Modeling for Scenarios for Stock Recovery of Russian Sturgeon

Acipenser gueldenstaedtii in the Sea of Azov in the Absence of Natural Reproduction

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Abstract—A new model describing the dynamics of sturgeon (Acipenseridae) population unable to recover or ranked as depleted is proposed as a depleted artificially-stocking population (DAP) model. The model composed of two submodels is implemented in the R language. One of the submodels provides the opportunity to adjust the appropriate parameters used in a global model (the rate of natural mortality of a mature fish stock in a population and the artificial reproduction efficiency) with the optimization-based methods, while the second submodel deals with various scenarios for fish stock recovery over the forecast period. Scenarios are characterized by two parameters: the quantity of juveniles released by sturgeon hatcheries and the commercial fish catch decline caused by the illegal fishing practices and the fish catch for science-based targets. The estimates for the pattern of the Russian sturgeon Acipenser gueldenstaedtii in the Sea of Azov indicate that its stock may be recovered to the target level of 10 thousand tons with the baseline and optimistic scenarios by 2037—2048 relative to the artificial reproduction efficiency and the extent of illegal, unreported, and unregulated fishing. With respect to pessimistic scenarios, the stocks are not expected to recover.

Keywords: Russian sturgeon Acipenser gueldenstaedtii, population, modeling, fish stock recovery, Sea of Azov

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INTRODUCTION

At present, a catastrophic decline in the Russian sturgeon Acipenser gueldenstaedtii in the Sea of Azov (Chepurnaya and Rekov, 2017; Rekov and Chepurnaya, 2018) can be observed. The authors focused on the task of estimating the possible ways to recover this fish stock under various factors affecting it. In order to consider the possible variants for recovering the Russian sturgeon population in the Sea of Azov, the long-term dynamics of the population size need to be analyzed, which may be done in general with the cohort, surplus production models, and the methods used in case of a lack of information (Babayan et al., 2018).

The cohort methods can provide the opportunity to consider the biological characteristics in modeling the fish population. However, they have the higher standards for volume and quality of the input data (including the data on the age structure in fish catches). However, they are unusable in case of insufficient statistics on commercial fishing.

Surplus production models are less demanding for input data. Within this approach, the population is considered as an aggregation of similar specimens without regard to their age structure. Parametrization of a production model requires the time series of fisheries statistics, including the annual catches and the fishing effort over many years. These time series should cover a rather long interval period, longer than the specimen life cycle for a certain population. In addition, the data on the fishing effort should be standardized.

The data limited methods (DLM) (Carruthers et al., 2014) were developed for cases described by the insufficient quality-dimension input data. They particularly involve the model based on the depletion-based stock reduction analysis (DB-SRA) (Dick and MacCall, 2011). It is based on the production model describing the mature stock recruitment functionally related to its biomass. This model can provide the opportunity to estimate the guide setting and the dynamics of retrospective study of stock biomass, which is followed by prognosis based on supposition that the production capacity of a population is not changed over time. The DB-SRA model was efficiently used to estimate the status of a population of the stellatus A. stellatus in the Caspian Sea (Ye and Valbo-Jørgensen, 2012; Sapharaliev et al., 2019).
However, its application relative to the Russian sturgeon in the Sea of Azov is impossible, since the natural reproduction in this species is absent for many years because of inaccessible spawning grounds after overregulation of streamflows of the Don and Kuban rivers.

According to the data obtained by Gorbacheva et al. (2020), the generations of the Russian sturgeon in the Sea of Azov, those born since 1972, comprise 100% of sturgeon hatchery-reared fish, except the generations as those born between 1978 and 1981, which comprise approximately 30% of specimens of natural reproduction. However, the last statement is of doubtful authenticity, since the error in age estimation of fish caught in the subsequent years cannot be avoided. Therefore, it can be considered that reproduction of the Russian sturgeon in the Sea of Azov in the last 30 years does not depend on the mature fish stock quantity or biomass. The data on the Russian sturgeon catches in the last 20 years are not available, because its commercial fishing in the Sea of Azov has been banned since 2000. In addition, the expert estimates for illegal, unreported, and unregulated fishing (IUU fishing) are available only for the 1994—1999 period (Chepurnaya et al., 2008). Therefore, it is not possible to use the production models including DB-SRA model because of the absence of natural reproduction of a sturgeon population and the missing data on fishing catches and efforts.

In this context, the actual task is to develop a model for population dynamics, based on the datasets of artificial fish stock recovery, retrospective patterns in commercial catches, IUU fishing intensity estimates, and biological characteristics of the Russian sturgeon Acipenser gueldenstaedtii.

**EXPERIMENTAL**

In order to assess the stock of the Russian sturgeon in the Sea of Azov in model dynamics, the depleted artificially-stocking population (DAP) model was developed. This model is implemented in the R language (R Core Team, 2016). It is composed of two submodels. One of the submodels refers to adjusting the model parameters with the method of least squares. An iterative procedure of comparing the model range values for the mature fish stock in a population \(B(y)\) and the values for the same stock, received with the accounting surveys data 1981—1999 \(B(\text{priority})\) is used.

Smoothing data of accounting surveys with the three-point moving average method is predominantly performed to separate out the interannual fluctuations and inaccuracy assessment with the direct method. This submodel records the time series for catch datasets over a long-term period, including both the catches in official fisheries \(C_f\) and the illegal, unreported, and unregulated catches \(C_{\text{iuu}}\). In addition, it includes the data on the annual juvenile fish release from the fish hatcheries \(N_{\text{juv}}(y)\) and the mature specimen medium weight \(W_M(\text{M})\) estimated with the data on the age-related dynamics of body weight \(W(x)\) based on the gender. The values for the catches of IUU fishing over 1989—1999 were produced with the piece-wise-linear approximation of expert reviews for 1994—1999 (Fig. 1). With respect to the 1981—1988 period, it was assumed that the IUU-fishing catches comprised 10% of the official fishery catches. Any values for this parameter in the Azov-and-Don water basin for the given period are unfortunately unavailable.

Setting up the model involves optimization of the parameters as the annual rate of mature fish natural mortality \(\varphi_M\), the post-release survival rate of juvenile fish up to the age at maturity \(rr\) (equivalent to the commercial stock recovery rate), and the mature-fish stock biomass for the first year of the selected period in the model settings \(B_0\).

Estimation of the mature-fish stock biomass per year is performed with the formula:

\[
B_{\text{rec}(y)} = N_{\text{juv}_{y-i}} W_Mrr,
\]

where \(i\) denotes the age at maturity and \(N_{\text{juv}_{y-i}}\) denotes the number of juvenile Russian sturgeon released per year \((y-i)\).

The agreed value \(rr = 0.01\ (1\%)\) is used as the initial value in the model, which is reconciled with the published data: 1.1—1.3% (Boiko and Kalinkina, 1961; Makarov, 1964; Rekov and Korneev, 1987) and 0.6% (Zaidiner et al., 2000).

The biomass of the mature stock at the start of the following year is estimated with the formula:

\[
B_{y+1} = B_y \left(1 - \varphi_M\right) + B_y \left(\frac{W_y}{W_M}\right) + B_{\text{rec}(y)} - C_{\text{total}(y)},
\]

where \(B_y\) denotes the mature stock biomass at the start of a year \((y)\), \(C_{\text{total}(y)} = C_f + C_{\text{iuu}_{y-i}}\), where \(C_f\) and \(C_{\text{iuu}_{y-i}}\) denote the time series for the official fishery catches and the IUU-fishing catches, respectively, per year \((y)\), \(\varphi_M\) denotes the time series for the official fishery catches and the IUU-fishing catches, respectively, per year \((y)\), \(W_M\) denotes the annual rate of natural mortality, \(W_M\) denotes the average body mass of the mature stock specimens, and \(W_f\) denotes the average annual body-mass gain in mature specimens.

The values for the relationship between the mature-specimen body mass and its age were estimated (for the males at 6—21 years old \((W1(x))\) and the females aged 10 to 25 \((W2(x))\). It was performed with the average long-term data (Kozlitina et al., 2005) and the linear functions \((R^2 = 0.97\ in \ both\ cases)\) as \(W1(x) = 0.8482x + 1.47\) and \(W2(x) = 1.764x - 5.013\), respectively. The agreed average values for the annual body mass gain in males and females (0.848 kg and 1.764 kg, respectively) \(W_f = 1.306\) kg were subsequently used in the estimates.

The average age at sexual maturity is determined based on the curve of the sexual maturity in the Rus-
sian sturgeon with the Logit-model method (Mikhail-
yuk and Piatinskii, 2020). The agreed value for it is 
14 years (17 years for females and 12 years for males), 
which is consistent with the results of the Chepurnaya 
and Rekov (2017). The average body mass of a speci-
men at the age at maturity ($W_M$) is considered as 17 kg.

It should be noted that the DAP model involves 
estimation for two periods, where the first period is 
selected for setting up the model (1981—1999), while 
the second period is prognostic (2021—2050). As a 
rule, there are some gap years between these periods 
under the fishing moratorium, when the model does 
not evaluate the stock.

The stock assessment is performed with the 
method of accounting surveys of sturgeon fish in some 
month ($m$) except at the beginning of a year. There-
fore, re-estimation of the $B_y$ model range was per-
formed prior to the moment of of accounting surveys. 
The biomass stock for month $m$ in year $y$ is calculated 
with the formula:

$$B_{my} = B_{y} + (B_{y+1} - B_{y}) \frac{m}{12}. \quad (3)$$

The second submodel deals with various scenarios 
to manage the fish stock in the forecast period. The 
estimates for the mature-stock biomass in the forecast 
period are performed with the same equation (2) and 
the same set of optimal values for rates ($\varphi_M$ and $rr$). 

However, it requires setting up the biomass stock for 
the previous year, 2020, since accounting survey 
showed the value close to zero. Therefore, it is agreed 
as $B_{0(2020)} = 0$.

The prognostic model analyzed 24 stock recovery 
scenarios for different combinations of two managing 
parameters: the number of hatchery-reared juvenile 
fish released relative to the time lag of 14 years equal to 
the age at maturity ($N_{juv_{y-14}}$) and the IUU catch share 
in the biomass stock at the beginning of each year ($biuu-coef$). Prior to 2020 included, the quantity of 
juvenile fish released to the wild ($N_{juv}$) is well known 
(the data of hatchery official statistics). Since 2021, the 
$N_{juv}$ constant value is set up for each scenario. Since 
2035, it intends to determine the amount of fish 
recruitment biomass ($B_{rec}$) according to formula (1). 
Different scenarios deal with the four $N_{juv}$ levels in the 
forecast period. They include the observed long-term 
average release level with 3 million units, the optimis-
tic release scenario version with 5 million units, the 
pessimistic scenario version with 1 million units, and 
the maximum value observed in the retrospective cycle 
with 7 million units.

The $biuu-coef$ coefficient values of 1, 5, 7, 10, 15, 
and 20% are set up in the range of 1 to 20% of biomass 
stock at the start of the year, which do not exceed the 
limits for this parameter in the retrospective period 
(20%).
In order to test the validity of a constructed model, the model sensibility test as a diagnostic procedure was performed. The sensibility test provides the opportunity to assess the model deviations of the local optima from the global optima of the model parameter estimates (stock biomass, recruitment biomass, and fishing mortality), which can cause the modeling errors, when setting up the optimal option scheme ($\phi_M$, $rr$, and $B_0$). The uncertainty test can provide the opportunity to measure the deviations in assessing the stock biomass, occurring because of the uncertainty in the estimates of the fishing mortality in the retrospective period.

The sensibility test was performed with 75% of all the three-parameter options ($\phi_M$, $rr$, and $B_0$) selected at random. Thereafter, re-estimation of all the characteristics for stocks (the biomass stock, its recruitment biomass, and the fishing mortality) is performed for each of the selected option sets. It is followed by sorting the estimates produced for each accounting year ($y$) in ascending order and determining the median estimates and 95-% confidence intervals for each year. The intervals calculated for each case represent the estimates for the potential degree of the actual stock size because of the model incorrect parameterization seemed quite possible. The sensibility test procedure is performed as an iterative procedure of the Monte-Carlo method. The produced median estimates and confidence intervals are compared with the model estimates produced via general optimization ($\phi_M$, $rr$, and $B_0$) in order to determine the degree of reliability and validity of the stock assessment.

The test for uncertainty of the dynamic system of “stock-fishery” to the factor associated with variability in the fishing mortality was performed according to the procedure of testing the models in ICES/FAO (Precautionary..., 1996; A Fishery..., 2002) (this test is especially important because of the uncertainty in the estimates for catches by IUU fishing). The idea of the procedure is in the potential degree of variability in the stock size relative to the previous period. This test is used to perform long-term forecasting of the potential variation in the stock biomass relative to the previous observations for the dynamic system “stock-fishery”. The standard deviation value for a range of values for the fishing mortality in the retrospective period is used as variability estimation. Thereafter, this value is converted to the scale of the stock biomass estimates. Based on the performed variability estimation and the known values for the averages of biomass stock in the retrospective period, the pseudo-random sequences for the biomass stock estimates are generated. The produced pseudo-random sequences are sorted in ascending order. Thereafter, the 95-% confidence intervals are estimated.

Despite the commercial fisheries of the Russian sturgeon in the forecast period is not expected, the acceptable catch validated by the science-based targets for research work and artificial reproduction (hereinafter, total allowable catch for research work (TAC RW)) is, nevertheless, modeled by the forecast sub-model. Assessment of TAC RW is performed in order to measure the exact amount of catch, which cannot significantly affect the mature stock in the prognostic model period. Therefore, a certain proportion of a confidence interval size is estimated to assess the biomass stock, based on the uncertainty test results and the baseline prognosis scenario ($biuu-coef = 0.1$, $NJuV = 3$ million units). This range can describe the potential degree of variability in the stock size each year. It is considered that a small catch share of this range should not significantly affect the stock biomass in the forecast period.

In order to determine an insignificant share of TAC RW, the share of the uncertainty range at several levels (1, 5, 10, 50, and 100%) was tested. In addition, the conclusion for the insignificant impact of TAC RW was taken based on analyzing its effect on the time period of achieving the guideline for management ($B_0$). The impact level was considered insignificant, when the time period of reaching the target baseline shifted no longer than a year.

RESULTS

The optimal decision-making procedure for the input data over the 1981—1999 period resulted in producing the estimates for three major parameters of the model (Table 1). The recruit biomass and stock biomass estimates (Fig. 2) for retrospective period were performed based on the optimal decisions for the model parameters with equations (1)—(3). An increase in the rate of fishing mortality (Fig 2c) at the end of setting up the model is associated with both the high-level estimates for illegal catch (Fig 1) and the sharp decline in stock biomass. The sensibility and uncertainty tests (Fig. 3 and Fig. 4, respectively) were performed to diagnose the results of modeling.

The analysis of the Russian-sturgeon stock dynamics produced for the retrospective study period in setting up the model (Fig. 2a) showed that the environmental conditions during the period favorable for the stock recovery (1988—1998) could provide the opportunity to maintain the population mature-stock biomass at the level of 10 thousand tons. Thus, the problem of fish stock recovery up to this level ($B_0 = 10000$ tons) as a baseline for management of the Russian sturgeon stock and fishing activities was considered to overcome with the projection-based scenarios. Therefore, the stock is considered recovered, if its biomass reached 10000 tons in modeling the possible projection-based scenarios.

With respect to the forecast period, the 24 scenarios with different combinations of the key parameters including the number of hatchery-reared juveniles
released 14 years ago (Njuv) and the biuu-coef coefficient constant throughout the entire forecast period were observed. A scenario with strategies of annual releasing 3 million hatchery-reared specimens (at the level of an average long-term release in the retro period) was sampled as a baseline (and most real) scenario at biuu-coef = 0.1 (10% stock biomass at the beginning of a year). Fig. 5 shows the estimates for the mature population stock and the recruitment biomass for the baseline scenario. The recovery of the Russian sturgeon for commercial fishing is not considered. However, insignificant catch validated by the TAC RW at the level of 1% of the confidence interval size measured by the uncertainty test for science-based target works and generation of the hatchery replacement broodstock is set up (Fig. 6).

The baseline scenario provides a guideline for the stock biomass of 10 thousand tons in 2048, which can continue to increase, if the fisheries regime remains the same (Fig. 5). The recruitment biomass tends to stabilize at 931 tons since 2035 in case of the annual hatchery-reared yearling release fixed at 3 million units.

Fig. 6 shows the stock dynamics with the confidence intervals estimated for the conditions similar to

| Parameter | Initial value | Target changing ranges | Optimal value |
|-----------|---------------|------------------------|---------------|
| ϕ₀       | 0.05          | 0.04–0.10              | 0.0412        |
| rr        | 0.01          | 0.005–0.020            | 0.0182        |
| B₀, tons  | 6000          | 4000–8000              | 4400          |

Table 1. Estimates for three parameters of DAP model for the stock of the Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov

![Fig. 2. Results of modeling the parameters for the stock of Russian sturgeon Acipenser gueldenstaedtii in the Sea of Azov in the period of setting up the model in 1981–1999: (a) stock biomass, (b) biomass of recruits, (c) fishing mortality rate, (---) denotes DAP model, (—) denotes data on fish-counting captures, and (···) denotes the target baseline for 10 thousand tons.](image)
Fig. 3. Sensibility test to estimate the stock biomass (a) and the fishing mortality (b) in Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov; the Monte-Carlo method, when setting up the optimal option scheme. (---) denotes model estimates relative to global optimization, (—) denotes median estimates after the Monte-Carlo procedure, (■) denotes confidence intervals (\( p = 0.95 \)) of median estimates, (○) denotes direct estimates of the mature stock with the accounting survey method.

Fig. 4. Uncertainty test to estimate the stock biomass of Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov relative to variation in its fishing mortality at setting up the model. See Fig. 3 for designation.
Fig. 5. Outcomes of prognostic dynamic model for stock biomass (—) and recruitment biomass (---) of Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov according to the baseline scenario, 2018—2050.

Fig. 6. Baseline scenario for prognosis for the stock biomass of Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov in 2018—2050: (a) sensibility test, (b) uncertainty test, (---) denotes model estimates for stock biomass, and (—) denotes the test median estimate; See Fig. 3 for the other designation.
Fig. 7. Total allowable catch for Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov for the research work and reproduction (TAC RW) targets by model outcomes for shares of uncertainty in 2020—2050. (a) a baseline scenario (*Njuv* = 3 million units., *biuu-coef* = 0.1), (b) pessimistic scenario (*Njuv* = 3 million units, *biuu-coef* = 0.2), (—) denotes the theoretically allowable level of TAC RW, (···) denotes the upper asymptote of a maximum potential for TAC RW (6.13 tons) by the logarithmic curve (*y* = 1.2664ln(*x*) + 1.7869, *R*² = 0.7559), and (— -) denotes logarithmic approximation for stock biomass estimates.

The equation for the total allowable catch in the forecast period after 2034 is expressed as the formula: 

\[
C_{total}(y) = C_y + C_{iuu-y} = C_y + biuu-coef \times B_y.
\]

Symbol *C*ₚ denotes the allowable catch for the TAC RW, insignificant for the mature-stock biomass, (Fig. 7) and *C*ᵢᵩᵫᵧ denotes the IUU-catch extent proportion of the mature stock biomass in the beginning of the year (*C*ᵢᵩᵫᵧ = *biuu-coef* × *B*ᵯ).

The test results for different levels of TAC RW throughout the forecast period showed that an insignificant shift for a year of achieving the model-based guideline is generated at 1% catch of a confidence interval size relative to the stock estimates in the uncertainty test. In order to prevent any disorder in the process of stock recovery because of uncertainty in IUU fishing, the limited (maximum permitted) quantity for TAC RW for different scenarios was decided to estimate taking into account the probability of occurring the most pessimistic scenario. The maximum value for TAC RW in all the scenarios was fixed at the maximum level estimated for the pessimistic scenario, which comprised 6.13 tons (*biuu-coef* = 0.2 and *Njuv* = 3 million units). This value corresponds to the maximum value for the non-line function describing the correlation between a given year and its annual catch limit in the forecast period (Fig. 7b). The probable TAC RW values produced for the baseline scenario are set up into all the modeling scenarios as the values for the legal fish catch (*C*ᵯ).

The other three scenarios for the fish stock recovery with the other values for *Njuv*, but the same value for *biuu-coef* = 0.1, estimated for the baseline scenario, are present in Fig. 8 along with the baseline scenario. The stock biomass for these four scenarios varies similarly up to 2034 as long as the real quantity of juvenile fish released determines the *Njuv*.

The outcomes of the prognostic submodel for all of the 24 scenarios of stock dynamics given in four variants of numbers of juvenile fish released annually (1, 3, 5, and 7 million units) at the six reference variants of values for *biuu-coef* (0.01, 0.05, 0.07, 0.10, 0.15, and 0.20) are present in Table 2.
Fig. 8. Four scenarios for biomass stock recovery of Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov (taking into consideration the catch for the TAC RW for a baseline scenario relative to $\text{biuu-coef} = 0.1$) relative to the different quantity of hatchery-reared juveniles for releases after 2034. (⋯), (—), (− −), and (− · −) denote 1 million units/year, 3 million units/year, 5 million units/year, and 7 million units/year, respectively.

played outside the confidence intervals and shifted aside the median to the same side. A meaningful conclusion based on this test may be drawn on the shift in the model estimates for three parameters relative to the absolute optimum setup, which can cause the upward and downward bias when measuring the stock biomass and the fishing mortality, respectively.

The uncertainty test outcomes (Fig. 4) also indicate the longer ranges of the probability estimates after 1990. Thus, a decrease in the predictive validity of a retrospective model setup is probably caused by the insufficient information on IUU fishing activities and the multifold intensity increase in its effects on the Russian sturgeon population from year to year. In addition, a decrease in the predictive validity of the produced estimates for stock biomass, recruits, and fishing mortality after the 1990s is probably caused by uncertainty and (or) time variability in parameters $rr$ and $\varphi_M$ in different model periods. Parameters $rr$ and $\varphi_M$ in the model are considered constant. This model assumption may be incorrect, however, this is considered appropriate with the limited data.

All the prognostic model scenarios excluding the most pessimistic scenarios generally indicate the opportunity to recover the Russian sturgeon stock in a long-term perspective. Thus, the most probable scenario, where the IUU-fishing catch is no more than 10% of stock biomass as of the beginning of a year and the number of hatchery-reared juveniles released into the wild remains at the level of the long-term average of 3 million units, assumes recovery the mature-fish stock biomass up to 10 thousand tons by 2048. With respect to the high numbers of the hatchery-reared juveniles released into the wild (5 million units), it may occur by 2037.

The more optimistic scenarios (under the stricter management of IUU fishing and with the increased capacity of hatcheries) provide the opportunity to recover the stock up to the model-based guideline level by 2028. In addition, the scenarios, where the number of the hatchery-reared juvenile fish released into the wild comprises 7 million units per year, seem quite optimistic. Thus, the $B_r$ guideline level may be reached, despite 15% IUU-fishing catches of the stock biomass.
Moreover, the more pessimistic scenarios are also observed. Thus, it seems impossible to reach the baseline level of stock recovery until 2050 regardless of the numbers of the hatchery-reared juvenils released in case of weakening the regulation on the IUU fishing activities (variant $biuu-coef = 0.20$). With respect to the low numbers of the hatchery-reared fish released (1 million units per year), the prognosis is also unfavorable, since the baseline level cannot be achieved, exhibiting a declining trend in the fish stock biomass.

The survey outcomes coincide well with the withdrawal decisions of the other authors (Chepurnaya et al., 2008; Chepurnaya and Rekov, 2017; Rekov and Chepurnaya, 2018), who report the critical state of the Russian sturgeon stock in the Sea of Azov in the period of fishing bans and the predominant negative effects of IUU fishing. In addition, they inform that releases of juvenils of 2.8 million units per year and no less are required for the stock recovery. This number of fish for release is used in the baseline scenario considered in this research paper. In addition, Shlyakhov et al. (2005) also indicate the IUU fishing practice as a predominant negative factor affecting the Russian sturgeon stock biomass.

Modeling the possible TAC RW for the scientific and reproduction targets indicates the available resources for catch with increasing the stock from 4.86 to 6.13 tons in 2022 and 2050, respectively, according to the baseline scenario (Fig. 7a). In the pessimistic scenario, the catch for the TAC RW and reproduction targets may comprise 3.46 tons and 5.90 tons, respectively (Fig. 7b). The outcomes of modeling have showed that the catch of such quantity cannot have any significant effect on the mature-fish stock biomass over the forecast period under consideration. This recommendation coincides well with the protocol on the "XXXII session of the Russian and Ukrainian Fisheries Commission for the Sea of Azov", where the Russian sturgeon fishing activities are banned. With respect to the catch for the scientific and reproduction targets, the TAC quotas for the Russian Federation and Ukraine were set at 3.81 and 0.20 tons, respectively. It should be noted that the present recommendations for the TAC RW are not expected to have any significant impact on the fish stock dynamics within the modeling scenarios.

### CONCLUSIONS

The proposed DAP model may be used in a case, when the stock reproduction is maintained only by releasing the hatchery-reared juvenile-fish. The other essential condition to use the model is relevant to the available estimates for the fish stock and the fisheries

### Table 2. Analysis outcomes for 24 scenarios for stock recovery of Russian sturgeon *Acipenser gueldenstaedtii* in the Sea of Azov

| Number of juvenile fish for release, million units/year | Item                      | $biuu-coef$ |
|--------------------------------------------------------|---------------------------|-------------|
|                                                        |                           | 0.01 | 0.05 | 0.07 | 0.10 | 0.15 | 0.20 |
| 3                                                      | Stock biomass in 2050, tons | 43150 | 21495 | 15915 | **10749** | 6386 | 4281 |
|                                                        | Year of achieving $B_{ir} = 10$ thousand tons | 2029 | 2032 | 2035 | **2048** | * | * |
|                                                        | Stock trends               | + | + | + | + | + |
| 5                                                      | Stock biomass in 2050, tons | 55061 | 29854 | 22977 | **16296** | 10216 | 7032 |
|                                                        | Year of achieving $B_{ir} = 10$ thousand tons | 2029 | 2032 | 2035 | **2037** | 2048 | * |
|                                                        | Stock trends               | + | + | + | + | + |
| 1                                                      | Stock biomass in 2050, tons | 31238 | 13136 | 8853 | **5202** | 2557 | 1532 |
|                                                        | Year of achieving $B_{ir} = 10$ thousand tons | 2028 | 2032 | * | * | * | * |
|                                                        | Stock trends               | + | + | + | + | + |
| 7                                                      | Stock biomass in 2050, tons | 66973 | 38213 | 30039 | **21843** | 14045 | 9781 |
|                                                        | Year of achieving $B_{ir} = 10$ thousand tons | 2028 | 2032 | 2035 | **2036** | 2039 | * |
|                                                        | Stock trends               | + | + | + | + | + |

*The target level is not reached; biomass stock trend after 2034: “+” and “−” denote increase and decrease, respectively; the outcomes of scenarios present in Fig. 8 are given with the demi-bold font*
resources in the favorable period of the stock development until the closure for fishing activities. The DAP model may by applied to both the sturgeon species and the other fish species with artificial reproduction.

It should be noted that it is rather difficult to estimate the real fishing mortality because of the uncertain level of IUU fishing and, especially, its variability. The factor of IUU fishing, which substantially exceeds the values for legal fish catch, tends to introduce the high percentage of uncertainty in the model output. The high uncertainty facing the authors’ development may be avoided in modeling, if the catch data represent the reliable time series data.

The outcomes can indicate the depleted status of the Russian sturgeon stock in the Sea of Azov at present. The long-term scenarios considered within the modeling involve both the optimistic turn of events followed by increasing the stock biomass and the pessimistic situation, which may cause the long-term population collapse. The published papers of the other authors (Shlyakhov et al., 2005; Chepurnaya et al., 2008; Chepurnaya and Rekov, 2017; Rekov and Chepurnaya, 2018) can prove a high probability of a pessimistic scenario.

The model outcomes have shown that implementation of the optimistic scenario requires the relevant administrative actions to prevent the IUU fishing practices and to intensify the hatchery-reared juvenile release activities.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interests.

Statement of the welfare of animals. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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REFERENCES

A Fishery Manager’s Guidebook: Management Measures and Their Application. FAO Fisheries Technical Paper No. 424, Rome: UN Food Agric. Org., 2002.

Babayev, V.K., Bobyrev, A.E., Bulgakova, T.I., et al. Metodicheskie rekomendatsii po otsenke zapasov prioritetnykh vidov vodnykh biologicheskikh resursov (Guide for Assessment of Stocks of Priority Species of Aquatic Biological Resources), Moscow: VNIRO, 2018.

Boiko, E.G. and Kalinkina, E.A., Survival of sturgeon juveniles of different weight groups, Rybn. Khoz., 1961, no. 4, pp. 18—22.

Carruthers, Th.R., Punt, A.E., Walters, C.J., et al. Evaluating methods for setting catch limits in data-limited fisheries, Fish. Res., 2014, vol. 153, no. 1, pp. 48—68.

https://doi.org/10.1016/j.fishres.2013.12.014

Chepurnaya, T.A. and Rekov, Yu.I., Dynamics of stocks of Azov sturgeons during fishing embargo, Trudy VIII Mezhdunarodnoi nauchno-prakticheskoi konferentsii “Ekologicheskie problemy. Vzglyad v budushchee” (Proc. VIII Int. Sci.-Pract. Conf. “Ecological Problems: Insight to Future”), Fedorov, Yu.A., Ed., Rostov-on-Don: Yuzh. Fed. Univ., 2017, pp. 511—514.

Chepurnaya, T.A., Tikhonova, G.A., and Rekov, Yu.I., Characteristics of the state of the Azov population of sturgeons in 2006—2007, in Osnovnye problemy rybnogo khozayvstva i okhrany rybokhozaisstvennykh vodoemov Azov-Chernomorskogo basseina (Fishery and the Protection of Fishery Reservoirs of the Azov-Black Sea Basin), Rostov-on-Don: Azov. Nauchno-Issled. Inst. Rybn. Khoz., 2008, pp. 118—124.

Dick, E.J. and MacCall, A.D., Depletion-based stock reduction analysis: a catch based method for determining sustainable yields for data-poor fish stocks, Fish. Res., 2011, vol. 110, no. 2, pp. 331—341.

https://doi.org/10.1016/j.fishres.2011.05.007

Gorbacheva, L.T., Gorbenko, E.V., Panchenko, M.G., et al., The development of artificial reproduction of the Azov sturgeons related with the 150th anniversary of sturgeon farming in Russia, Vodn. Bioresur. Sreda Obitaniya, 2020, vol. 3, no. 4, pp. 111—119.

https://doi.org/10.47921/2619-1024_2020_3_4_111

Kozlitina, S.V., Zhilyakova, L.Yu., Luts, G.I., and Belousov, V.N., Forecasting of the total permissible catch of the main commercial fishes of the Sea of Azov, in Metodi rybokhozyaistvennykh i prirodokhrannykh issledovanii v Azov-Chernomorskom basseine (Methods of Fishery and Nature Protection Studies in the Azov-Black Sea Basin), Volovik, S.P. and Korpakova, I.G., Eds., Rostov-on-Don: Azov. Nauchno-Issled. Inst. Rybn. Khoz., 2005, pp. 215—231.

Makarov, E.V., Evaluation of the survival of sturgeon juveniles grown in the Don fish farms, Tr. VNIRO, 1964, vol. 56, pp. 141—170.

Mikhailyuk, A.N. and Piatinskii, M.M., Assessment of parameters of sexual maturation of hydrobionts in the absence of visual features of maturity of some of the sexually mature.
individuals, *Vodn. Bioresur. Sreda Obitaniya*, 2020, vol. 3, no. 2, pp. 24–29. https://doi.org/10.47921/2619-1024_2020_3_2_24

*Precautionary Approach to Fisheries Part 2: Scientific Papers. FAO Fisheries Technical Paper No. 350*, Rome: UN Food Agric. Org., 1996.

R Core Team, *R: A Language and Environment for Statistical Computing*, Vienna: R Found. Stat. Comput., 2016. https://www.R-project.org/.

Rekov, Yu.I. and Chepurnaya, T.A., The main trends of restoration of commercial stocks of Azov sturgeon fishes, *Materialy Mezhdunarodnoi nauchno-prakticheskoi konferentsii “Aktual'nye voprosy rybolovstva, rybovodstva (akkvakul'tury) i ekologicheskogo monitoringa vodnykh ekosistem”* (Proc. Int. Sci.-Pract. Conf. “Current Problems of Fishery, Fish Farming (Aquaculture), and Ecological Monitoring of Aquatic Ecosystems”), Rostov-on-Don: Azov. Nauchno-Issled. Inst. Rybn. Khoz., 2018, pp. 211–214.

Rekov, Yu.I. and Korneev, A.A., Efficiency of reproduction and replenishment of Azov sturgeon stocks, in *Vosproizvodstvo zapasov osetrovykh v Kaspiiskom i Azovo-Chernomorskom basseinakh* (Reproduction of Sturgeon Stocks in the Caspian and Azov-Black Sea Basins), Moscow: VNIRO, 1987, pp. 9–10.

Safaralieva, I.A., Ruban, G.I., and Bulgakova, T.I., *Kaspiiskaya sevryuga: raspredelenie, otsenka zapasa i stsenarii vosstanovleniya volzhskoi populyatsii* (Caspian Stellate Sturgeon: Distribution, Stock Assessment, and Recovery of the Volga Population), Moscow: VNIRO, 2019.

Shlyakhov, V.A., Gubanov, E.P., and Dem’yenko, K.V., Stocks and unrecorded catches of Azov sturgeons, *Materialy nauchno-prakticheskoi konferentsii “Problemy i resheniya v sovremennom rybnom khozyaistve na Azovskom basseine”* (Proc. Jubilee Sci.-Pract. Conf. “Problems and Solutions in Modern Fishery Industry in the Azov Basin”), Mariupol: Renata, 2005, pp. 59–61.

Ye, Y. and Valbo-Jørgensen, J., Effects of IUU fishing and stock enhancement on and restoration strategies for the stellate sturgeon fishery in the Caspian Sea, *Fish. Res.*, 2012, vol. 131–133, pp. 21–29. https://doi.org/10.1016/j.fishres.2012.06.022

Zaidiner, Yu.I., Gribanova, S.E., and Rekov, Yu.I., New data on the efficiency of sturgeon reproduction in the Azov-Don basin, *Materialy Mezhdunarodnoi konferentsii “Osetrovye na rubezhe XXI veka,” Tezisy dokladov* (Proc. Int. Conf. “Sturgeons in the Turn of 21st Century,” Abstracts of Papers), Astrakhan: Kasp. Nauchno-Issled. Inst. Rybn. Khoz., 2000, pp. 243–244.

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