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Simulation of the flemish cap bank redfish fishery taking into account dependence of the parameters on stock density

by

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Abstract

Study subject – The Flemish Cap Bank redfish of the North-West Atlantic NAFO Division 3M. Study goal – proposals to enhance management of redfish fishery taking into account relationship of parameters and stock density.

Simulation procedures of average mass and maturity ogive of redfish were developed depending on changes of a stock size. Limiting and buffer biological reference points of the redfish stock B_{lim}, B_{pa}. F_{tr}, F_{lim}, F_{max}, F_{med} and $F_{0.1}$ were estimated in order to use them for fisheries enhancement and development of fisheries management strategy.

It has been shown that optimum mean annual catch depends on the recruitment value. It can be obtained if fishing mortality is 0,08 - 0,2 and it can compose 10,000-18,000 tons depending on the recruitment value. So that stock remains in biologically safe limits (spawning biomass is within the range of 20,000-40,000 tons).

Key words: REDFISH, STOCK, ABUNDANCE, SIMULATION, PARAMETERS, FISHING MORTALITY, FISHERIES MANAGEMENT.

Introduction

Three species of marine redfish: deep-sea redfish (*Sebastes mentella*), golden redfish (*Sebastes marinus*) and Acadian redfish (*Sebastes fasciatus*) are regarded as a management unit of the Flemish Cap Bank redfish stock.

The major information for estimation of marine redfish stock in NAFO Division 3M is based on EU annual stratifiable bottom trawl surveys (from 1989). Since the late 1990s NAFO Scientific Council has been annually considering the results of redfish stock assessment by various models (mainly by XSA). This data is used in decision making on stock status and TAC estimate and in analysis of possible stock status under various fisheries scenarios.

This paper presents the simulation results of variations of redfish average mass and maturity ogive subject to stock changes. Biological reference points of precautionary approach were estimated and on this basis redfish management advice depending on recruitment value were given.

Materials and methods

Statistic data of national and international redfish fishery on the Flemish Cap Bank (1956-2016) were derived from the PINRO database of daily vessel reports, as well as from the NAFO databases of fisheries statistics STATLANT 21A and STATLANT 21B.

Working documents for the annual sessions of NAFO Scientific Council, SC annual reports, reports of EU annual stratifiable bottom trawl surveys provided with biomass and abundance indices, length and age catch composition, mean mass at length and age, length-age keys for catch recalculation into biomass at catch in abundance. Biological reference points were calculated by procedures in Excel. Correlation and regression analysis was used to simulate average mass at age and maturity ogive.

Simulation of biological parameters dynamics

Average mass

Based on 1989-2016 data analyses of individual's mass changes subject to age at year-classes using the von Bertalanffy relationship by mass was made [1]:

$$w_t = W_\infty\left(1 - e^{-K(t-t_0)}\right), \qquad (1)$$

Where W_∞ - average asymptotic mass;

K – Brody growth rate;

t – age;

t_0 – hypothetical age at which mass w_t could be equal to 0 subject to growth always followed this correlation.

It was set that fully exploited year-classes have parameter t_0 significantly linked to stock biomass (correlation rate minus 0,89); growth rate (K) well correlates with parameter t_0 (R=0,84), and parameter W_∞ with parameter K (Fig 1). Using the known correlations, parameters of the von Bertalanffy's equation are determined and mean mass of redfish at age is calculated using the formula (1).

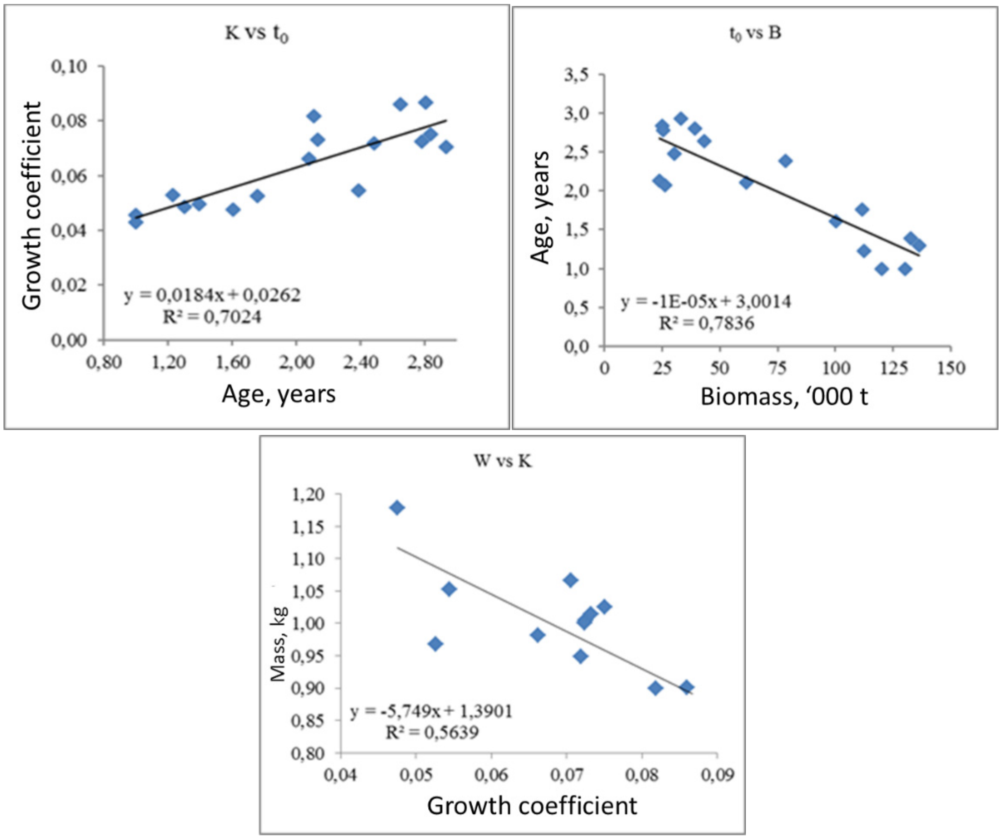

Fig.1. Correlations between parameters of the Bertalanffy's equation for growth and biomass of the Flemish Cap redfish stock

Maturity ogive's simulation

An approach similar to that used for simulation of an average mass in a stock was used to simulate redfish maturity ogive at age. Maturity rate of redfish at year-classes was considered. Actual annual data of maturity at age (NAFO SC data) were maturity curve fitted:

$$\check{p} = \frac{1}{1+e^{-(a+bt)}}, \tag{2}$$

Where t – age; a and b - parameters.

For fully exploited year-classes, parameter t_{50} has significant correlation with stock biomass (determination rate R^2=0,73), parameter b in the equation (3) is well correlated with parameter t_{50} (R^2=0,73), and parameter a is well correlated with parameter b (Fig 2). Using the known correlations, parameters of the equation are determined and portion of mature redfish at age is calculated.

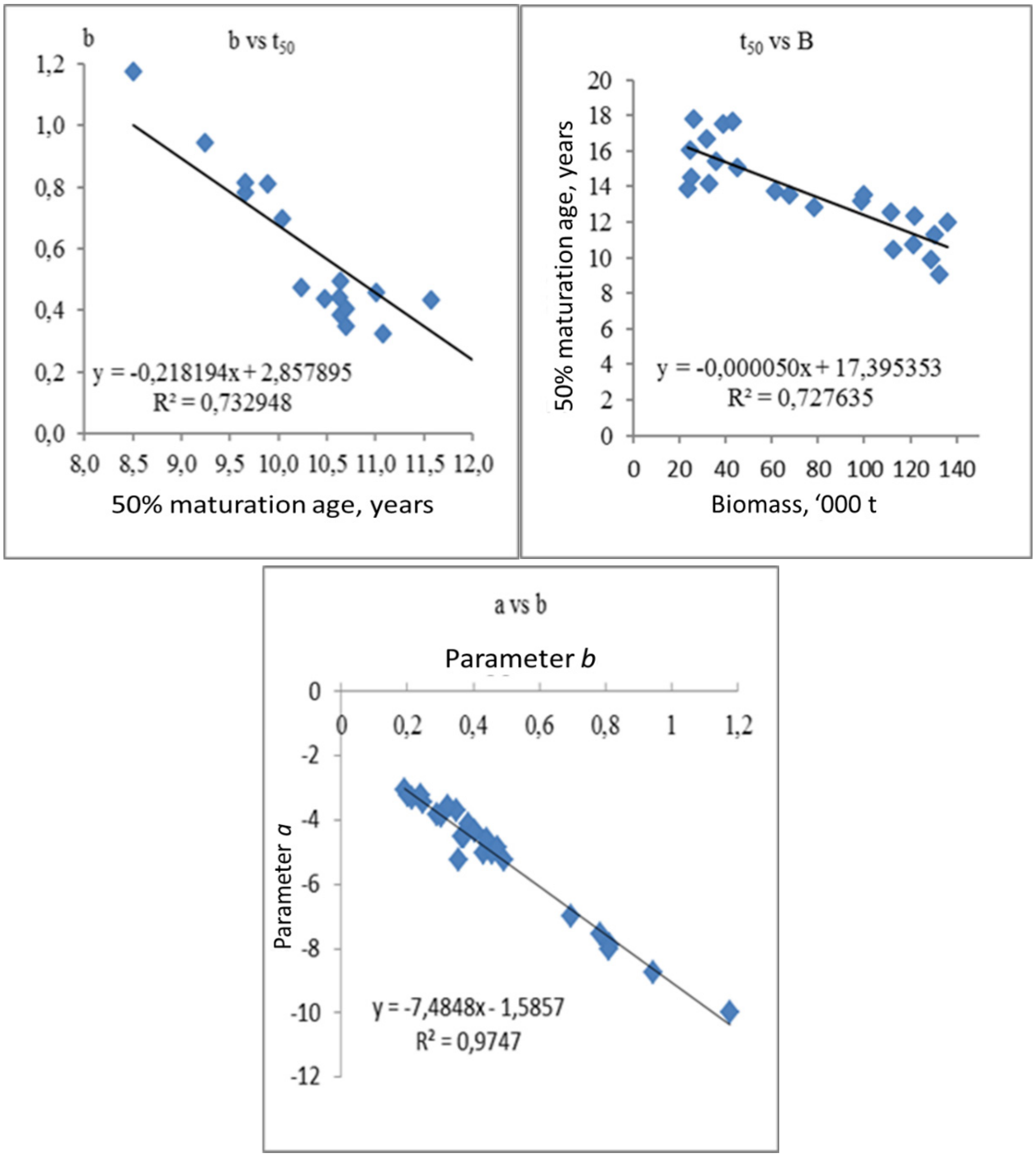

Fig. 2. Correlations between parameters of the equation for sexual maturity and biomass of the Flemish Cap redfish stock

Algorithm of mature portion calculation aged *t* is the following:

1. Age of 50% redfish maturity per YEAR is calculated
   t_{50} = -0,000050*B(YEAR) + 17,395353
2. Parameters a and b of the equation (2) are calculated
   b = -0,218194 * t_{50} +2,857895 a = -7,4848 * b -1,5857
3. Mature portion aged t per YEAR is calculated
   P(t) = 1/(1+ exp(-(a + b * t)))

Recruitment simulation

An approach based on The Beverton–Holt model [2] was used for simulation of recruitment dynamics regardless a lack of relation “stock-recruitment”.

With a use of the recruitment-parental stock curve by Beverton and Holt (4), recruitment is calculated:

$$R = \frac{1}{\alpha + \beta / P}, \qquad (3)$$

where R – number of recruits; P – parental stock (could be set in both abundance or mass); α and β – parameters.

Spawning biomass is used as a parental stock.

Algorithm of recruitment simulation in this case is the following:

1. R_{simul}. is calculated using the formula (1)
2. Bias of actual recruitment values (R_{act}.) from the simulated ones. (R_{simul}) for each year are calculated with a use of logarithm bias = $Ln(R_{act.}/R_{simul.})$.
3. Error is randomly selected from a range of calculated bias.
4. New value of recruitment is calculated given the random error: R = R_{simul} exp (random error).

Model of population’s dynamics and optimum fishery

Stock dynamics prediction uses the same relations as a restoration of stock dynamics retrospective. In prediction, these relations apply to sequential calculation of the year-classes parameters from younger to older, i.e. in the opposite direction.

Stock calculation in a starting year

An abundance of age groups in a starting year is considered equal to the abundance estimated in XSA model for terminal year and recalculated for beginning of the next year. Recruitment in a starting year is considered as long-term average value of recruitment abundance calculated by XSA for 1989-2012 (2013-2015 are excluded due to the possible unreliable estimates of recruitment).

Calculation of abundance at age *a* for the each following year (y+1, …)

Last age group *m* is considered as N_m^+ plus-group. Abundance at age groups taking into account natural mortality (M_a) and fishery ($F_{a,y}$) is calculated for a year *y + 1*, the following way:

$$N_{1,y+1} = R_y, \qquad (4)$$

$$N_{a,y+1} = N_{a-1,y} \cdot \exp\left(-\left(F_{a-1,y} + M_{a-1}\right)\right) \quad \text{for } a = 2, \ldots, m-1, \qquad (5)$$

$$N_{m,y+1} = N_{m-1,y} \cdot \exp\left(-\left(F_{m-1,y} + M_{m-1}\right)\right) + N_{m,y} \cdot \exp\left(-\left(F_{m,y} + M_m\right)\right). \qquad (6)$$

Where: $N_{a,y+1}$ – abundance at age *a* per year *y+1*; $F_{a-1,y}$ – fishing mortality of redfish at age *a-1* per year *y*; M_{a-1} – natural mortality at age *a-1*.

Yield calculation

The following formula is used for yield calculation at year and age $C_{a,y}$:

$$C_{a,y} = N_{a,y} \frac{F_{a,y}}{F_{a,y}+M_a} \left(1 - \exp\left(-\left(F_{a,y} + M_a\right)\right)\right). \quad (7)$$

Fisheries management

Target value of fishing mortality $F_{цел} = F_{tr}$ is used to calculate yield for every year (e.g., F_{MSY}). Distribution of fishing mortality at age (exploitation model) $F_{pattern}$ is assumed as either mean long-term value or mean value of fishing mortality rates at age for the last three years. Spawning biomass (SSB) is calculated for each year and is compared to biological reference points B_{lim} and B_{pa}. If SSB < B_{lim}, than F_{tr} corresponds to zero. If B_{lim} < SSB < B_{pa}, than target value of fishing mortality is corrected (decreased) pro rata to SSB/B_{pa} (F=F_{MSY}* SSB/B_{pa}). If SSB > B_{pa}, and F_r < F_{MSY}, than F_{bar} is corrected towards increase. If SSB > B_{pa}, F > F_{MSY} и F_{bar} < F_{lim}, than fishing mortality for the next year corresponds to fishing mortality for a current year.

Model run

Term «run» has a very loose sense. In this paper «run» means «confirmation of software's correct work». So that we check if the model has adequate results. We assume XSA calculations as the actual results. We compare results obtained through the developed model (new methods of mean mass and maturity ogive determination) and actual results (XSA calculations), we check reality of the suggested methods for mass and maturity ogive simulation of the Flemish Cap redfish, and we check if the software works correctly.

Run calculations used actual (XSA) recruitment assessments, and fishing mortality at age was assumed as mean long-term values of fishing mortality estimated by XSA, aged 4-16. Natural mortality was assumed to be constant and equal to 0,1. Calculations show that the model in general describes well dynamics of population parameters, calculated by XSA (Fig 3).

Major population parameters: abundance, fishing biomass, spawning biomass, yield calculated with mean long-term values of fishing and natural mortality, as well as with actual 1989-2008 recruitments have good correspondence with XSA calculations (Fig 3). After 2009 simulated abundance and biomass estimates are higher than the XSA estimates. This could be explained by the fact that XSA calculations use hypothesis of natural mortality four times growth during 2008-2010 (from 0,1 to 0,4). This hypothesis was not used in the preliminary calculation.

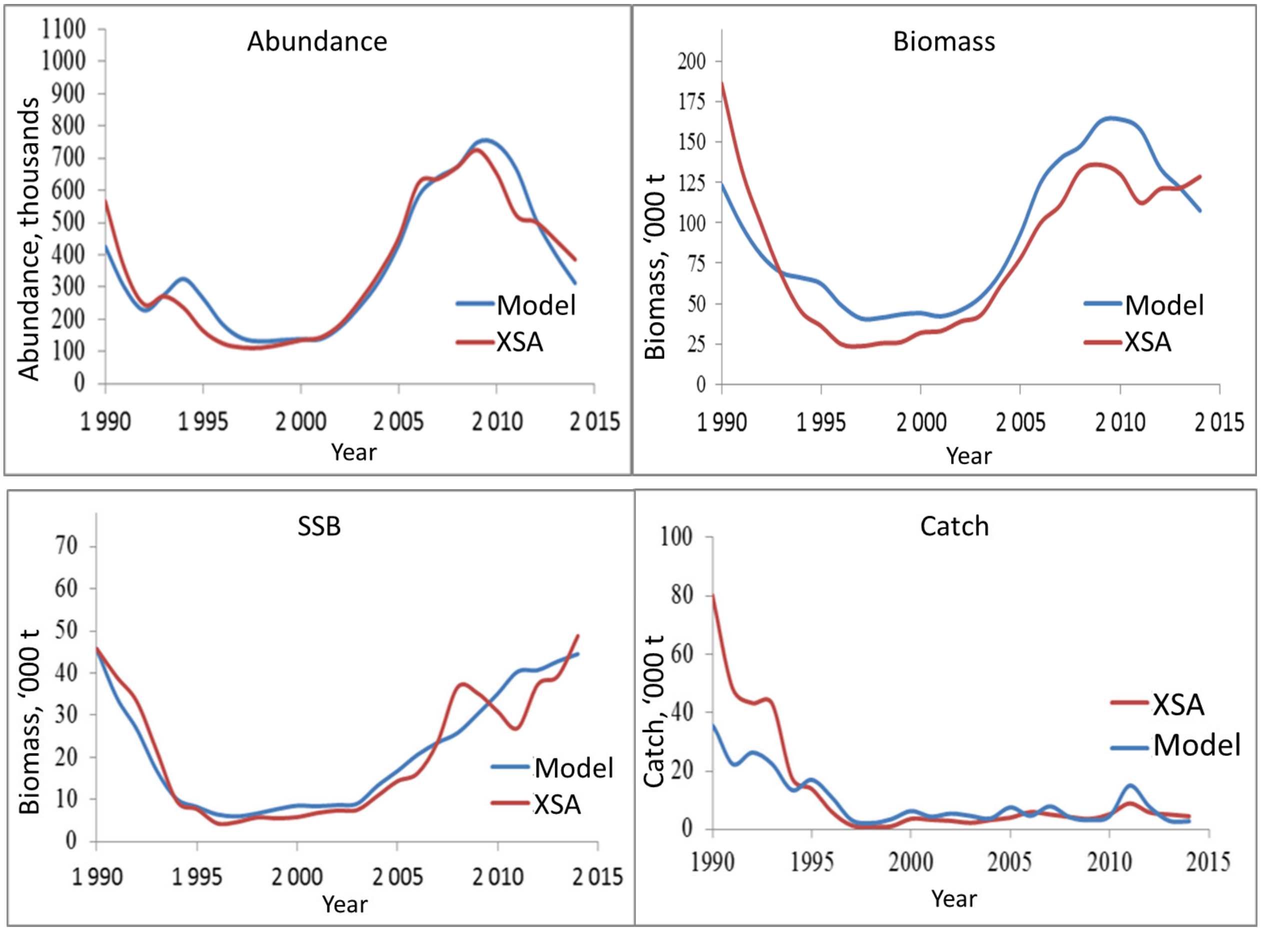

Fig. 3. Abundance, fishing and spawning biomass, the Flemish Cap redfish yield both simulated and XSA calculated

Results

We considered two options of the Flemish Cap redfish fisheries optimization: maximum yield under exploitation with constant fishing mortality and fisheries optimization under abovementioned precautionary approach.

Fisheries optimization based on fishing mortality control

For fisheries optimization by constant fishing mortality, F was equal to 0,02-0,4, step 0,02. Among the factors affecting abundance dynamics of redfish stock in the long-term, the main (determining) factor is the recruitment. The following recruitment variations in the predicted period were addressed:

a) recruitment is equal to mean long-term values of recruitment for 1989-2012, calculated in XSA (94,5 million ind.);

b) recruitment is assumed as geometric mean value of recruitments (calculated in XSA) for 1989-2002, when mostly poor generations had occurred (33,8 million ind., pessimistic scenario);

c) recruitment is assumed as geometric mean value of recruitments (calculated in XSA) for 1989-2012 (63,8 million ind.);

d) recruitment is calculated by the Beverton–Holt curve without using a random error;

e) recruitment is calculated by the Beverton–Holt curve with a use of a random error.

Simulation results based on “a-d” options show big relation of maximum yield estimate and the recruitment value (Table 1). Catch curves based on these options have inexplicit maximum. When fishing mortality increases over 0,2, yield insignificantly declines. This is explained by the fact that when fishery is optimizing with a constant recruitment irrespective of stock size, relatively high recruitment values (compared to the 2000s poor recruitments) allow maintaining high yield even under low fishing and spawning biomass. Therefore, when recruitment decreases, there is a quite high risk of stock undermining.

Table 1 – Assessment of maximum (optimum) yield under the constant recruitment values

Option number	Recruitment, millions of ind.	Fishing mortality	Stock biomass, thou tonnes	Spawning biomass, thou tonnes	Yield, thou tonnes
a) arithmetic mean recruitment for 1989-2012	94,5	0,21	105	30	15,6
b) geometric mean recruitment for 1989-2002	33,8	0,2	44,8	9,5	5,9
c) geometric mean recruitment for 1989-2012	63,8	0,16	111	43,3	10,7
d) the Beverton–Holt recruitment without random error	120	0,18	178,5	70	22,6
e) the Beverton–Holt recruitment with a random error		0,2 0,18-0,22	145,0 123,0-163,5	50,8 39,5-63,8	20,0 16,3-23,3

An “e” option involves recruitment variation based on the Beverton–Holt model. The Beverton–Holt curve “stock-recruitment” has no maximum, and when spawning biomass grows, recruitment is slowly increases. For the Flemish Cap redfish, the “stock-recruitment” curve is not so steep, merely when SSB is less than 8,000-9,000 tons, it plummets up to zero. Under medium and high values of SSB, recruitment grows slowly and in fact in this part of the curve is little different from the arithmetic mean value (staying higher than it). Unlike two first calculation options, catch curve in this option has a prominent maximum, though absolute values of catch differ insignificantly. When fishing mortality is 0,35, catch declines from 22,600 to 16,000 tones. Fishing and spawning biomass declines much faster: fishing biomass decreases to 105,000 tones, spawning biomass decreases to 24,000 tones, i.e. they are halved.

A “d” option involves recruitment variation based on the Beverton–Holt model taking account of error that was randomly chosen from logarithms array of bias of actual recruitment and recruitment calculated by the Beverton–Holt curve. The Beverton–Holt curve poorly describes the observed recruitments so bias is rather high. Recruitments calculated with a use of random errors could differ from each other by more than five times, and random choice makes them unpredictable at years. Stochastic approach was used for this option. 500 iterations were made for each value of fishing mortality and then its average value was calculated. Given the random choice of recruitment, the maximum of catch curve is defined within the range of fishing mortality from 0,18 to 0,22 and makes up around 20,000 tones. At the same time, recruitment biomass varied from 120,000 to 172,000 and at average composed about 145,000 tons, and spawning biomass varied from 39,500 to 63,800 tons and at average composed 50,800 tons.

Fisheries optimization with a precautionary approach

History of the Flemish Cap redfish fishery showed that even under low values of fishing and spawning biomass, small catches and insignificant recruitments for the decade (2000-2010), redfish stock has recovered to the former abundance (more than 100,000 tones). Biological reference points of a precautionary approach for fisheries management - B_{lim} and B_{pa} estimated with a use of standard procedures [3] with account of historic fishery (1989-2015) compose less than 10,000 tones. Along with that, it is assumed that during 1989-2006 when spawning biomass was less than 10,000 tones, the population was in a depressed state and the purpose of fisheries management was stock recovery to spawning biomass of 30,000-40,000 tones. Stock has been recovered under relatively high recruitments of 2004-2009 (XSA assessments). Geometric mean recruitment for that period made up more than 160 million ind. Considering that estimated biological reference points were rather low, it was assumed a priori that B_{lim} and B_{pa} were equal to 20,000 tons and 40,000 tons respectively.

Assessments based on a precautionary approach used the same recruitment options as in the first approach. If recruitment abundance maintains at a low level (33,8 million ind), only exploitation at the level of 0,02-0,08 will allow the population to be above the assumed limiting level B_{lim} and stock biomass is very likely could fall below this level. At the same time, redfish yield should not exceed 5,000 tons (Fig 4A).

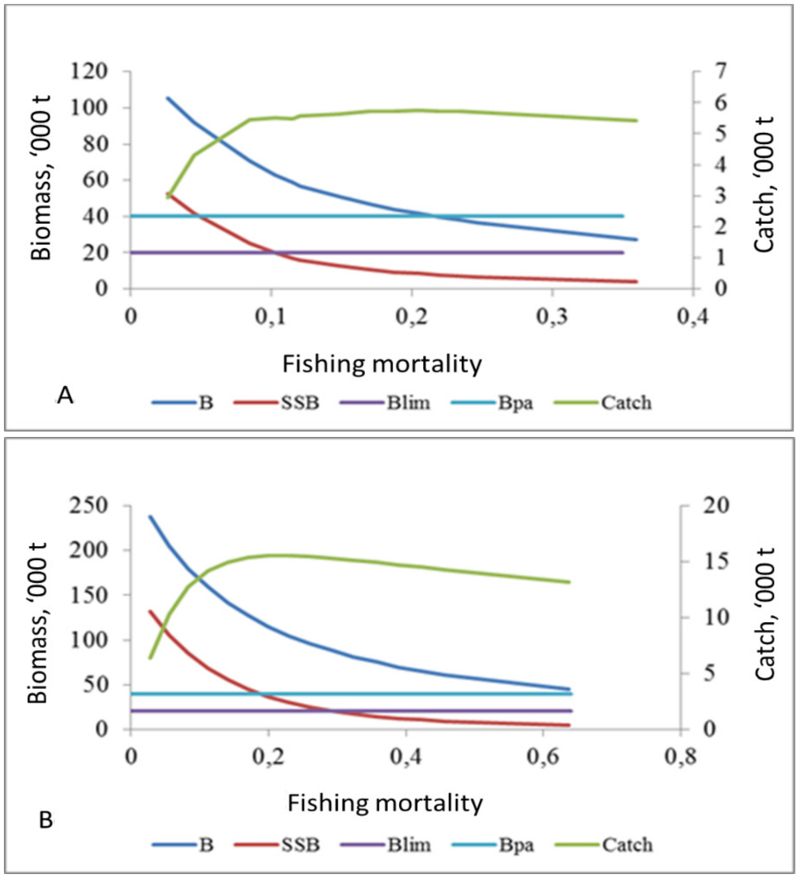

Fig. 4. Dynamics of fishing and spawning biomass and of yield depending on fishing mortality with constant recruitment values of the Flemish Cap redfish commercial stock (A – low recruitment 33,8 million ind., B – mean long-term recruitment 94,5 million ind.) under the set values of biological reference points B_{lim} and B_{pa} equal to 20,000 tons and 40,000 tons respectively

If recruitment is equal to an average value for 1989-2012, than fishery may be conducted with fishing mortality not exceeding 0,24 in order to maintain spawning biomass at the Bpa level. Maximum yield of 15,600 tons can be achieved if fishing mortality is 0,21 (Figure 4B).

In our opinion, the most interesting are the simulation results based on recruitment variation by the Beverton–Holt model using a random error. Within the range of targeted fishing mortality values (F_c) 0,05–0,3, for each F value 100 model runs were made and 5, 50 and 95 percentiles of each parameter distribution were determined: biomass of fishing and spawning stock, abundance, actual fishing mortality (F_{fac}t) and yield. Limited stochastic calculations (100) are due to large amount of computer work required. It takes about 1 minute of processor time for one run; therefore it takes no less than 8 hours to make 500 runs. It was checked that if a number of runs was increased to 1000, an average value and confidence intervals of stock parameters would unlikely change significantly. Calculation results are presented in the Table 2.

In this simulation option maximum yield of 18,900 tons could be obtained if fishing mortality was 0,22; and stock biomass would compose 130,900 tons (confidence interval l117,7-147,0), spawning biomass would be 41,800 tons (confidence interval 37,2-48,4) (Table 2). Average recruitment value for the period would be 114,300,000 ind (confidence interval 97,700,000-131,800,000 ind).

Table 2 – Percentiles of major parameters distribution of the Flemish Cap redfish population in the stochastic prediction of 100 steps forward

		Targeted values of fishing mortality Fc								
Indices		0,05	0,06	**0,07**	0,09	0,1	0,15	0,2	0,25	0,3
F_{fact}	5 %	0,055	0,082	**0,203**	0,240	0,249	0,285	0,303	0,332	0,345
	50 %	0,074	0,117	**0,219**	0,252	0,259	0,298	0,321	0,346	0,365
	95 %	0,155	0,172	**0,230**	0,265	0,274	0,313	0,333	0,363	0,363
B	5 %	178,4	152,4	**117,7**	111,4	106,9	91,7	80,9	75,0	68,6
	50 %	247,1	200,5	**130,9**	116,1	111,1	96,1	85,1	78,1	72,7
	95 %	283,2	252,6	**147,0**	121,8	117,2	101,0	90,1	81,8	76,2
SSB	5 %	73,3	58,5	**37,2**	31,7	29,4	21,9	17,5	14,9	12,9
	50 %	126,8	90,5	**41,8**	33,0	30,5	22,8	18,3	15,4	13,5
	95 %	154,9	128,1	**48,4**	34,5	32,0	23,8	19,1	16,1	14,0
N	5 %	590390	559415	**339284**	397437	341267	328208	326154	275846	277255
	50 %	850680	738447	**553264**	505674	487858	453523	412567	383197	351425
	95 %	100937 6	935413	**782761**	642722	589535	572386	511590	464975	417519
C	5 %	13,3	16,3	**16,2**	17,1	16,9	15,8	14,6	14,3	13,4
	50 %	15,0	17,7	**18,9**	18,4	17,9	17,0	15,9	15,2	14,7
	95 %	20,0	19,3	**21,8**	19,9	19,6	18,5	17,4	16,5	15,9
R	5 %	112908	109186	**97661**	104499	-	96724	-	-	83876
	50 %	124636	122514	**114270**	111053	-	104386	-	-	93217
	95 %	134942	134367	**131706**	121431	-	115494	-	-	101133

Figure 5 shows the dynamics of major population parameters in order to get optimum value of targeted fishing mortality Fc.

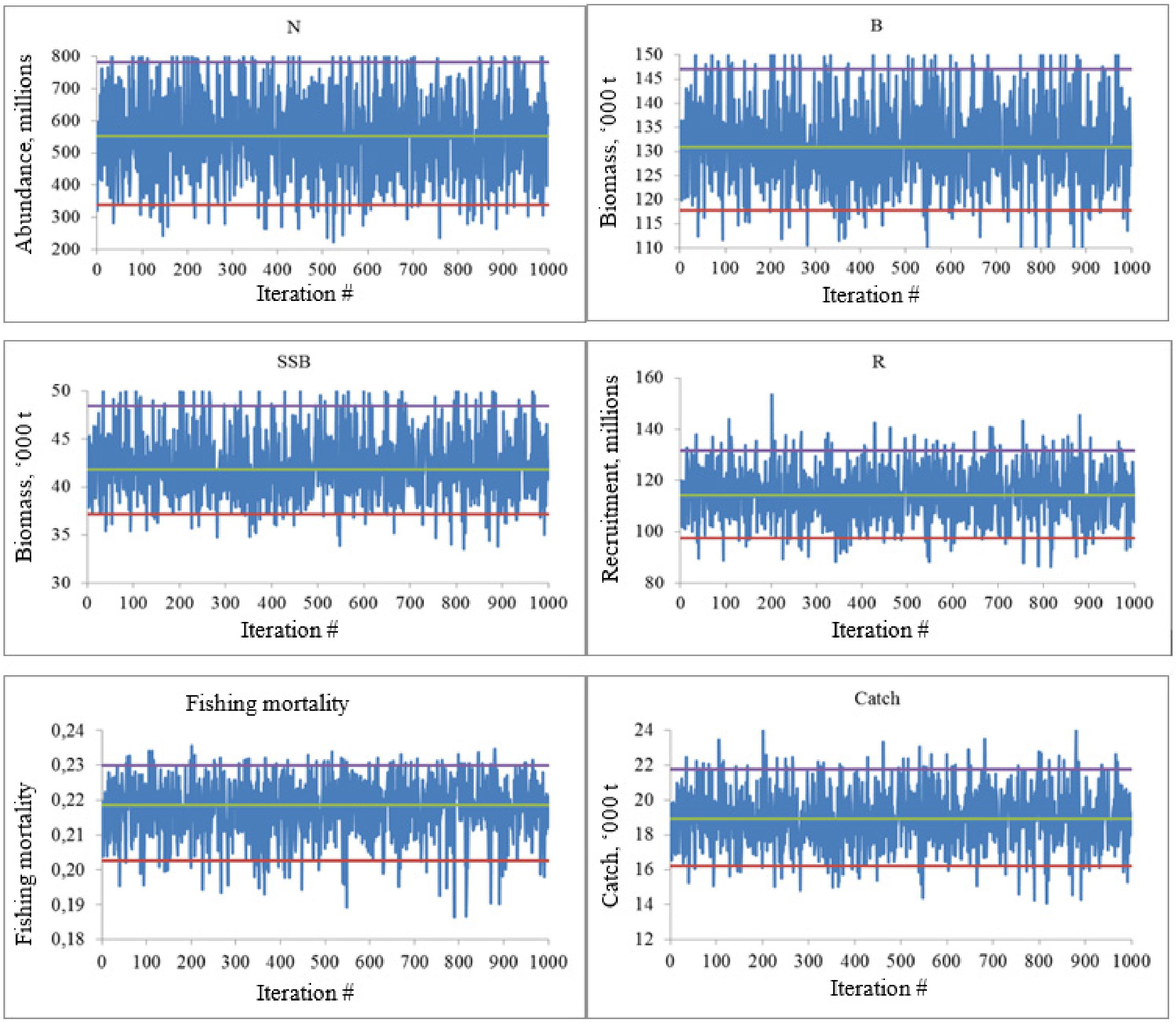

Fig. 5. Range of variations of the Flemish Cap redfish population parameters under the stochastic option of optimum fishery

Discussion

Russian and foreign scientists took numerous researches on applying mathematical models to estimate the Flemish Cap redfish stock [4, 5, 6, 7, 8]. This paper attempted to assess biological reference points for the Flemish Cap redfish stock and to apply precautionary approach to regulate its fishery. Unfortunately, the considered period of historical fishery (1989-2015) is short, and in most of it (1991-2005) the stock was in a depleted state and in the recovery process. Therefore, biological reference points of stock biomass estimated by the accepted methods are rather low to our mind and that's why our calculations used the values corresponding to the current recovered redfish stock, i.e. B_{lim}=20,000 tons and B_{pa}=40,000 tons were used. Biological reference points of fishing mortality were not reconsidered.

The studies have shown that in the long-term the Flemish Cap redfish stock is determined by the recruitment value. When recruitment values exceed 95,000,000 ind (arithmetic mean for 1898-2012) under both constant recruitment and recruitment simulation by the Beverton–Holt curve taking into account a random error, optimum fishery can be implemented if fishing mortality F is in the range of 0,18-0,22, which is close to targeted reference point F_{max} (0,21) and much higher than F_{msy} (0,08). Under such fisheries intensity, yield could compose 15,000-20,000 tons, and fishing and spawning biomass could vary within a range of 120,000-160,000 tons and 40,000-50,000 tons respectively.

The studies have shown that biological reference points of a precautionary approach for fishing mortality were acceptable for the stock exploitation. However, the choice of its values against fisheries management depends on the assumed recruitment abundance of a commercial stock (especially in the long-term). If recruitments are lower than mean long-term values, fishery with F equal to F_{msy} (0,08), $F_{0.1}$ (0,11) or close to that values can be recommended, yield may reach about 10,000 tons. In case recruitments are predicted to be at the level above 100,000,000 tons, the exploitation level can grow up to F_{max} (0,2), and yield may increase to 15,000-20,000 tons subject to the recruitment value. In this context stock will be within safe biological limits (spawning biomass is very likely to exceed 25,000 tons). NAFO SC currently manages redfish stock under assumption of low recruitment (approximately 64,000,000 ind) and fishing mortality close to F_{msy}.

Conclusion

The main (determining) factor of a stock state and the Flemish Cap redfish fishery in the long-term is the recruitment value. Simulation of redfish fishery with various recruitment values has shown that under constant recruitment estimated at 95,000,000 ind (arithmetic mean for 1898-2012) and under recruitment simulation by the Beverton–Holt curve taking into account a random error, optimum fishery can be carried out if fishing mortality F is in the range of 0,18-0,22 which is close to targeted reference point F_{max} (0,21) and much higher than F_{msy} (0,08). Under such fisheries intensity yield could compose 15,000-20,000 tons, and fishing and spawning biomass could vary within a range of 120,000-160,000 tons and 40,000-50,000 tons respectively. If recruitments are lower than mean long-term values, fishery with F equal to F_{msy} (0,08), $F_{0.1}$ (0,11) or close to that values can be recommended, yield may reach about 10,000 tons.

The studies have shown that biological reference points of a precautionary approach for fishing mortality were acceptable for the Flemish Cap redfish stock exploitation. However, the choice of its values for fisheries management depends on the assumed recruitment abundance of a commercial stock (especially in the long-term). Biological reference points for biomass were not reliably estimated by standard procedures. When simulating the fishery, taking into account a precautionary approach, biomass reference points were chosen a priori.

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