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A Model of Structural Interaction of Biophysical Factors during Invasive and Hydrological Changes in the Biosystem of the Caspian Sea

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Abstract—Prediction of biophysical processes under the conditions of a rapid change in the composition of the interacting components of a biosystem requires flexible approaches and a logical analysis of the direction, time, and level of strength of systemic interactions. It is unrealistic to construct a predictive model based on the methods developed by the author for organizing hybrid computing structures for a key component of a biophysical system (such a link is usually considered the most valuable population for the economy) without a scheme for the mutual influence of factors acting on the biotic environment. Direct interaction of the "predator—prey," "parasite—host," or "resource—consumer" equations does not fully describe the dynamics of a real biosystem, especially after invasions of aggressive species. This article is devoted to the application of cognitive formalisms of model structuring of conceptual information about the interaction of natural and anthropogenic factors based on the development of graph theory methods. The purpose of the work is to mathematically formalize how a change in one factor will affect the state of other components of biosystems. The new model allowed us to explore mediated interactions that are not always immediately visible, but are critical. To understand the processes after invasions, we will develop a method for analyzing the distribution of indirect effects in biosystems on directly disconnected components. The results of computational studies are logically followed step by step by a theoretical interpretation of the observed changes in the behavior of the model trajectory. A formal analysis of impulses in a sign digraph in the context of the studied situation of bioresources degradation in the Caspian Sea after a large-scale intervention in the biosystem and due to the penetration of the harmful stenophora *Mnemiopsis leidyi* has been carried out. It is shown that the choice of a mathematical approach to the description of the situation is successfully based on the results of the analysis of cycles of influence of ecological interlinkages. Previously unaccounted-for links that led to the low efficiency of attempts to artificially reproduce bioresources were revealed. It was confirmed on the basis of the impulse process in the cognitive graph that the purposeful introduction of alien mollusks from the Black Sea into the Caspian Sea to increase the biomass of bottom fauna was one of the factors in the degradation of valuable biological resources with an increase in the level of the Caspian Sea. Alien mollusks (*Abra ovata*, *Mytilaster lineatus*) replaced the native benthic fauna. At the end of the 1980s, the salinity of the Northern Caspian decreased; then, the invaders adapted to more saline water drastically reduced the biomass. Competition in the trophic chains of unstable biosystems should not be aggravated in order to increase their productivity for valuable populations. The mass release of juveniles of valuable fish is not a panacea for the degradation of the entire Caspian biosystem. The results of the impact distribution analysis in the cognitive graph are applied to the original hybrid dynamic system for modeling the efficiency of artificial reproduction of the Caspian sturgeon. The model showed that degradation of the Caspian biosystem could have been avoided as early as 2005.

Keywords: computational modeling of biophysical processes, methods of cognitive structuring of factors, graph schemes of interactions, hybrid dynamic systems, invasive species in the Caspian Sea, comb jelly *Mnemiopsis leidyi*, cyclicity of the Caspian level, degradation of biosystems due to alien species

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INTRODUCTION

In a series of studies, the author has developed methodological foundations for formalizing biosystemic interactions with both the physical environment and the biotic environment of a population [1]. A method for organizing hybrid computational models of biophysical processes with structural changes has been proposed [2]. The concept of "predicatively redefined dynamical systems" was developed based on the extension of the formalism of hybrid automata with the inclusion of the model structure of trigger functionals as dynamically corrected coefficients, the values of which depend on the initial conditions at the beginning of the time frame [3].

Computational structures with hybrid time are a powerful tool for analyzing scenarios with the logic of effects on biosystems. However, to analyze the factors leading to the development of this particular situation, it is necessary to know the structural relationships of elements, similarly to how it is displayed in the chemical formulas of complex organic substances. Interactions of biofactors are not atomic, but spatial. The transfer of influence between components is not limited to a one-to-one interaction, but spreads its influence along a chain of neighboring factors. A simple example of this is the trophic chain of energy transfer from producers to consumers of higher orders, but this is a hierarchical and, at first glance, quite simple structure of interaction for modeling; however, there are many phenomena in the ecodynamics of populations (outbreaks and collapses) that models cannot now predict.

There are examples of mediated biophysical interactions that form closed loops of connections. An example of indirect links of species can be found in the classic book of Charles Darwin: in the villages of England, where housewives keep cats, they catch mice and, thus, prevent rodents from destroying bumblebee nests. Insects pollinate clover, a favorite food for cows, which produce more milk. As a result, there is enough cottage cheese and cheese for both people and cats, and the chain of factors is closed. This example is a positive circuit. Similarly, a negative effect that worsens the state of the final links of the chain can also spread. Invasive Japanese giant hornets *Vespa mandarinia* destroy local pollinators of important crops, and mice are not at all frightening for these hornets. Bee colonies in Japan itself have developed a collective defense against hornets, but bees are vulnerable in the United States.

CHAINS OF INFLUENCE TRANSFER IN BIOPHYSICAL SYSTEMS

It is very difficult to develop a model in which one factor can have both a positive and a negative impact on the biota biomass, for example, an increase in the freshwater flow of the Volga River into the Northern Caspian. One indicator of negative changes in the aquatic environment and the level of nutrition is the secondary immunodeficiency of Caspian fish, as shown in the works of Borisova [4].

On the one hand, with a larger flood, the area for fish breeding increases, but, on the other hand, a change in the environment occurs. Cycles are a natural process for the Caspian sea level. However, shellfish were previously artificially introduced into the Caspian to feed fish from the Black Sea. The invaders *Abra ovata* and *Mytilaster lineatus* displaced native Caspian endemics from the North Caspian. Previously, sturgeon and stellate sturgeon juveniles found food in the zone between the river and the sea. With the artificial release of juveniles, competition for food resources intensified and the efficiency of reintroduction was much lower than planned [5]. Biologists conducted research and used model calculations that the biomass of benthos for fish food is insufficient and proposed a solution: to introduce other species of sea-bottom animals that grow and multiply faster. The level of the Caspian Sea at that time was decreasing.

However, another chain of influence was launched. At the end of 1980, the water content of the Volga was high, desalination occurred, and the salinity gradient decreased. Thus, the zone of minimum species for bottom biota increased—places where the water was too fresh for marine organisms and already too salty for freshwater mollusks. As a result, the amount of food and available food is reduced for species of biological resources valuable for the economy, which are supported by artificial reproduction, like the sturgeon populations of the Volga. These species were destroyed by predatory fishing by the end of 2000.

In 1990, stratification of muscle tissue was recorded on a large scale in sturgeons coming to spawn in the Volga. Such a phenomenon cannot be caused by any toxic substances. The hypothesis of cumulative polytoxicosis was refuted by Basurmanova in [6]. This is how long starvation affects fish during migration and hungry fish utilize muscles.

The aim of this work is to develop a method based on graph analysis with the propagation of impulse action along graph arcs to obtain theories about the functioning of biophysical processes after changes that have been induced in a biosystem, for example, due to invasions of new competing species.

In this article, we will consider the methodology of system analysis of the biophysical problem of the ecosystem level based on the structuring of the interaction of factors and the distribution of influence on all components. To formalize the interaction, we propose an improved method of cognitive graph structures and impulse processes between graph vertices. The impulse will be launched from some free vertex and propagate along the paths of the graph, exerting a positive or negative influence, which is established by oriented arcs between the vertices. For the formalism of vertices, one needs to choose a set of concepts.

THE METHOD OF ADDITION OF COMPUTATIONAL MODELS OF BIOPHYSICS WITH COGNITIVE METHODS OF SITUATION ANALYSIS

Initially, the principles of model development in the field of biophysics were borrowed from theoretical physics. However, physics is a universal science; it deals with four fundamental interactions that are the same at all points of the Universe, while in ecology the reciprocal influence of factors can develop feedback, sometimes turning into an oppositely directed process. One factor can have both a direct positive and an indirect negative impact on the well-being of the reproductive process. For example, when the territory of reservoirs is flooded, the area of spawning grounds will increase, but silting of the soil will worsen the conditions for fish spawning. The relativity of the "sign" of influence can be compared with how ordinary water in a reactor absorbs thermal neutrons, but also slows down the neutron flux.

The well-known predator–prey model for zoologists is an example of a stereotypical approach of mathematicians to environmental problems, since fluctuations in the number of hares occur outside the habitat of lynxes. Vito Volterra adapted his developments in the field of solid mechanics to biological problems. The classical mathematical model formalizes some ideas about the nature of interactions as being invariant in time. For example, the biomass of prey goes into the biomass of predators in proportion to their product. Volterra, the founder of the mathematical approach to population dynamics, intended to describe the interaction of species with a system of integrodifferential equations, but, due to the difficulty of their analysis, the approach was not developed in practice. There are many varieties of predator–prey models expressed in systems of differential equations, including modern developments for equations with variable delay [7].

It seems to us methodologically useful to develop a systematization of population models. In this area, models can be classified according to their properties as dynamic systems, but can be divided according to the theoretical hypotheses embedded in their structure. As we noted earlier [8], nonlinear ichthyological models with different theoretical bases, have similar qualitative changes in the behavior of the trajectory. Qualitative behavior metamorphoses, bifurcations with a transition to chaotic motion, and other complex dynamic regimes represent a separate little-studied problem for computer simulation of population processes. Within the framework of the problems of the ecosystem under study, the question of comparing nonlinear effects with the description of observations is of interest. The adequacy requirements impose restrictions on the possibilities of interpreting the computational results, delimiting the ranges in the space of model parameters.

For the stage of analyzing information about the contradictory influence of various factors, cognitive methods of system analysis are developed that work with qualitative information. This article discusses methods of cognitive structuring, which can become a signpost in the formation of dynamic models of ecological processes and be used in the essential interpretation of the results of computational experiments.

ANALYSIS OF THE STRUCTURE OF PROCESSES, MULTIPLE FACTORS, AND THE IMPACT OF CHANGES IN THE CASPIAN SEA

In the 20th century, vast freshwater ecosystems underwent massive anthropogenic changes. The long-term assessment of the diversity of the consequences of an intervention is a task of interdisciplinary research.

Most significantly, the consequences of river-flow regulation affect the breeding opportunities for anadromous species, salmon and sturgeon. Fish maturing in the sea loses their access to previously used areas suitable for spawning in the upper reaches of the river. It was proposed to make up for losses in the reproduction of populations of valuable commercial fish of the Volga through the technology of artificial insemination of eggs, artificial rearing of juveniles, and their subsequent release.

In 1975, a strategy was adopted to maximize the annual catch (up to 30 thousand tons) by releasing juvenile sturgeons (about 90 million) as the main source of stock formation, which would be capable of not only compensating losses in natural reproduction that took place during hydraulic construction, but also increase it above the previous level. As a result of the construction of fish-breeding enterprises for the artificial rearing of juveniles, the goal of a sharp increase in the scale of release was approached. In 1977, sturgeon catches reached their maximum of 27.3 thousand tons, but, then, began to steadily decrease [9]. The situation with the Caspian sturgeon fishery developed in strict accordance with the warning expressed in 1950 by the founder of the method of hormonal injections, Prof. N.L. Gerbilsky, that "it is immeasurably easier to support a relatively prosperous herd in terms of numbers than to restore it from miserable remnants." At the moment, experts from the International Union for Conservation of Nature have noted the degradation of three populations of Caspian sturgeon, which have had the status of "Critically Endangered" in the *Red Book* since 2010. Commercial sturgeon fishing is banned today even in Russia, which, according to the UICN, is an extremely belated decision.

Ichthyologists have repeatedly reassessed the real value of the commercial return from artificial reproduction, and obtaining a reliable estimate is a significant difficulty. It has been confirmed that the commercial return rate of hatchery fry, which was originally planned in the 1970s to be 3%, turned out to be overestimated. In 1989, it were determined to be 1.2% for sturgeon, 1% for stellate sturgeon, and 0.1% for beluga, and, in 1998, 0.7% for sturgeon, 0.83% for stellate sturgeon, and 0.07% for beluga [10].

An assessment of the dynamics of a decrease in real survival at the early stages of the life cycle of fish is important when planning measures to conserve the gene pool of degraded populations. A separate task is to analyze the reasons for the failure to fulfill the forecasts of the 1970s in comparison with the dynamics of ecosystem changes against which the fish breeding process was organized and the value of the allowable catch was determined.

Hydroconstruction led to changes in the trophic chain of the ichthyocenosis of the Lower Volga, changing the ratio of dominance of autochthonous fish and contributing to the resettlement of herbivorous invasive species. For natural reasons, the hydrological situation in the region changed. The period of regression was replaced in 1978 by a rise in the level of the Caspian Sea that rapid and unexpected by climatologists. For a drainless lake with an area of more than 370 000 km^2, level fluctuations are historically typical, which are difficult to predict. The amplitude for the observation period is 3.8 m. The rise of the sea was considered by experts as a favorable factor, since an increase in the area of the Northern Caspian water areas suitable for feeding juvenile fish [11] and an improvement in the trophic situation were predicted. A number of significant factors were not taken into account in the forecasts. Thus, against the background of sturgeon degradation, the catches of their food competitors similarly decreased, which does not fit into the conclusions from the Volterra model describing the dynamics of two limited populations competing for one resource [12].

From historical information about the fishery, it is known that, in the 19th century, four populations of sturgeon species were more numerous than at the beginning of the regular trawl count in 1968. It is a feature of the habitat of the populations studied by the author that, in the conditions of brackish shallow water, an autochthonous benthic fauna was formed, where the salinity barrier limited the distribution of freshwater organisms. During the period of regression, endemic species of mollusks were replaced by invaders. The level increase was accompanied by desalination of the water area. Changes in conditions have affected the area of distribution of mollusk species of the Mediterranean faunistic complex that were artificially introduced in the 1960s, which have become an important food resource for fish. In the Caspian Sea, historically, it was the forage base and, accordingly, high food competition that served as a limiter for the development of fish resources [13]. Studies in the 1950s showed that, per unit of biomass of the benthic fauna of the Northern Caspian, there were several times more of its consumers than in the Sea of Azov, according to the works of Nikitina [14].

It is an interesting observation that, after the degradation of the main predators of sturgeon fish, there was no increase in the biomass of the Caspian mollusks, which is their main prey. The trophic niche of sturgeons was occupied by other victims of sturgeon hunting—endemic species of bottom fish of the family Gobiidae, which are numerous in the Caspian Sea and that had actively multiplied and became much larger. Previously valueless species of small Gobiidae fish have now received commercial status. Juveniles of sturgeons reintroduced to the Caspian have acquired serious competitors.

It is obvious that the evolutionarily established breeding strategy of sturgeons, which is expressed in the existence of several seasonal races and long migration routes, made it possible to maintain a high fish biomass with a relatively small food biomass. Accordingly, it is important to create a computer model for the formation of population replenishment, which made it possible to analyze scenarios for the discrepancy between the development of fisheries and the evolutionary trend of anadromous fish in the Caspian Sea.

METHOD OF COGNITIVE STRUCTURING AND ANALYSIS OF GROUPS OF INTERACTING FACTORS IN A GRAPH MODEL

Intervention in the natural reproductive process has launched, like falling dominoes, a complex of feedbacks previously unknown to experts in the mechanisms of environmental regulation. The introduction of species of various faunal complexes, instability of the river runoff, and changes in the periods of regression and transgression of the sea, in conjunction with anthropogenic factors, led to an unpredictable development of the situation. Analysis of the possible reasons for the discrepancy between the planned efficiency of artificial reproduction and the predicted value of the commercial return is an urgent task for research using computer simulation of scenarios for the development of a contradictory situation.

The formal study of processes in large ecosystems belongs to the field of system analysis of weakly formalized problems. A promising approach for obtaining a formal representation of the relationship of factors lies in the methods of cognitive structuring of heterogeneous information, which are, for example, used in work [15] for informational support in the construction of problem-oriented biomedical knowledge bases. The interaction between a finite set of factors should be studied at the level of describing qualitative changes, since they are reflected in the literature by specialists in comparative and evaluative formulations, such as “favorable conditions for feeding fish.” One approach to the flexible transformation of knowledge into data structures in weakly formalized areas lies in the methods of constructing and analyzing cognitive digraphs in specialized information environments [16].

We will consider the cognitive digraph primarily as a tool for creating the most complete theoretical schemes about the chain of factors that link aspects of the functioning of the population process under certain external influences. The use of conceptual structuring can change the existing stereotypes that are used in the subject area and contribute to the development of modified mathematical approaches to predicting the risk of depletion of exploited biological resources, which happened in the Caspian Sea.

The cognitive approach involves the formalization of the hypothesis of the functioning of the system in the form of a signed digraph, the vertices of which are associated with the selected set of factors, and the signs "−" and "+" are associated with the edges. Edges can be assigned weights if a universal scale of interactions is defined for the entire problem under consideration. At present, modifications of the methodology for the use of cognitive graphs are being developed, which make it possible to formalize the situation at a qualitative level in the form of a set of concepts and directions for transferring influence [17] along various paths. The formalism of weighted signed graphs is an extension of the representation of the digraph $G(X, E)$, which is supplemented by a set of vertex parameters V, where each vertex x_i is assigned concept parameter $v_i \in V$ and arc transformation functional $F(V, E)$, which determines the sign (or weight).

The transformation functional is defined as follows:

$$F(v_i, v_j, e_{ij}) = \begin{cases} +u_{ij}, & \text{if on increasing } v_i \;\; v_j \text{ also increases} \\ -u_{ij}, & \text{if on decreasing } v_i \;\; v_j \text{ also decreases,} \end{cases}$$

where u_{ij} can take values from a finite set B when considering only the influence sign $\mathrm{B} = \{-1, 1\}$. In our task, we also need to indicate the relative level of impact, such as strong/slightly negative and weak/strongly positive. The neutral factor is the absence of an arc. However, under some additional conditions, a connection may arise and an arc of the graph may appear immediately connecting two vertices with a strong influence. This happens when the factor reaches a threshold value—for example, the lethal concentration of a pollutant and/or the critical level of hypoxia dramatically begin to affect the survival of organisms. The oxygen content is not the most important factor when it is above the critical norm, but, if the process of biochemical eutrophication of the reservoir has reached the limit, then the hypoxia zone rapidly develops and oxygen deficiency is already an important factor in the death of the population. The cognitive graph is an evolving structure.

In a popular monograph, F. Roberts suggested that successive changes in the values of parameters corresponding to vertices be considered as impulsive processes in discrete time [18], but, according to the concept we are developing, it is possible to construct a hierarchy of discrete events.

We define the momentum at a vertex as the change in the value of its parameter v_j at time n:

$$p_j(n) = v_j(n) - v_j(n-1) \quad \text{if} \quad n > 0.$$

In the impulse process, the value of the vertex parameter will change:

$$v_i(n+1) = v_i(n) + \sum_{\substack{j=1 \\ j \neq i}}^{N} F(v_i, v_j, e_{ij}) p_j(n). \tag{1}$$

The most interesting conclusions can be obtained by considering impulsive processes of the form (1) in graphs with closed paths.

COGNITIVE MODEL BASED ON THE GRAPH OF INTERACTIONS FOR THE NORTHERN CASPIAN

Let us structure the data that we have summarized from various and often contradictory sources about the nature and severity of the interaction of factors affecting the well-being of the Volga sturgeon populations in the form of a sign cognitive digraph.

A retrospective analysis of fishing statistics and various expert opinions made it possible to identify the main factors suitable for cognitive structuring. The judgments of experts are often contradictory, but the computer environment can implement a set of comparative scenarios. The software implementation of the weighted digraph is based on standard object-oriented programming tools.

As concepts that determine the processes in the ecosystem and affect the dynamics of sturgeon stocks, we single out the following 12 natural and anthropogenic factors and put them in correspondence with the vertices of our cognitive digraph $G(X, E, V)$:

v_1 is the number of spawning stock of sturgeons, v_2 is the number of recruits, v_3 is the natural (compensatory) mortality, v_4 is the favorable feeding conditions for sturgeons, v_5 is the efficiency of natural reproduction, v_6 is the scale of artificial reproduction, v_7 is the level of commercial exploitation of the spawning part of the population, v_8 is the biomass of the dominant mollusk species, v_9 is the density of egg clutches at the spawning ground, v_{10} is the change in the level of the Caspian Sea, v_{11} is the degree of pollution of the Lower Volga, and v_{12} is lengths of available anadromous migration routes.

As a result of comparing observational data, analyzing the literature on the historical development of the ecosystem, and formalizing a number of expert opinions and the results of his own research, the author managed to form a cognitive directed graph. The model includes 12 graph vertices corresponding to the concepts and a set of weighted graph arcs reflecting the sign and degree of mutual influence. A directed graph, where $\mathrm{B} = \{-1, -0.5, 0.5, 1\}$ is given, is shown in Fig. 1a and analyzed in the instrumental computing software (Fig. 1b, the graph analyzer program has a Russian-language interface).

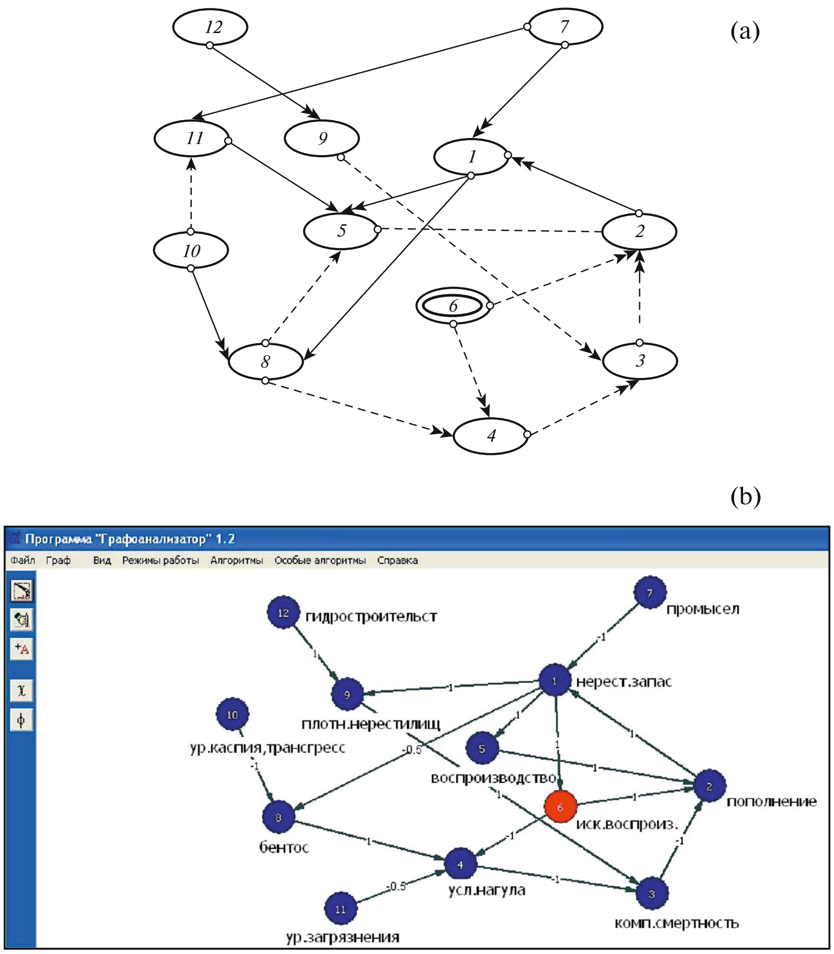

Fig. 1. (a) Cognitive graph for modeling the interaction of ecodynamic factors in the Caspian Sea. (b) Cognitive digraph of mutual influences in the Caspian ecosystem in the graphic analyzer program.

Significant for the hypotheses turned out to be digraph contours having a common dependent vertex, which we called "competing paths." In the original modification of the formalism of cognitive graphs, the selected vertices are made the control. The vertices are divided in our graph model into ones that are dependent on the influence of other concepts and ones that are free, which have only arcs emanating from them. The approach allowed the author to consider successive changes in the initially given values of the parameters corresponding to the vertices as impulsive processes in discrete time.

It is obvious that the qualitative influence represented by arcs varies in its severity; therefore, as physicists do, it is reasonable to characterize conditionally "strong" and "weak" interactions in ecology, but only with a sign (there are hypothetical models with antigravity in physics). The negative impacts of fishing and pollution (when pollution does not exceed the critical threshold) on bioresources differ; therefore, the latter impact is defined as "weakly negative" with $u = -0.5$. It is expedient to launch impulse processes for the cognitive graph from v_6 or v_7 vertices, these factors being available for control as the scale of the artificial reproductive process. However, the scale of release of juveniles now depends on the number of fish individuals from which suitable eggs can be taken and fertilized. There is currently not enough suitable caviar for the release of sturgeon fry in the previous quantities.

In the context of commercial harvesting, it is better to talk about regulation of impact rather than management. In biophysics, according to the author, the classical theory of optimal control is not applicable, and all attempts to optimize the exploitation of bioresources are harmful and lead to the development of the scenario of the collapse of reserves [19]. A biophysical system cannot be a fully controlled object unless it is an artificially created cell in a laboratory. The result of the impact has turned out many times to be unpredictable for managers and decision makers as concerns the level. Regulation of the sturgeon fishery in the Caspian Sea was carried out by experts who substantiated the permissible level of withdrawal, but no one knows the real level of withdrawal.

The Northern Caspian is just such a case: all decisions to change the composition of species and to block certain sections of the sea with dams not only led to benefits for the abundance of biological resources, but contributed to the catastrophe and degradation of all valuable populations (and not only sturgeon, but also Caspian herring) against the backdrop of predatory fishing. The survival of the beluga *Huso huso* is in question. The reproductive cycle of the beluga has been completely disrupted. For other species of the Acipenseridae family, there is an alternative: breeding technology. Azerbaijan has successfully started aquaculture cultivation of domesticated sturgeons, which the author has read about on social networks kindly provided by Lala Babaeva from Baku.

DYNAMIC MODEL OF THE REPRODUCTIVE PROCESS OF THE CASPIAN BIORESOURCES

Based on the assessment of the dynamics of values v_4 and v_2 of the digraph, the hypothesis was developed that the growth rate of juveniles should affect the rate of decrease in the number of generations and, at the same time, there should be a certain threshold weight value, after which the effect of unfavorable factors should sharply decrease. The nature of the fluctuation of value v_3 predicts that the growth rate, in turn, should depend on the density of the aggregation of juveniles, and then a dependence of survival on density with several extremes can be observed, which is not described by previously known models.

Taking into account the formed hypotheses, it seems appropriate to expand the ideas of the ecological concept about the existence of a dependence between the size of the spawning stock and the resulting replenishment of the commercial stock using new mathematical methods for its formalization. New methods should further expand the theory of the formation of bioresource recruitment for predicting and assessing the state of fish populations supported by artificial reproduction.

Modeling of aspects of the reproductive cycle of aquatic organisms is being developed within the framework of mathematical methods of the theory of the formation of population replenishment founded by the Canadian scientific schools of F. Neave and S. Beaverton. The work of Ricker [20], despite the imperfection of the then-available methods for analyzing the behavior of discrete dynamical systems of the form $R_{n+1} = f(R_n)$, has an undeniable advantage, since it was carried out on the basis of a generalization of the actual material of observations. The main results in the dynamics of differentiable mappings and the theory of renormalization appeared later than the articles by Ricker and the works of Beaverton and Holt, and more fundamental research by biologists in this area was not carried out.

The Ricker model is known as function $R = aS\exp(-bS)$, which relates recruitment R to size of the spawning stock S. More interest is presented by the evolution of the dynamic system $R_{n+1} = aR_n\exp(-bR_n)$, where a is the bifurcation parameter, which is interpreted as the reproductive potential of the spawning part of the population. Accordingly, parameter $b < 1$ reflects the cumulative effect of all limiting environmental factors. The parameters are unequal, and the stability of the stationary state $R^* = f(R^*)$ is affected only by a:

$$f'(R) = ae^{-bR} - bRae^{-bR},$$

$$R^* = \frac{\ln a}{b},$$

$$f'(R^*) = ae^{-b\frac{\ln a}{b}} - b\frac{\ln a}{b}ae^{-b\frac{\ln a}{b}}$$

$$= \frac{a(1-\ln a)}{e^{\ln a}} = 1 - \ln a.$$

It is easy to determine the moment of violation of the stability criterion using the value of the derivative at a stationary point: $|f'(R^*)| < 1$. Earlier, we described the comparative properties of dynamic systems based on the models of Ricker and Shepard [21], including the features of the appearance of chaos (Fig. 2) through an infinite cascade of doubling the period of the cycle according to the scenario of M. Feigenbaum described in [22]. With a subsequent increase $a > 14.2$, periodicity windows appear with stable cycles of odd periods, followed by an internal crisis of the chaotic attractor.

The appearance of complex dynamic regimes and sharp nonlinear effects in simple discrete models leads to a number of problems in the study of models of biological communities, which refutes the popular belief that this approach to modeling in ecology is characterized by accessibility and clarity.

Let us represent a dependence similar to the Ricoeur model in the form of a differential equation for the decrease in number $N(t)$ solved on a certain interval $[0, T]$:

$$\frac{dN}{dt} = -(\alpha N(0) + \beta)N(t), \quad t \in [0, T]. \tag{2}$$

The constants in (2) correlate with the Ricker parameters: $a = \lambda\exp(-\beta T)$, $b = \alpha T$, λ is the average fecundity of individuals in the population, which determines the initial conditions $N(0) = \lambda S$.

The hypothesis in (2) that mortality is dependent on the initial abundance $N(0)$ is very specific only for a situation of strong cannibalism. It is necessary to supplement modified equation (2) reflecting the average size development in the conditions of limited

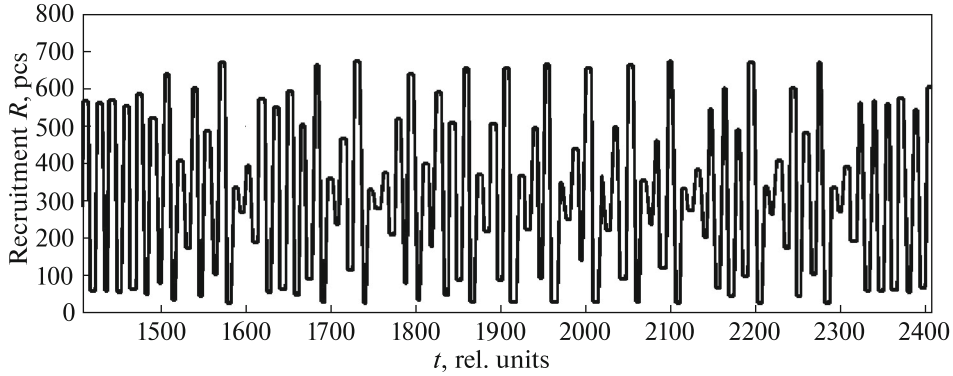

Fig. 2. Chaotic dynamics in the Ricker model.

available food organisms. Let us take into account the characteristic circumstance that the vulnerability to predators of juveniles decreases sharply as they grow, since adult sturgeons have no natural enemies. We represent the rate of dimensional development in an equation that depends inversely on the fractional degree of density:

$$\frac{dw}{dt} = \frac{g}{\sqrt[k]{N(t)} + l}, \quad k < 3, \tag{3}$$

where g is the parameter of the volume of available food resources and l takes into account the limitation of the rate of development not related to the number of generations.

The duration of the interval of vulnerability, the period in the life of a generation when mortality depends on density, can be calculated in the model depending on the growth rate of the generation, which is ecologically justified. Let us assume that, when a certain value $\hat{w}$ is reached, mortality is due to commercial causes. Let us form a system of differential equations that describe the dynamics of the decrease in the number of a generation before entering the spawning part of the population $S = N(T), T = v(w)$:

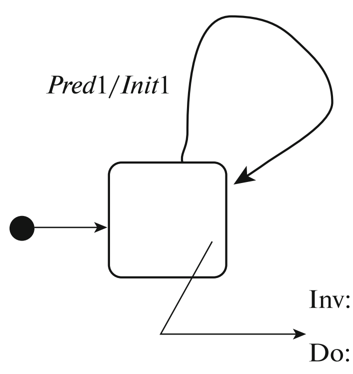

Fig. 3. Simple hybrid machine with entry and one switch.

$$\begin{cases} \frac{dN}{dt} = -(\alpha w(t)N(t) + \bar{f}(N(0))\beta)N(t) \\ \frac{dw}{dt} = \frac{g}{\sqrt[k]{N(t)} + l}, \quad k < 3, \quad w < \hat{w}, \end{cases} \tag{4}$$

where α is the instantaneous coefficient of compensatory mortality, β is the density-independent decompensation mortality rate, and the initial conditions are given: $w(0) = w_0, N(0) = \lambda S$. Function $\bar{f}$ must have the property $\bar{f}(S) > 1, S < L$ and $\bar{f}(S) \to 1, S \gg L$ reflecting the fact of a sharp decrease in the efficiency of reproduction with a small number of spawning herds, less than some critical L.

IMPLEMENTATION OF A HYBRID AUTOMATON IN A REPRODUCTIVE MODEL

Replenishment formation model (4) is considered as a continuous-discrete dynamic system and is algorithmically implemented in the AnyLogic computing environment in the form of a hybrid automaton [23] with a predicative transition. Unlike discrete maps of states of event models, a hybrid automaton (Fig. 3) can be considered a map of changes not in states, but in the behavior of the system.

In the applied approach, switching of the automaton with continuous-discrete (hybrid) time in form (5) occurs between modes of changing the state of the system. Each transition must be associated with a set of predicates, and each mode of behavior must be associated with conditions for terminating the activity. The confirmation of the truth of predicate *Pred*1 is followed by the initialization of the computational problem, for which redefinable initial conditions *Init*1 of differential equations are formed. The predicate control function determines the choice of the currently solved Cauchy problem in the computing environment with the initialization of new initial conditions or stops the calculations when boundary values are reached. In the analysis of the properties of event-driven or continuously discrete dynamic systems, for algorithmic

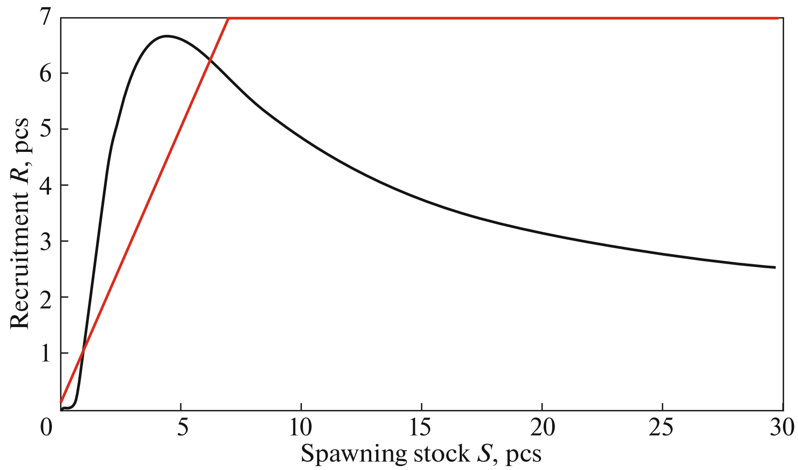

Fig. 4. Reproduction curve $\varphi(S)$ according to the solution of system (4).

implementation of the model, we use hybrid time as a multiset that introduces an eventfulness component when managing a change in a continuous process:

$$\vartheta = \bigcup_n \{R\_\tau_n, [t_{n-1}, t_n], L\_\tau_n\}, \quad (5)$$

where P_τ and L_τ are selectable events with instantaneous duration, limiting the intervals of continuous time on the right and on the left.

At some designated moment of hybrid time, the initial conditions for the calculation of the Cauchy problem are redefined at the next continuous time frame in the sequence. The behavior of a hybrid system is "glued together" from a continuous change in state and discrete events that redefine the development of the process.

MATHEMATICAL PROPERTIES OF THE HYBRID MODEL OF THE REPRODUCTIVE PROCESS

The set of solutions to the Cauchy problems for admissible $S \in Z^+$ will determine dependence $\varphi(S)$ in which we are interested, which is called the "reproduction curve" of the population. Graph (4) obtained in the computing environment (Fig. 4) defines a unimodal curve with a nonzero horizontal asymptote and two nontrivial intersections R_1^* and R_2^* with the bisector of the coordinate angle $R = S$, the locus of stationary points.

The resulting dependence with a gentle ascending branch and a falling right branch with a decreasing slope made it possible to overcome two important shortcomings noted by specialists who used the Ricker function for practical problems of predicting an acceptable fishing regime. The main disadvantage of function $f(x) = ax\mathbf{e}^{-bx}$ is that the largest value of the derivative is achieved when the argument tends to zero, but it is unlikely that the greatest increase in reproduction can be achieved under such conditions:

$$f'(x) = a\mathbf{e}^{-bx}(1 - bx),$$
$$\lim_{x\to 0} a\mathbf{e}^{-bx}(1 - bx) = a.$$

The inconvenient property $\lim_{x\to\infty} ax\mathbf{e}^{-bx} = 0$ does not correspond to the experimental data, and was usually eliminated during modeling by a simple redefinition in the computational algorithm $f(x)$ into a piecewise given function with constant value interval $f(x) = K$, $x > x_1$.

The qualitative difference between the developed continuous-discrete dynamical system and the previously proposed discrete models is the presence of two areas of attraction of attractors in the phase space Θ_1, Θ_2. The boundary between the areas is the unstable stationary point of the first intersection with bisector R_1^* when point R_2^* is stable until doubling bifurcation takes place. The attractor for the region Θ_1 is the origin, i.e., trivial balance. Consequently, R_1^* is a critically admissible number for the long-term existence of the population. The transition of the model trajectory into the region Θ_1 is interpreted as the start of the process of irreversible degradation of the population.

THE ROLE OF MEANS OF COGNITIVE STRUCTURING IN MODELING BIOPHYSICAL INTERACTIONS

Successful mathematical formalization of ecological processes, as a rule, turns out to be noninvariant for different ecosystems. It is advisable to start modeling a certain situation from the stage of system analysis of processes, not relying on a ready-made apparatus that has been successfully applied once, but under different conditions. Conceptual structuring based on the generalization of observational data will help create hypotheses for modifying known methods, as was done for the reproduction model. Note that the hybrid dynamic system that we are developing for other ecological and physiological conditions of fish spawning may turn out to be inadequate. Salmon and sturgeon have a similar breeding cycle, but we can hardly expect the appearance of dome-shaped dependences on the graph according to data on northern populations spawning in the sea water column.

System analysis and subsequent computational analysis of the model based on system of differential equations (4) shows that, for anadromous fish populations with a long life cycle, the popular strategy of optimal fishing, which sets the goal of obtaining the maximum allowable stable catch, is inapplicable. Risky fishing can lead to the beginning of a process of irreversible degradation of populations. It is unrealistic to compensate for losses in natural reproduction against the background of fishing pressure, achieving only the mass release of hatchery juveniles into riverbeds. Artificial reproduction requires new studies of the life cycle of juveniles, and so now it is based on the results obtained under other ecological conditions.

It is advisable to note some shortcomings of the formalism of cognitive graphs in relation to the problem of system analysis of environmental problems and the dynamics of commercial stocks. Factors influence each other at different rates. Ecological processes are characterized by the phenomenon of time lag. For example, the provision of individuals with the necessary resources does not depend on the current population, but on the generation density at the previous stage of development, and, in this case, on the right side of the equation, it is necessary to use a functional with a deviating argument: $\Psi[N(t-\tau)]$. A possible improvement is represented by the admissibility for the subsystem model of subgraph selection $G_1(X_1, E_1, V_1)$ with functional of transforming arcs of a different form. It is quite possible to provide for a predictive change in the sign of the arc between concepts in the digraph processing algorithm, since the "positiveness" of the influence can also be relative.

A separate problem of real models of interactions in biosystems is the essential biophysical interpretation of the results of a computer study of nonlinear dynamic models, for example, unimodal mappings, which is shown in my work [24] and that of Dubrovskaya [25]. Chaotization of the model is not the only harmful property. The chaotization of the model imitates natural volatility.

When the bifurcation parameter changes, qualitative changes in the behavior of the trajectory "nonlinear effects" occur, as a transition to chaotic motion and back to stable cyclic motion. Each parameter in a biological model carries a certain interpretation, which is reflected in the formation of practical conclusions. It would be possible to break the range of allowable parameter values up into a finite set of limited intervals of distinguished qualitative behavior, but the union of parameter-value ranges corresponding to chaotic dynamics is a fractal set.

CONCLUSIONS

The shortcomings of approaches to predicting changes in biophysical systems are expressed in many crisis phenomena. No one has been able to predict the existing diversity of coronavirus strains in 2020, and the concept of creating a vaccine based on the antigens of a single SARS-COV-2 spike protein, which turned out to be extremely variable during evolution, was chosen. In Japan, quarantines were relied upon and it could not be foreseen that the country would have to face much more transmissible strains of the virus in 2 years. Many epidemic dynamics models have been constructed, but no one was able to foresee that there would be a new outbreak of COVID in India in April due to the new XBB.1.16 strain. Most experts expected that the epidemic would end in 2023 and that the pandemic would transition to a subsiding endemic stage due to the immunity accumulated in the population. However, recent work [26] shows a structural diagram of the evolution of the viral spike protein in which it is clear that the process of changes in the key protein is far from complete.

Erroneous conclusions and overestimated forecasts are reflected in the fact that critical reductions in bioresources and the death of valuable populations in the form of their immediate collapse are regularly observed [27]. At the same time, the harvesting of such bioresources is regulated using scientifically based recommendations, which were constructed on the basis of correlation or regression analysis.

Preventing such situations is the task of organizations that control the rules of nature management and make decisions based on incomplete retrospective information about the state of biological resources and extrapolate it into forecasts. Obviously, the expectations formulated on the basis of incomplete data will be acceptable only if the factors that acted earlier and global trends are preserved. Mathematical models in equations are often really powerless in predicting complex situations, but it is possible to formalize expert knowledge in the form of an interaction scheme.

Nonlinear dynamic models make it possible to consider qualitative changes in processes, but there is a problem of their essential biological interpretation and criteria for the objectivity of construction for the problems of calculating the optimal exploitation of biological resources. The author's experience shows that, even when choosing the optimal values of operation parameters in computer models of population dynamics based on solutions of finite-difference equations, it is difficult to assess the response of ecological systems under conditions of anthropogenic impact and the introduction of new species. Specialists have long discussed the need to use flexible methods for structural analysis of information about the dynamics of interrelated processes under study, which was noted by Riznichenko [28].

The cognitive approaches that were developed by the author are relevant for structuring contradictory biophysical information, which is often obtained on the basis of conflicting expert opinions. Schemes of interactions with impulses in graphs will form the basis for the development of simulation models [29] and be used at the stage of ecological interpretation of the results of computational experiments [30].

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