1. Environmental problems of modern fisheries

Fish and other types of aquatic biological resources are some of the most important sources of food raw materials, and the demand for these is constantly growing. In the period from 1961 to 2016, the average annual growth rate in the consumption of fish food products (3.2%) was twice faster than the population growth rate (1.6%) and exceeded the overall increase in meat consumption (2.8%). Per capita consumption of edible fish increased from 9 kg in 1961 to 20.5 kg in 2017. Fish consumption is expected to grow by 20% by 2030. Fish and seafood are the main source of animal protein for almost half of the Earth’s inhabitants and make up about 17% of the consumption of this essential food component [1].

However, further increase in fish and seafood consumption faces a number of problems. At the end of the last century, permissible exploitation of most natural aquatic biological resources reached the limit. Many aquatic ecosystems fail to maintain previous production volumes. Fishing companies have significantly expanded fisheries in remote parts of the oceans to stop the decline in catches in traditional fishing areas, and now cover 90% of its area. Fisheries is conducted in severe weather conditions at great depths, and involve new previously unused aquatic species.

Fishing business expands, and its pressure on the ocean increases. The state of many traditional fisheries is at a critical level and continues to deteriorate. About half of the world’s fish stocks are now classified as depleted or at risk of depletion. In particular, according to the Food and Agriculture Organization of the United Nations (FAO), the proportion of marine fish stocks exploited at biologically unsustainable levels increased from 10% in 1974 to 33% in 2015 [1]. In addition, ocean
pollution by human waste (industrial and domestic waste, and particularly plastic waste) and global warming cause serious aftereffects for marine ecosystems, decreased biodiversity and irreversible aquatic life degradation. Among other things, these aftereffects have an economic effect. According to some estimates, they can decrease income from world fisheries by 35% by 2050 [2].

Some countries recognize the growing threat to fish stocks and take measures to improve resource management. However, these local efforts are suppressed by the growing overfishing in other regions, as well as high volumes of illegal fishing and waste [3, 4]. This results in reduced catches, higher fishing costs (and hence market prices), higher unemployment among fishermen and in related industries, and ultimately in reduced well-being of many people.

In conditions of the limited potential of natural aquatic biological resources, the development of aquaculture can solve the problem of meeting the growing needs of mankind in protein food. Over the past three decades, the share of aquaculture in fish production has consistently increased and reached almost half of the total production. In 2016, the share of aquaculture in the total volume of world production of fish and aquatic organisms accounted for 47%, and made up 52%, excluding nonfood products (fishmeal, fish oil, etc.). In some countries (e.g., China, Thailand, Vietnam), the volume of food aquaculture exceeds the volume of traditional fisheries [1]. Production indicators of fisheries remain next to stable (since the mid-1980s, the amount of caught ‘wild’ fish has not exceeded 85–95 million tons per year); however, aquaculture actually provides all the additional human needs for fish products. Many experts assert that the industry has good prospects for further development [5]. In particular, the volume of aquaculture food production is expected to increase by 37% by 2030 compared to that in 2016.

Although aquaculture is viewed as an alternative to fisheries, its development in conditions of existing technological approaches also entails adverse effects on natural systems. Massive and intensive rearing of fish in limited coastal areas causes severe pollution of the aquatic environment, and control of diseases inevitable due to overcrowding of fish requires harsh medications that have an adverse impact on ecosystems and worsen the quality of grown products. This results in not only violation of the stability of natural complexes, but also important socio-economic effects, which in fishing causes a decline in social welfare.

2. New approach to fishery management

Impossibility of further increasing and difficulty in maintaining of ‘wild’ fish catches, as well as an increasing adverse impact of aquaculture production on the environment require modernization of the fishery regulation system that implies strengthening of regulatory requirements and public control over it. It should be realized, however, that regulations alone could not eliminate the aftereffects of overfishing and extensive aquaculture development. Comprehensive solutions are required to ensure sustainability of the industry development trajectory, economic attractiveness and social acceptability of its activities with minimal impact on the natural environment. Improvement of the system of fisheries analytics is one of the conditions for elaborating optimal solutions. Rapid development of digital technologies has recently provided new algorithms for collection and analysis of data, and their use in management, which are widespread in various industries. Among other things, analysis and modeling of fisheries based on such technologies allow the development of environmentally balanced solutions to meet the interests of society and business.

According to McKinsey, agriculture (including fisheries and aquaculture) is characterized by low digitalization level [6]; however, this sector is highly potential for digitalization. These technologies are gradually becoming one of the most important elements of long-term strategies for fishery development. For example, in our country, the formation of an economically efficient nature-saving fishing is one of the priorities for development of the digital economy formulated within the technological initiative Marinet [7]. The scientific and methodological basis for this priority area of the Russian fishery development is the Ecosystem-Based Fishery Management (EBFM) or Ecosystem Approach to Fisheries (EAF), which has recently become the main global direction of development of the industry. The EBFM/EAF approach is a holistic way to manage fishery aimed at maintaining
ecosystems as its basis in an economically, ecologically and socially sustainable state [8]. The fundamental difference between this approach and traditional strategy for fishery management is its complexity and coverage of many aspects of activities. The use of EBFM/EAF implies the availability of a versatile, flexible and operational system for data collection and compilation to adequately access and manage the processes in industry development [9]. The end result of fishery management in this case is the achievement of a broadly sustainable productivity of aquatic ecosystems, which can be considered as further development of the Maximum Sustainable Yield (MSY) concept, which has become very popular today.

The most significant disadvantage of the MSY concept recognized by many authors is the complexity of its practical implementation. Problems usually arise from inaccuracies and incorrect assumptions made in theoretical models describing fishery resources, their habitats and fishing activities themselves, as well as insufficient reliability of data used in these models. In particular, model developers do not always have data to correctly estimate the current and prospective size of the resource population, to assess the capacity and other parameters of the natural environment, and to take into account all the effects of the impact of economic activity on its state [10]. Digital technologies eliminate many data limitations and approach the optimum use of the potential of ecosystems. However, the effect of their application concerns not only technical improvements, it is fundamental, and in fact, and lays foundations for formation of a new management paradigm.

We can talk about the consensus regarding possible areas for implementing digital technologies in fisheries. Some of the most promising areas are provided below.

1. Data collection by means of digital data pickup devices (sensors). Sensors for data collection, which are the basis of modern information systems describing the state of fish resources and their habitats, are becoming more versatile, universal, compact, and less expensive. At the same time, the variety of digital platforms to deploy these devices is growing. This enables collection of data covering a wide variety of aquatic ecosystems faster and over longer distances. The current state and the prevailing trends in digitalization of the fishing industry show the most promising areas for implementation of digital data collection systems:

   - Satellite systems based on optical and radar sensors mounted on space objects and giving a holistic view of the environment with high spatial and temporal resolution. Optical sensors used to measure light reflected by the water surface provide many important physical parameters of the aquatic environment. Radar sensors that use microwave radiation can provide important topographic and traffic data. In contrast to optical sensors, radar systems collect data even in bad weather and in low light conditions.

   - Drones are autonomous flying surface or underwater vehicles equipped with cameras or other sensor devices designed to explore the aquatic environment. Compared to satellite systems and oceanographic vessels, drones are cheaper, and they provide a wider range and flexibility in data collection. An important advantage of drones is the ability to group them to significantly expand the horizons of the environmental analysis [11]. Drones only monitor small areas; however, they are capable of providing detailed data and detecting smaller objects or processes.

   - Airborne devices on fishing and research vessels, or as part of aquaculture complexes. Data collected by these devices are used for in-depth assessment of fishing and production activities, and provide comprehensive catch data. These devices currently record typical parameters such as vessel position, types of gear used, characteristics of the catch including species, volume and biophysical characteristics of fish caught, by-catch discards, etc. Onboard sensors facilitate and automate operational control of fishing and production activities and generate versatile and reliable data.

The data obtained by different types of sensors and devices are integrated into platforms that operate within various kinds of electronic monitoring systems. In some countries, commercial fishery regulations require all fishing vessels to be equipped with vessel monitoring systems (VMS). Originally developed in the US and EU, this technology that supports monitoring, control and surveillance of fishing vessels is now widely used in most of the fishing countries worldwide. VMS provides data on the vessel position, speed and heading. Vessel operators also use VMS to transmit
data such as estimated catch, start and end time of their fishing operations to data centers. The system of operational control of fishery in our country functions in a similar way, where VMS-monitoring of the location of vessels is part of an integrated sectoral system for monitoring aquatic living resources [12]. Among other things, the data collected by this system enables tracking fishing vessels in real time.

Further development of digital systems for monitoring fisheries will aim at expanding groups of users of the data obtained by sensors through involvement of public organizations in monitoring and predicting the state of aquatic ecosystems. A large number of technical developments and solutions based on sensing platforms and data collection systems have become available for commercial use in the field of fishery and fish farming.

2. Improved data transfer technologies. The development of the Internet of things (IoT), and terrestrial and satellite mobile networks greatly facilitate collecting data from fishing vessels and aquaculture farms. For example, ships can use IoT to monitor and transmit data on fuel consumption in real time. Similarly, fish farms can transmit data about the state of fish being farmed and its habitat. The collected data are then supplied to data centers via wireless mobile networks or satellite communications.

3. Advanced data analysis. The current stage of digitalization features rapid growth of the computing power of the equipment, which facilitates data processing and makes it possible to use more and more complex algorithms for their analysis. One of the most important advances of digitalization, which makes the semantic ‘core’ of the new stage of technological progress, is rapid development of artificial intelligence and machine learning and its penetration into a wide variety of areas. These technologies open up new possibilities for data analysis to identify hidden relationships in large amounts of data. Over the past decade, significant advances have been made in the development of tools for image recognition and object detection based on artificial intelligence technologies. Hardware and software solutions are currently available in the field of visual data processing to analyze a number of important parameters of the catch in real time, for example, the species, volume and size of fish. Leading companies in the fishing industry are transforming their operational and business processes and employ in-depth data analysis technologies across all links of the value chain, including fishery management, detection, catching and processing of wild fish, monitoring and control of aquaculture fish farming, as well as preparation of various reports. In this case, not single tools, devices and sensors, but their combinations are used to cover all production stages.

4. Monitoring of illegal, unreported and unregulated fishing. In-depth analysis of data, in particular VMS geolocation data, provides ample opportunities to combat illegal, unregulated and unreported fishing. This analysis shows whether fishing vessels are actively fishing. If geolocation data are not available, collection and analysis systems determine the location of ships using image recognition algorithms from satellites or drones. This greatly facilitates monitoring fishery and detecting any illegal activities, such as fishing in restricted areas or transferring raw fish from one vessel to another to hide catch. Analysis data can be used not only by the government but also by public organizations. For example, the Global Fishing Watch non-profit organization provides publicly available data on the activities of the global fishing fleet based on VMS and satellite imagery in order to expand public monitoring of fishing activities and improve fishing sustainability.

5. More accurate fish detection. Most of the world’s fishery operate with limited data on the state of fish stocks, and management decisions are often taken based on unreliable data. This is typically discrete catch and other data recorded at specific time in the past, and they may not reflect the current state of fish stocks. Advanced analytics tools can provide dynamic, reliable and detailed insights into environmental patterns, intensity and outcomes of fishing activities, and thus help improve understanding of the status and spatial distribution of fish stocks. In particular, there are sufficiently accurate predictive models based on a variety of data that provide daily advice on where to fish and how to avoid by-catch to increase the fishery efficiency [13]. With a more detailed and dynamic data on fish stocks, fishing companies can reduce the time and effort required to obtain a catch. Similarly, data can be used to improve public resource management.
6. **Improving fishery transparency and traceability.** As noted above, the data obtained during monitoring of fishery are sent to the relevant state or public regulatory authorities, and to the managers and owners of companies. Digitalization of monitoring automates this process and provides more detailed and reliable data for decision making. Digitalization of companies makes advanced analytics increasingly relevant, since it provides a new level of understanding of the key business drivers. An important effect of digitalization is improved traceability of fishery supply chains, which is extremely challenging, since many participants are not inclined to disclose data [14]. At the same time, the lack of transparency means not only violation of the fishery regulations, but it does not guarantee the quality and safety of fishery products. Digital technologies enable creation of secure databases that include data about all transactions with goods along the supply chain. The data in this database, including analytical data, will be available to all authorized users in real time. Such innovations can be implemented by means of blockchain technology, which accumulates data along the entire product value chain [15]. There are other technologies for tracing fishery products, such as tags and codes for identifying goods to speedily obtain the required data.

The innovations listed above have already been partially practiced in fisheries. Although many companies use digital systems for collecting and transmitting data and advanced analytics, their final decisions still largely depend on intuition and experience. The opportunities provided by digital technologies are not yet fully exploited by fishery authorities. This is due to unwillingness of both private and state authorities to employ new management methods, especially in developing countries [16]. At the same time, the growing deterioration of the state of fish stocks and the natural environment requires more active implementation of digital technologies in fisheries. As noted above, technological development facilitates these processes through new solutions that lead to permanent reduction in the cost of collecting, storing and processing data. In turn, the increased availability of digital technologies provides more and more advanced analytical tools for fisheries.

In addition to direct production effects, digital analytics improves assessment of ecosystems, which in turn allows better understanding of their state and provides a solid basis for the ecosystem-based approach to fishery management. Digital technologies ensure complex assessment of the ecosystem state and cover the interests of various beneficiaries of the services of these ecosystems (for example, fishing and fish farming, shipping, energy generation, agriculture, manufacturing, recreation). As a result, the integrity of the management is ensured, which ultimately allows optimal decisions on the use of natural resources. Optimization of the management of aquatic ecosystems through digital technologies implies accurate setting of the load capacity to ensure ecosystem sustainability. example, in the case of fisheries, advanced analytics leads to a more flexible, dynamic setting of catch quotas, which provides for adjustment of the allowed volume of catch during the year using data on the amount and type of real-time catches [10]. The benefits of digital technologies for fish farming are even greater. In addition to the rational use of natural resources that takes into account the interests of other users, digital technologies open up opportunities for managing many parameters of products to better meet consumer demands.

3. **Modification of the methodology for managing resources of aquatic ecosystems**

Aquatic ecosystems are complex and dynamic natural complexes that produce goods and services with a variety of economic and non-economic benefits. Similar to any other economic activity, fishery affects ecosystems; therefore, a balanced approach to its implementation is required to take into account, among other things, ecosystem effects [17]. At the same time, due to the lack of a clear understanding of driving forces and mechanisms of ecosystem functioning, as well as due to the complexity of distinguishing between natural and human-induced changes in ecosystems, their response to external effects is not always predictable [18].

There are different views on the assessment of the environmental impact of fishery [19–21]. This activity is often considered in terms of the occurrence of various kinds of aftereffects for people and covers two main aspects:
The ecosystem-based approach to fishery is based on close relationship between human and ecological well-being. It recognizes the need to maintain the productivity of ecosystems for present and future generations, which cannot be achieved without cooperation between all consumers of ecosystem goods and services. Thus, the overall goal of the ecosystem-based approach to fishery is to improve management efficiency in terms of both human and ecological well-being. Therefore, it is necessary to employ control methods that take into account the widest possible range of effects. Digital technologies can become a reliable basis for these methods to open up new opportunities for introducing ecosystem management into fishery.

An integral part of the modern ecosystem management is modeling of the ecosystem state, which is a formalized algorithm based on digital solutions to describe the ecosystem response to certain impacts. The study of ecosystems affected by fishery employ various models chosen and detailed largely with regard to study objectives, characteristics of the studied ecosystem and available data [23].

Current digital solutions in the field of environmental modeling are mainly based on two main types of models: agent-based models that describe disaggregated parts of the system and system dynamics models that consider the system as a whole [24]. The agent-based approach to modeling is usually used to study complex adaptive systems, it focuses on interactions at the micro level and is used to explain the patterns of ecosystem functioning. In turn, system dynamics identifies and studies a set of attractors that characterize the ecosystem equilibrium, and considers the properties of systems near attractors [25]. It is used to model complex feedbacks and nonlinear interactions between the system components, management effects, and efficiency indicators [26]. The obtained results can vary significantly due to the different orientation of agent-based and system dynamics models [27].

Digitalization opens up new opportunities for a better understanding of the mechanisms of ecosystems functioning that yields optimal management decisions related to the economic use of their potential. The development of digital technologies and, in particular, the improvement of artificial intelligence systems create a new area in ecosystem management that takes into account close relationships between environmental, economic and social dynamics – the so-called multi-agent modeling. This type of modeling is a complex system that includes a network of distributed agents interacting to collectively solve problems affecting the interests of all agents [28]. At the same time, the development of collective solutions with regard to the interests of all existing and potential beneficiaries of the services provided by aquatic ecosystems is a non-trivial task that requires an individual approach in each specific case. Imperfection of many aspects of digitalization in the economy and, in particular, in the field of fisheries, as well as the need to revise public relations due to digital transformation, complicates massive implementation of multi-agent modeling methods in the industry management. In this case, compromise solutions are required. A relatively simple and effective way of making management decisions in fisheries, whose activities are related to the exploitation of aquatic resources, is a well-known bioeconomic approach. Digital technologies and greening of the industry did not diminish the significance of this approach but modified and expanded its capabilities in the fishery regulation.

The theoretical basis for the bioeconomic approach is a variation of the classical input-output model, the Gordon-Schaefer model [29], which originally describes fisheries, but it can be applied to aquaculture with minor changes. This model includes two components – biological and economic. The biological component describes the change in the volume of stocks (ecosystem resources) due to their exploitation using the function \( x' = F(x) - H \), where \( F(x) \) is the function of the growth of biomass \( x \) per unit of time, and \( H \) is the volume of catch per unit of time. The catch is described by the Cobb-Douglas function with a unit elasticity of the species: \( H(e, x) = q \cdot x \cdot e \), where \( e \) is the fishing effort, \( q \)
is the catchability coefficient that shows the efficiency of fishery and the resource specificity. The indicator of biologically sustainable fishery is a zero increase in stocks: \( x' = 0 \), that is, when the increase in biomass corresponds to the catch volume: \( F(x) = H \). The economic component of the model is a profit function \( \pi \) calculated as the difference between the total income and costs of fishermen: \( \pi = p \cdot H(e, x) - C(e) \), where \( p \) is the fish price, \( C \) is labor costs and capital. Profit maximization yields the optimal amount of fishing effort (with regard to the beneficiaries who try to make the most of available resources).

A feature of most natural resources (ecosystem goods and services, including uncaught wild fish) is that they are considered as a common asset and cannot be an object of purchase/sale and, therefore, do not have an explicit market price. At the same time, the utility and economic value of these resources cannot be estimated by direct market valuation. One of the characteristics of this hidden value is shadow value, which reflects all external positive and negative effects of the use or non-use of natural resources and is proportional to the alternative costs unaccounted for in the market price of goods and services created by this resource. The difference between the market price of the resource unit and its shadow value is an adjusted price, which can be interpreted as the net (public-private) gain obtained as a result of the use or non-use of the unit of a given resource: \( p_c = p - s \), where \( p_c \) is adjusted price, \( p \) is market price, and \( s \) is shadow value.

Although the shadow value of natural resources is fictitious (usually it is not paid to anyone), it plays an important role in regulating the economic use of ecosystems. It must be considered if the task is to determine the optimal value of anthropogenic load on ecosystems in terms of public and private interests, taking into account both explicit and latent effects and aftereffects.

With regard to the above, the classic Gordon-Schaefer model is subject to some changes. In case, a marketable resource is exploited by \( N \) participants \((i = 1, 2, ..., N)\), each of which is guided by his own economic benefit \( \pi_i \) and chooses an individual level of effort \( e_i \) with the corresponding costs \( C_i(e_i) \), the standard bioeconomic model of fishery with a set of independent players takes the form

\[
\sum_{i=1}^{N} p \cdot H(e_i, x) - C_i(e_i) \rightarrow \text{max}, \quad (1)
\]

under a naturally specified (determined by biological resistance and other parameters that characterize the ecosystem properties) limitation of the catch volume

\[
F(x) = \sum_{i=1}^{N} H(e_i, x) \quad (2)
\]

This direct task, which simulates profit maximization, corresponds to a dual task that describes an alternative goal of minimizing the load on the ecosystem. This problem can be solved by constructing an auxiliary Lagrange function of the form:

\[
L(e, x, s) = \sum_{i=1}^{N} p \cdot H(e_i, x) - C_i(e_i) + s \cdot H(e_i, x), \quad (3)
\]

where \( s \) is the Lagrange multiplier, and in the optimal solution, it is equal to the shadow value of the resource unit.

The following conditions are restrictions:

\[
(p - s) \cdot H(x) - C'_i(e_i) = 0, \quad \text{if} \quad e_i > 0, \quad (4)
\]

\[
F(x) = \sum_{i=1}^{N} H(e_i, x) \quad (5)
\]

According to (4), in order to maximize profit in the field with numerous independent participants, the resource exploitation should be at the level when the marginal value of the cost of monetized benefits from the use of this resource for each of the participants is equal to the maximum value of the cost of non-monetized (shadow) effects. Considering this condition in terms of the ecosystem sustainability (in biological, economic and social terms), the shadow value can be interpreted as the lost benefit of an additional increase in the future ecosystem benefits, which could be used in case of
ceasing its current consumption [30]. Thus, shadow value reflects the hidden private and social effects associated with the use and existence of aquatic ecosystems that provide both economic and non-economic benefits.

The main limitation for widespread use of shadow prices in fishery was the difficulty of establishing their values due to insufficient data and the lack of possibilities for data processing. The development of digital technologies for collecting, processing and analyzing data eliminates this problem. A higher digitalization level makes it possible to more accurately determine all the parameters required for calculating shadow prices to consider them in fishery regulation, and to establish their optimal scales that provide a widely interpreted sustainability of aquatic ecosystems exploited in fishery.

4. Conclusion
Models that show dynamic interaction of socio-economic and ecological processes will allow careful consideration of all aspects of fisheries. The construction of such models requires a large amount of versatile data about a complex relationship between social, economic and environmental variables. Simpler input-output models can be used to avoid these difficulties, assess the heterogeneous effects of fishery and reach a trade-off between ecological, economic and social goals of fishery management. Digitalization of collection, processing and analysis of data on the use of resources and the state of ecosystems can significantly improve the quality of management decisions made using these models.

The ecosystem-based approach to fishery regulation requires an understanding of its principles. First of all, the goals associated with specific tasks of social economic development should be set within the ecosystem-based fishery management, for example, in terms of target catch or production volume, income and employment. In addition to the goals, indicators that reflect the environmental or socio-economic limitations of economic activity are also chosen (for example, the minimum amount of biomass required for self-reproduction, the minimum income, the state of the natural environment). Fishery based on the ideas and principles of the ecosystem-based approach implies a close relationship between goals and constraints. In contrast to the traditional approach that focuses on the goals while observing the constraints, the ecosystem-based approach eliminates the dichotomy in management. As a result, environmental constraints in traditional fishery management (for example, conservation of spawning grounds and fish habitats) become management problems within ecosystem management. However, goals in traditional management (for example, employment for fishermen) are transformed into constraints in terms of ecosystem management. Thus, the concept of ecosystem management requires the unity of goals and constraints, and their simultaneous use to assess the effectiveness of economic activities. The ecosystem management, which deals with ecosystems as complex, dynamic and unpredictable objects, results in the refusal to maximize their functions (i.e., to focus on one aspect of the ecosystem). In this regard, it is appropriate to speak not about maximization, but about optimization of the indicators of fishery management.

The goals of fishery management are often not directly related to management measures. This is due to the absence of an effective system for monitoring the achieved results, which is based on versatile, reliable and efficient data [31]. Therefore, it is necessary not only formally arrange the goals of fishery into a system of universally recognized, transparent and measurable indicators of sustainable development, but also develop an appropriate infrastructure for collecting and analyzing data on the activities of the industry and the environment, including all significant aspects of interaction of fishery with natural environment. Based on the above, it can be asserted that digital technologies enable transition to a new bioeconomic platform in fishery, which implies responsible involvement of biological resources in the economic circulation, and balanced functioning of business and ecosystems that will allow human and nature to coexist in productive harmony.

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