	5,562E-08	-1,495E-06	-0,03821	-	-	-	0,83
10	0,426332	9,160E-08	-2,371E-06	-0,02713	-0,02967	-	-	0,80
11	0,452583	-6,798E-08	-2,217E-06	-0,06026	-	0,01651	0,051308	0,77
12	0,554013	-6,521E-08	-2,082E-06	-2,45E-02	-2,444E-02	-	-	0,78
13	0,621049	-1,442E-07	-3,094E-06	-	-0,06278	-	-	0,84
14	0,896181	-	-4,275E-06	-0,03959	-0,06383	-	-	0,83
15	0,704130	-3,434E-08	-3,702E-06	-0,03719	-0,04585	-	-	0,80
16	0,714243	1,248E-07	-4,273E-06	-0,10139	-	0,03032	0,081386	0,84
17	1,039846	9,795E-08	-3,936E-06	-0,04434	-0,04541	-	-	0,77
18	0,818623	3,239E-07	-5,144E-06	-0,11137	-	0,02167	-	0,81
19	0,890192	-2,633E-07	-5,779E-06	-0,13163	-	0,04878	0,132433	0,75

SST - water surface temperature, T bottom - bottom temperature, T50 - temperature at a depth of 50 m, NAO - North Atlantic Oscillation Index

Table 2. Sum of squares of deviations of the observed weight of one redfish individual by age from the simulated one

Name	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Mod.1$^{1)}$	0,018	0,084	0,106	0,157	0,331	0,123	0,233	0,082	0,106	0,251	0,064	0,056	0,163
Mod.2$^{2)}$	0,018	0,062	0,038	0,044	0,097	0,061	0,043	0,018	0,019	0,168	0,043	0,041	0,079
Name	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Mod.1	0,127	0,111	0,079	0,095	0,125	0,155	0,128	0,179	0,222	0,310	0,258	0,165	0,131
Mod.2	0,051	0,088	0,032	0,245	0,091	0,198	0,059	0,221	0,056	0,166	0,039	0,058	0,178

1) ^{1}Mod1 - a model made on the dependence of the growth of Bertalanffy,
2) ^{2} Mod2- regression model.

When modelling recruitment abundance, the method of stepwise multiple regression was also used. Among the large number of environmental factors under consideration, any significant correlation with the abundance of the recruitment was not found for any of them. With the help of four predictors, it was possible to obtain a multiple regression equation that described well the observed dynamics of the recruitment abundance (Table 3).

Table 3. Regression results for the dependent variable "recruitment" R = 0.908; R^2 = 0.824; adjusted R^2 = 0.7885; F (4.20) = 23.367; p <0.005

Predictors	BETA	St. er. BETA	B	St. er. B	t(20)	p-values
Intercept term			100016	39147	2,5549	0,01888
Biomass	0,81992	0,10286	1,002	0,13	7,9713	0,00000
T50 m	-0,7565	0,10866	-126482	18168	-6,9616	0,000001
SSB	-0,3071	0,10171	-3,04	1,10	-3,0197	0,00677
NAO J_M	-0,2445	0,10622	-127436	55363	-2,3018	0,03223

The multiple regression coefficient of the equation is significant, and equals to R = 0.91. The correlation matrix of the variables included in the equation shows the independence of these variables. The value of the Durbin-Watson coefficient is 2.11, and the serial correlation of the residues is - 0.07, which indicates the absence of autocorrelation in the residues and the adequacy of the made equation. A significant correlation relationship is observed only between the biomass of the stock and the recruitment, which automatically makes this equation unsuitable in optimizing the fishery. Given the high correlation between the stock biomass and the recruitment, with optimization, i.e. maintaining a relatively high stock biomass, we will always have strong recruitments. Therefore, this approach differs little from the use of a constant average long-term value of the recruitment.

Previously, the abundance of the recruitment was shown as the determining factor in the dynamics of the stock of redfishes on the Flemish Cap Bank [6]. In the same paper, the variants of optimal fishing for different constant recruitment values were considered. The most interesting thing, in this case, in our opinion, is the optimization of the fishery with the recruitment, determined with the help of the Ricker curve, with the inclusion of a random error. This model involves receiving both rich and poor recruitment in a random way. Briefly, this approach can be described as follows,

1) On the historical data series, the parameters of the Ricker stock recruitment curve, α and β, are calculated:

$$R = \alpha * SSB * \exp(-\beta * SSB)$$

where R – the abundance of the recruitment;

SSB – spawning biomass:

α and β - parameters.

2. The deviations of actual recruitment values (R fact) from those modelled by the Ricker curve (R model) for each year, using the logarithm of their ratio are calculated: Dev. = Ln(Rfact./R model).
3. From the range of calculated deviations, the error value is randomly selected.
4. The new value of the recruitment is calculated taking into account a random error: R = R * exp.(Deviated).

The optimization of the fishery was carried out taking into account the precautionary approach, based on the use of biological reference points. Values of biological reference points B_{lim}, B_{pa}. , B_{tr}., F_{tr}, F_{pa}, F_{lim} had been estimated by us earlier [8-9]. Their detailed description and values are given in the research report for 2016 [8]. To calculate the catch for each year, the target value of fishing mortality (F_{tr}) is adopted. The distribution of fishing mortality by age (operating model) $F_{pattern}$ is taken equal to the average value of the fishing mortality rates by age for the last three years, calculated using the XSA method.

Spawning biomass (SSB) is calculated and compared with the values of the reference points B_{pa} and B_{tr} for each year. If SSB <B_{lim}, the fishing mortality F is assumed to be zero (no fishing). If B_{lim} <SSB <B_{tr}, the target value of fishing mortality decreases in proportion to the SSB / B_{pa} ratio ($F = F_{tr} * SSB / B_{pa}$). If SSB> B_{pa}, and F_{bar} <F_{tr}, the F_{bar} value is adjusted upward. If SSB> B_{pa}, F_{bar}> F_{tr} and F_{bar} <F_{lim}, the fishing mortality for the next year is assumed equal to the fishing mortality in the current year.

Results

The values of the biological reference points B_{lim} and B_{pa} are assumed equal to 20 and 40 thousand tons, respectively. Various F values including F_{MSY}=0.08, $F_{0.1}$=0.10, F_{max}=0.21 were used as target values for fishing mortality. To study the dependence of the calculation results on the initial (starting) abundance, two starting years ,1989 and 1995, were used. In 1989, the stock of redfish species was at a good level (more than 200 x 10^3 t according to the XSA calculations), and, in 1995, - at a low level (about 37 x 10^3 t). In addition, recent work to assess the dynamics of redfish stock by the XSA method shows that the natural mortality of redfish can be higher than it is commonly believed. Taking this into account, the model calculations were performed with a natural mortality of 0.1 and 0.125. Table 4 presents the results of modelling the dynamics of the redfish stock parameters in the long-term period.

Table 4. Mean long-term values of abundance, biomass, spawning biomass, recruitment and yield of redfish species from the Flemish Cap Bank in the long term, while optimizing the fishery under precautionary approach conditions for different values of target fishing mortality

Starting parameters	Fishing mortality	Biomass, x 10^3 t	SSB, x 10^3 t	Abundance, x 10^6 ind.	Recruitment, x 10^6 ind.	Yield, x 10^3 t
1 F=0,08 1989 M=0,125	0,08 (0,07-0,09)	136 (96-170)	45,0 (32,6-56,5)	550 (356-756)	106 (7,2-200)	7,8 (5,3-9,6)
2 F=0,08 1995 M=0,125	0,08 (0,07-0,09)	143 (121-172)	53,0 (44,6-61,2)	568 (439-694)	114 (6,5-186)	9,0 (7,6-10,3)
3 F=0,1 1989 M=0,125	0,09 (0,07-0,11)	130 (84-192)	40,1 (28,8-61,8)	537 (303-823)	92 (22,1-200,0)	8,4 (5,2-13,0)
4 F=0,11 1995 M=0,125	0,11 (0,09-0,12)	129 (102-161)	44,4 (37,0-55,5)	520 (354-699)	81 (21,6-200,0)	10,2 (7,9-12,7)
5 F=0,14 1989 M=0,125	0,13 (0,10-0,14)	129,0 (88-156)	38,0 (27,9-34,6)	554 (360-693)	94 (23,6-200,0)	11,1 (6,1-13,3)
6 F=0,2 1989 M = 0,125	0,17 (0,17-0,19)	122 (85-151)	33,3 (27,1-37,7	543 (355-720)	106 (16,9-200,0)	12,2 (8,8-15,2)
7 F=0,23 1995 M=0,125	0,19 (0,15-0,22)	120,0 (82-138)	34,5 (26,3-38,4)	508 (340-656)	99 (24,6-200,0)	14,6 (8.8,-17,4)
8 F=0,23 1989 M=0.125	0,19 (0,14-0,21)	119 (85-160)	32,0 (25,3-38,3)	533 (348-779)	123 (28,1-200,0)	13,2 (8,3-17,9)
9 F=0,23 1995 M=0,1	0,21 (0,19-0,24)	126 (92,6-149,3)	37,5 (30,8-41,7)	534 (349-707)	102 (20,4-200)	16,7 (9,6-17,4)
10 F=0,25 1989 M=0,1 R=Const	0,19 (0,16-0,20)	109 (88,8-109,9,0)	30,6 (25,4-31,2)	486 (405-489)	95 (95-95)	12,9 (9,6-13,3)

The first column of the table shows variant number, starting year, natural mortality rate, initial target value of fishing mortality. In the other columns of the table, the values (mathematical expectations) of the different stock values for the forecast period (90 years) and the yeild of redfishes are given, and, in parentheses, the 5 and 95% change intervals are shown for each parameter. It should be borne in mind that recruitment is determined randomly and other indicators may be caused by this reason.

Variants of Calculations 1 and 2 show that in a fishery with a low fishing mortality of 0.08 (F_{msy}), spawning biomass is set at a high level (45-53 x 10^3 t), higher than B_{pa}, regardless of the starting year. In this case, the average catch is 7.8-9.0 x 10^3 t. The relatively large difference in the parameters for these two options is, in our opinion, due to the average recruitment abundance, which is estimated at 106 and 114 x 10^6 individuals, but not based on the starting year.

With an increase in the fishing mortality F to close to $F_{0.1}$ (Variant 4), the fishing and spawning stocks decrease somewhat, but continue to remain above B_{pa}. The catch is increased to 10.2 x 10^3 t with a smaller average recruitment (81 x 10^6 individuals). A further increase in fishing mortality to 0.13 (Variant 5) leads to a decrease in the spawning stock to a level close to B_{pa} and an increase in yield to 11.1 x 10^3 t. Fishing with F close to F_{max} (Variants 7 and 8) (F = 0.19) increases the catch to 13.2-14.6 x 10^3 t. At the same time, the average spawning biomass will be established at the level of 32-34.5 x 10^3 t.

In Variant 9, as in Variant 8, the target value of fishing mortality is assumed to be 0.23. Unlike Variant 8, in Variant 9, the natural mortality is assumed to be 0.1 (the commonly used value). Reduction of natural mortality leads to an increase in the spawning stock to the level of B_{pa}, with the average catch increasing to 16.7 x 10^3 t.

The performed calculations make it possible to propose a strategy for managing fishery of the redfish from the Flemish Cap Bank. The new calculations show that the main strategy for fishing of the redfish is to maintain spawning biomass at a level of above 30 x 10^3 t. The highest average annual catch is obtained at a fishing mortality close to F_{max}, namely, with an actual average F of 0.17-0.19 (options 6-10 in Table 4). The average annual catch at the same time will be 12.2-16.7 x 10^3 t , even with a higher than expected natural mortality (F = 0.125), and the average long-term forecasted recruitment is assumed to be close to the average long-term actual recruitment (96 x 10^6 individuals). At the same time, considering the wide range of the confidence interval limits for optimal catch, which, in our opinion, is caused by the large amplitude of fluctuations in the recruitment abundance, the operating regime should be set depending on the spawning biomass and recruitment.

The forecasting of the recruitment along the Ricker curve with allowance for a random error gives a random set of recruitment from low to high values. Naturally, it will not reflect the real dynamics of the recruitment of the commercial redfish stocks at any particular time interval. At the same time, such an approach makes it possible to trace changes in the stock biomass, and, accordingly, fishing mortality and catch as a result of the change in the recruitment abundance.

Figure 1 presents one of the options for the dynamics of the Flemish Cap Bank redfish stock parameters, which demonstrates how to implement the fishing strategy when changing the recruitment abundance. In this example, the initial values of the parameters correspond to Variant 8 in Table 4. In the forecasted period, the abundance of recruitment varies from weak to strong at random (Figure 1). In accordance with this, other stock characteristics including abundance, commercial and spawning biomass, as well as fisheries mortality and catch are changing. The variant of the change in the dynamics of the redfish abundance on the Flemish Cap Bank shown in Figure 1 is only a sample (one of many variants) of calculations with equal starting conditions for random recruitment modelling. In this example, it is possible to demonstrate the strategy of redfish exploitation during 1990-2080. Over the entire period under review, the catch varies from 8.3 to 17.8 x 10^3 t (Table 4, Variant 8, last column).

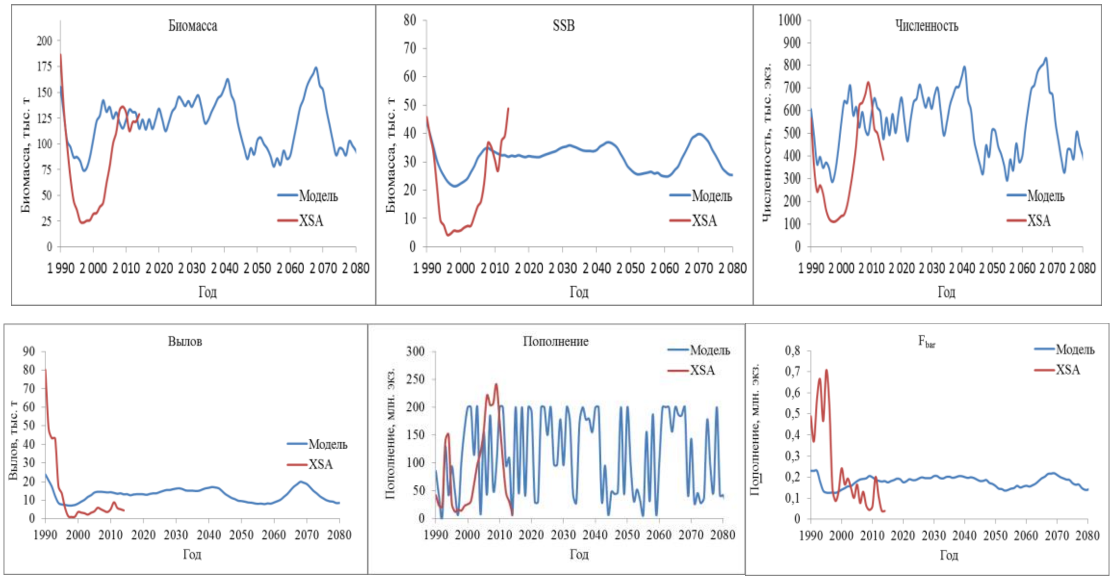

Fig. 1. Dynamics of the main characteristics of the stock of redfish species from the Flemish Cap Bank for 1989-2080 while maintaining a stock with fishing mortality of F = 0.19 and a natural mortality of 0.125

The fishing mortality varies depending on the change in the recruitment abundance, and, consequently, in the spawning stock after a certain time. For example, after the appearance of several poor recruitments in 2041-2048, within the precautionary approach the model reduces catch in 2048-2056 from 13 to 8-9 x 10^3t, and, conversely, with the appearance of several strong recruitments in 2060-2065 catch can be increased to 18 x 10^3t (Figure 1). The average (for the whole period) catch will be approximately 13 x 10^3t.

The above example shows one of many random variants of calculations with the same starting values. To estimate the error of the each mean stock parameter, 200 iterations were performed at F = 0.11 with a natural mortality of 0.125. Figure 2 shows the frequency distribution of the occurrence of parameter values over equal length intervals for an array of 200 values.

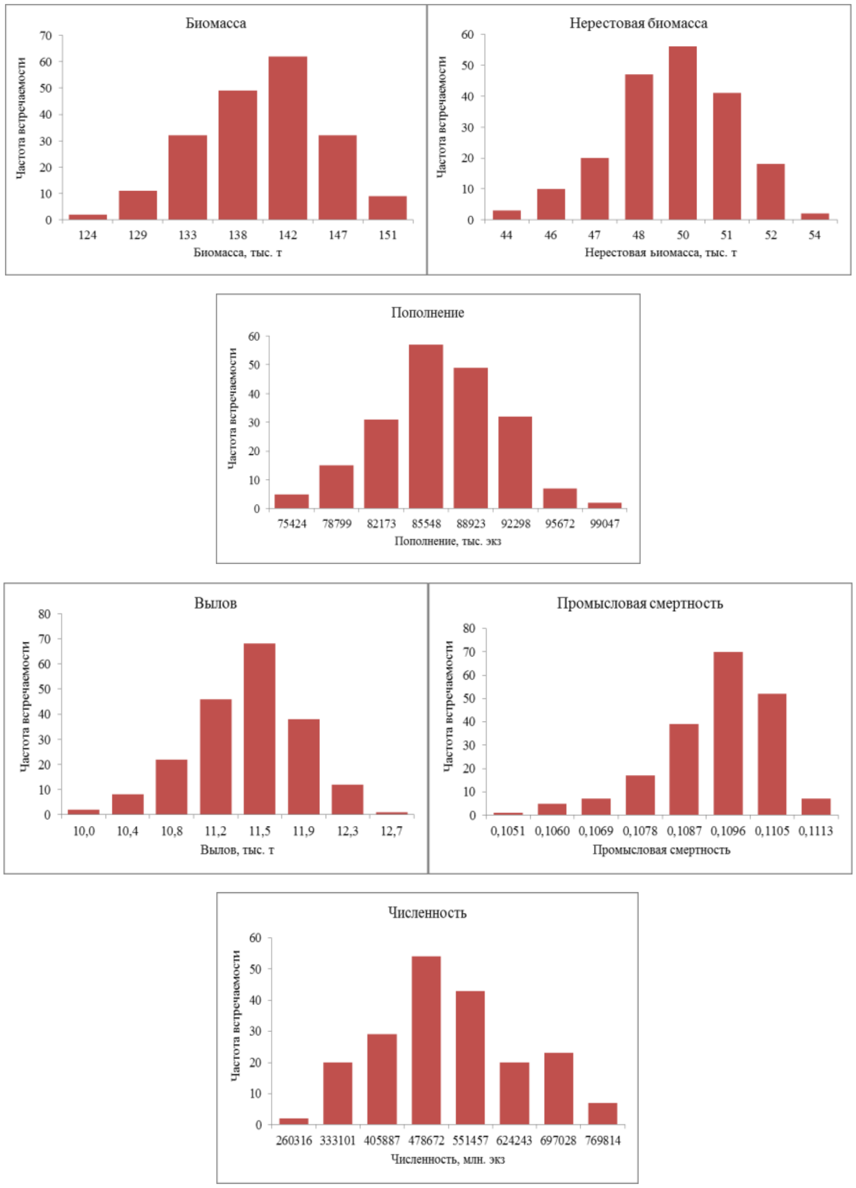

Fig.2. Distribution of the parameters of the Flemish Cap redfish species in the optimization of the fishery with the target fishing mortality of 0.11 and the random recruitment abundance

In the fishery with F = 0.11, the most probable catch (in frequency of occurrence) is forecasted within the range of 11-12 x 10^3 t, spawning biomass of the stock will remain at a high level ranged from 48 to 51 x 10^3 t, and the recruitment abundance - at the level of 86-89 x 10^6 individuals, slightly below the average long-term observed value.

Conclusion

The studies carried out to optimize the fishery of redfish indicate that the most appropriate method for determining fishing strategy for redfish is the precautionary approach. The aim of the fishery should be maintaining the stock at the level of B_{pa}, which was determined as 40 x 10^3 t . If the spawning stock is exceeding this level, the fishing mortality ratio should increase, and, with the spawning stock reduction, - decrease in proportion to the SSB/B_{pa} ratio.

The main indicator of the expected decrease or increase in the value of SSB is the level of recruitment. If a few weak year-classes appear in a row, the fishing mortality tends to decrease, and, conversely, with several strong year-classes, it increases. The period of change in operating conditions, depending on the size of recruitment should be investigated additionally. A short-term forecast of the redfish stock for 3-5 years ahead with an average value of recruitment for the last 5-6 years can serve as one of the methods of such research.

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