Observation of cetaceans' population dynamic in the Black Sea waters including the negative impact of Russian invasion: A System Dynamics Approach

By

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Abstract

This research focuses on the representation of the population dynamics of cetaceans in the Black Sea. The impact of a full-scale Russian invasion is also taken into account. With the help of the approach of System Dynamics, it becomes realistic to estimate the behavior of the population dynamics, and if it is possible to return to the pre-war state.

Therefore, during the work, Stella Architect was used to build a CLD diagram in order to understand the main variables, their relationships, and their behavior. Subsequently, a comprehensive model was built that covers the various factors affecting cetacean populations in the Black Sea. Major variables include: water pollution, habitat state, changes in food distribution, and other factors related to military activity.

The results make it possible to analyze the impact of military activity on the population of cetaceans in the Black Sea. The main indicator is the number of cetaceans in the Black Sea. After the research, it was found that within 50 years after the beginning of the invasion, the restoration of the population of Black Sea cetaceans to the pre-war state is real.

The study provides grounds for the further development of strategies for the protection and management of cetaceans in the Black Sea, in particular in the context of the impact of military conflicts. This model is only the beginning of this research, and further in-depth study of this topic will allow obtaining more realistic results.

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I. INTRODUCTION.

1.1 Background.

The Black Sea is a large natural complex, which has specific natural conditions and resources. The surface area of the Black Sea is about 422,000 square kilometers. The Black Sea washes the shores of Ukraine, Romania, Bulgaria, Turkey, Georgia, and Russia (Encyclopedia Britannica, Black Sea, 2023). In my work, I depict the Black Sea as a natural environment for three species of marine mammals, namely cetaceans: two species of dolphins, Bottlenose Dolphins, and Common Dolphins, as well as the smallest cetaceans in the world – Harbour Porpoises.

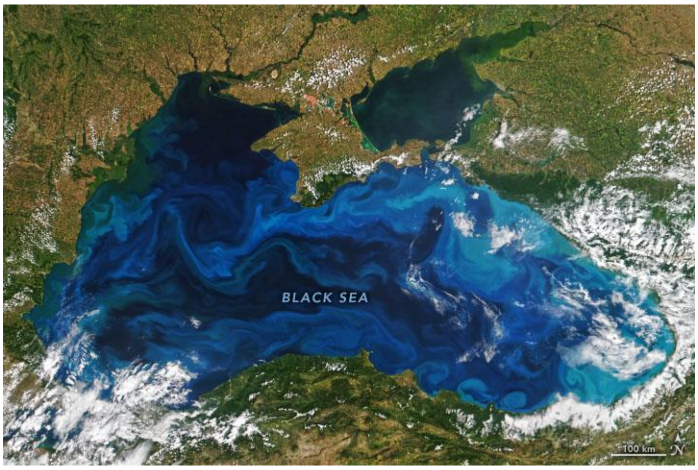

Image 1 - The Black Sea (Credit: NASA Earth Observatory)

About 60% of the total area has been observed in the Black Sea and it has been estimated that about 253,000 cetaceans live in this area (Milanova, Y. 2021, "Світ довкола", LIGA.Life). In particular:

- 41 000 Bottlenose Dolphins;
- 118 000 Common Dolphins;
- 94 000 Harbour Porpoises.

Despite the partial recovery and stabilization of cetacean populations in the Black Sea, all three species remain on the Red List of Endangered Animals maintained by the International Union for Conservation of Nature (IUCN).

«*The Black Sea is even more problematic because of poaching, which is very difficult to fight*» says Pavlo Goldin from the Kyiv Schmalhausen Institute of Zoology (Kreger, A. 2023, BBC News Ukraine) However, this is not the only problem that harmed marine mammals in the sea before the full-scale invasion.

According to the research carried out by the website «О, море», it is difficult to say that the condition of the water in the Black Sea is even suitable. Tons of plastic, chemicals, and pesticides from different countries get there every year. According to ecologists, as of 2017, the Black Sea was twice as polluted as the Mediterranean.

With the beginning of the full-scale invasion of Russia on the territory of Ukraine on February 24, 2022, the state of the waters of the Black Sea only began to deteriorate faster. The cetacean population, which was not in perfect condition and desirable numbers before, also began to decline at an even faster rate.

1.2 Problem-setting.

The Workshop Report «The Status and Distribution of Cetaceans in the Black Sea and Mediterranean Sea» states that the Black Sea ecosystem, including the habitat of common dolphins and the populations of their prey species, has experienced significant degradation since the 1970s. Factors such as overfishing, habitat deterioration, pollution, and the proliferation of invasive species have contributed to the decline. The most severe impacts were observed in the late 1980s and early 1990s. As a result, prey populations have greatly declined, affecting the overall health of the ecosystem (Reeves R. and Notarbartolo di Sciara G., 2006, IUNC).

Till the time of the full-scale Russian invasion of Ukraine, the population of cetaceans and their prey in the Black Sea waters was not in the best condition, but it did not decrease as sharply as after the invasion.

«The mass beaching of animals onto the coast began almost immediately after the Russian invasion,» says Pavlo Goldin from the Kyiv Schmalhausen Institute of Zoology (Kreger, A. 2023, BBC News Ukraine).

A significant part of the territory of the Black Sea (about 20%) (Sitnikova I., 2023) is controlled by Russia. As a result of hostilities, the population of cetaceans is subject to numerous negative impacts, which significantly affect their numbers. I would like to highlight the most important factors of ecocide in the Black Sea:

- Military actions, such as explosions and landmines, directly kill dolphins or cause severe damage to the cetacean auditory system, making feeding and spatial orientation impossible (Michael J. Lawrence et al, 2015).

«In the case of strong noise and acoustic trauma, the dolphin may not die, but may suffer an injury similar to blindness and deafness, which, in fact, equates to death,» says Natia Kopaliani, a professor at the Institute of Ecology at Illia University (Tbilisi) (Mosiashvili, T. 2023) Oil spills and pollution affect the state of the natural environment.

- The presence of military ships, leads to water pollution and changes in environmental conditions, which negatively affect cetaceans and the natural environment in which they are living.

The decrease in the population of cetaceans is a sign of the deterioration of the ecological state of the sea (Haddad, N. M. et al, 2015). The re-establishment and preservation of cetacean populations is an important task for nature conservation and the balanced functioning of the marine ecosystem. Furthermore, the decline of cetacean populations in the Black Sea is a global problem, as it affects the ecological stability, biodiversity, and health of the marine environment, and will have consequences for people who depend on the resources and services provided by the sea.

Ivan Rusev - ecologist, doctor of biological sciences, and head of the research department of the National Park «Tuzlivski Lymani» says: «*It will take about 30-50 years to restore the population of at least the pre-war period. We already have the support of the Ministry of Environment to create such a marine reserve with an area of three thousand square kilometers*» (Gembarska, L. 2023, Ecopolitic).

As a solution to the problem of a rapid decrease in the number of Black Sea cetaceans, it is planned to expand the National Park "Tuzlivski Lymani", which includes the marine territory. The water area must adhere to very strict conditions so that cetaceans feel safe, which was even difficult to achieve in pre-war times.

1.3 Research Objective.

The purpose of my research is to observe the trend in the population of Black Sea cetaceans, taking into account the influence of military activity. Also, in research, I pay considerable attention to the state of the natural environment and the presence of a sufficient number of fish as prey for cetaceans.

I take into account the pre-war state of the environment and its impact on the population, during the war and after the war. As part of the research, I plan to assess changes in population size under the influence of various factors, such as pollution, habitat degradation, changes in the amount of available prey, and the impact of military activity, including explosions, oil spills, and other forms of pollution. I want to represent the cause-and-effect relationships between these factors and changes in the population of Black Sea cetaceans.

I use a System Dynamics approach to model the situation and analyze population dynamics to gain a deeper understanding of the impact of environmental and military factors on cetacean numbers in the Black Sea. The research is aimed at understanding the real impact of the environment and military activity on the population of cetaceans in the Black Sea, which should cause resonance and prompt actions to invest in the preservation and protection of these species, as well as in the cleaning of water areas.

1.4 Research questions.

Since in my research, I pay special attention to the dynamics of the population of Black Sea cetaceans and factors of the impact, the main research questions to which I provide answers are:

- How do cetacean populations change over time if no conservation and restoration measures are taken?

- How do environmental changes such as pollution, and changes in prey availability affect cetacean populations?
- What is the impact of military activity on cetacean populations and their natural habitat?

II. METHODOLOGY.

2.1 Methodological approach.

The System Dynamics approach was chosen for the research because of its ability to effectively describe the relationships between the elements of complex real-world systems that undergo changes over a period of time. The use of System Dynamics in the study of the population of Black Sea cetaceans is the most expedient, as it allows the analysis of quantitative characteristics of the population by building relationships between factors that directly affect the state of the population. With the help of SD, time delays, dependencies, and feedbacks can be taken into account, which allows gaining a deeper understanding of population dynamics and predicting the possible consequences of different scenarios. This approach allows taking into account the complexity of the system, which is characteristic of population's processes.

As it was stated before the SD approach is suitable for modeling feedbacks and interactions in complex systems. This approach allows including a large number of components that interact with each other. The application of System Dynamics modeling provides an opportunity to estimate the value of unknown parameters through optimization and also provides advanced tools for validating of the model, including sensitivity analysis and other tools included in the Stella Architect software package. Given these advantages, System Dynamics becomes a powerful tool for understanding and modeling complex systems.

A SD approach is often used to represent population dynamics. A well-known example is the Predator-Prey model, also known as the Lotka-Volterra model (*Image 2*), which simulates the interaction between predator and prey populations. In addition, was used a model the subject of study of which was habitat interactions with wider ecology (*Image 3*). These models were used as a reference for modeling and analyzing the population of cetaceans in this study.

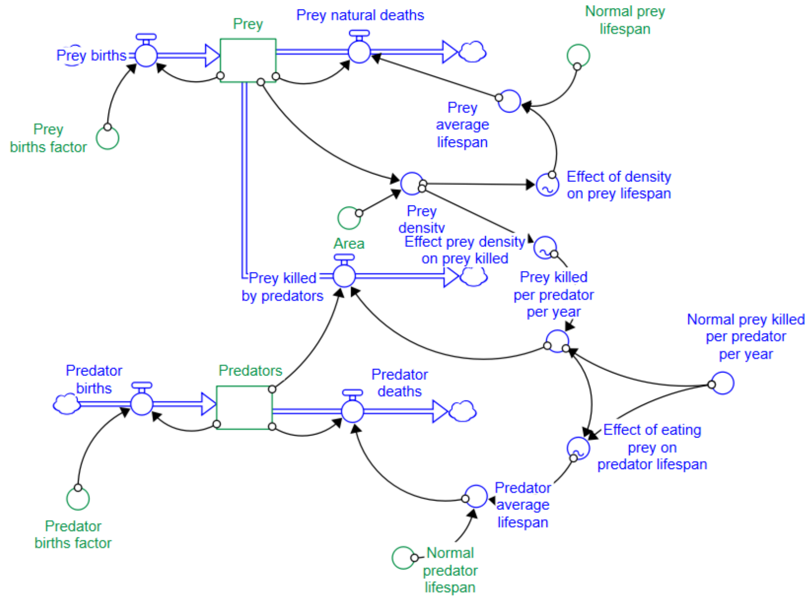

Image 2 - The Preditor-Prey model (Credit: isee Exchange)

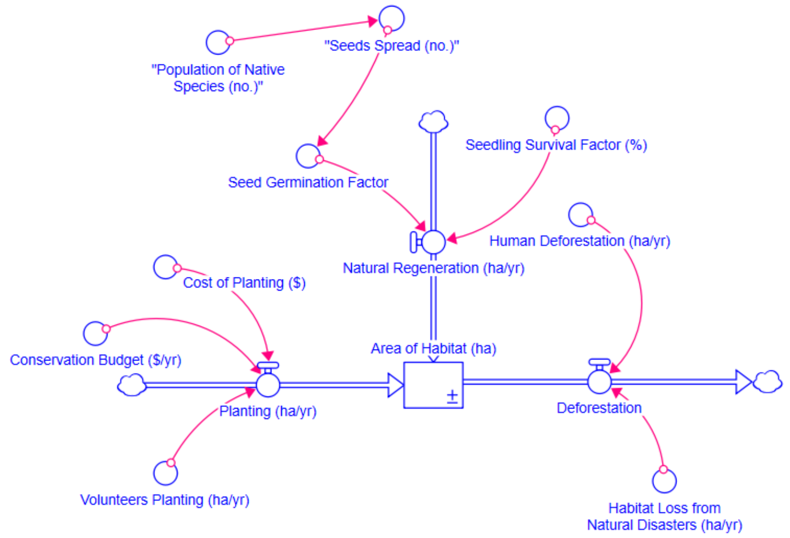

Image 3 – The Model of Habitat Interactions with Wider Ecology (Credit: isee Exchange)

2.2 Data Collection.

Information from articles on the state of cetacean populations and the ecological situation in the Black and Mediterranean Seas was used for the research and directly for the construction of the model. Articles that were used to build relationships in the model, as well as to check its validity, mostly belong to such online collections of scientific research as ScienceDirect; scientific portals such as ResearchGate; an open access repository and publishing platform for scholarship PDXScholar. Internet news sources such as BBC, RadioSvoboda, Ecopolitic, Ecolog-ua, Ukrinform, Nsirogozy.city, Life.Liga and others also played the most important role in my research.

To search for relevant information, I mostly used the combinations of the following keywords: "Black Sea cetaceans", "dolphins", "situation in the Black Sea", "natural environment of dolphins", and "population of cetaceans".

My search for information has mostly focused on basic information about cetacean life, and possible dolphin conservation projects. I was also focused on obtaining new and necessary knowledge about the impact of the war on the marine fauna within the Black Sea and what kind of injuries cetaceans experience within these limits.

Data collected from different sources can be divided into three main groups.

- Information about cetaceans: the initial number of cetaceans in the pre-war period (as of 2019), average life expectancy, the average amount of food consumed per year, the percentage of reproductive individuals in the population, the number of cubs, the number of cetaceans killed by explosions.

- Information about prey: the initial amount of potential loot (as of 2019), Average life expectancy, percentage of fish caught overtime.

- Information about the state of the environment: Initial area of natural habitat suitable for life (as of 2017), Percentage of maritime territory occupied by Russia, The number of military enemy ships, The initial amount of garbage in the sea, The amount of garbage entering the Black Sea every year.

All received information was subjected to critical analysis and logical processing, as well as verified by comparing information from different sources. This approach made it possible to ensure the reliability and validity of the obtained data and research results.

However, I also faced difficulties in finding information. It is quite difficult to find an exact number for the population of cetaceans since the observation was carried out by several countries at different periods of time. Also, the information about pollution is based on the read, but the data is quite vague. Also, due to military activity, it is difficult to assess the scale of damage caused to the environment. The only marine national natural park on the territory under the control of Ukraine is «Tuzlivski Lymani». Before the full-scale invasion of the Russian Federation into Ukraine, researchers had access to 44 kilometers of the sea coast. Currently, they are allowed to monitor only 5 kilometers (Nazarchuk, I. 2022, RadioSvoboda).

2.3 Data Analysis.

The collected data were used to determine the key factors affecting the population of Black Sea cetaceans and their environment. Using the information obtained during the search, realistic relationships were created in the model between such components as the population of cetaceans and the amount of prey, the relationship between the state of the habitat and the ability of cetaceans to feed, between the habitat and prey, as well as the relationship between habitat degradation and water pollution, which made it possible to represent the most realistic situation.

The comparison of the obtained model with the models of population studies made it possible to establish relationships between these factors of influence on the population. When building the model of System Dynamics, real data that could cause changes in the environment, including the impact of military activity, pollution, and other factors, were taken into account. The model reproduces the dynamics of the Black Sea cetacean population, considering the influence of these factors on their lifespan and interaction with their habitat.

The collected data was an important element for model calibration and validation so that corresponds to real observations. This made it possible to use the model to predict and analyze the impact of various scenarios on the population of Black Sea cetaceans.

The obtained results were interpreted taking into consideration the context of the study. Considering the limitations and possible alternative explanations, the interpretation of the results provides valuable information about the state and future development of the Black Sea cetacean population.

III. MODEL OVERVIEW.

3.1 Dynamical Hypothesis.

Pollution and military activity accelerate the degradation of the habitat, which has a negative impact on the population of Black Sea cetaceans (Parsons E. C. M., 2017). These marine mammals depend on a suitable environment for their reproduction and food supply (Encyclopedia Britannica, Cetacean, 2023). However, due to constant water pollution and damage caused by military actions, the area of suitable habitat is decreasing.

A decrease in the area of suitable habitat has a negative effect on the population of cetaceans. First, the reduction of acceptable habitat space leads to a decrease in the number of surviving calves. Cetaceans need safe and favorable places to give birth and raise their young. Also, under conditions of stress, calves are born less often than usual (Gembarska, L. 2023, Ecopolitic). Second, the reduction in the area of suitable habitat also leads to a decrease in the amount of food available for cetaceans. They depend on fish for their nutrition. Pollution and the decline in fish numbers due to habitat change led to a lack of food for cetaceans, which negatively affects their survival.

Consequently, pollution and military activity cause habitat degradation, which reduces the available space for breeding and providing food. This leads to a decrease in the number of populations due to a reduction in the number of calves that survive and a lack of food, which affects their lifespan.

3.2 Feedback Loops Overview.

For a general understanding of the model's behavior, let's first consider the feedback loops included in it. Feedback loops are an important mechanism that affects model behavior and system development. It reflects the relationship between elements, where a change in one element affects other elements, and the result of this influence is fed back to the original element, changing its behavior. Meadows (2008) describes a feedback loop as: A closed chain of causal connections from a stock, through a set of decisions or rules or physical laws, or actions that are dependent on the level of the stock, and back again through a flow to change the stock.

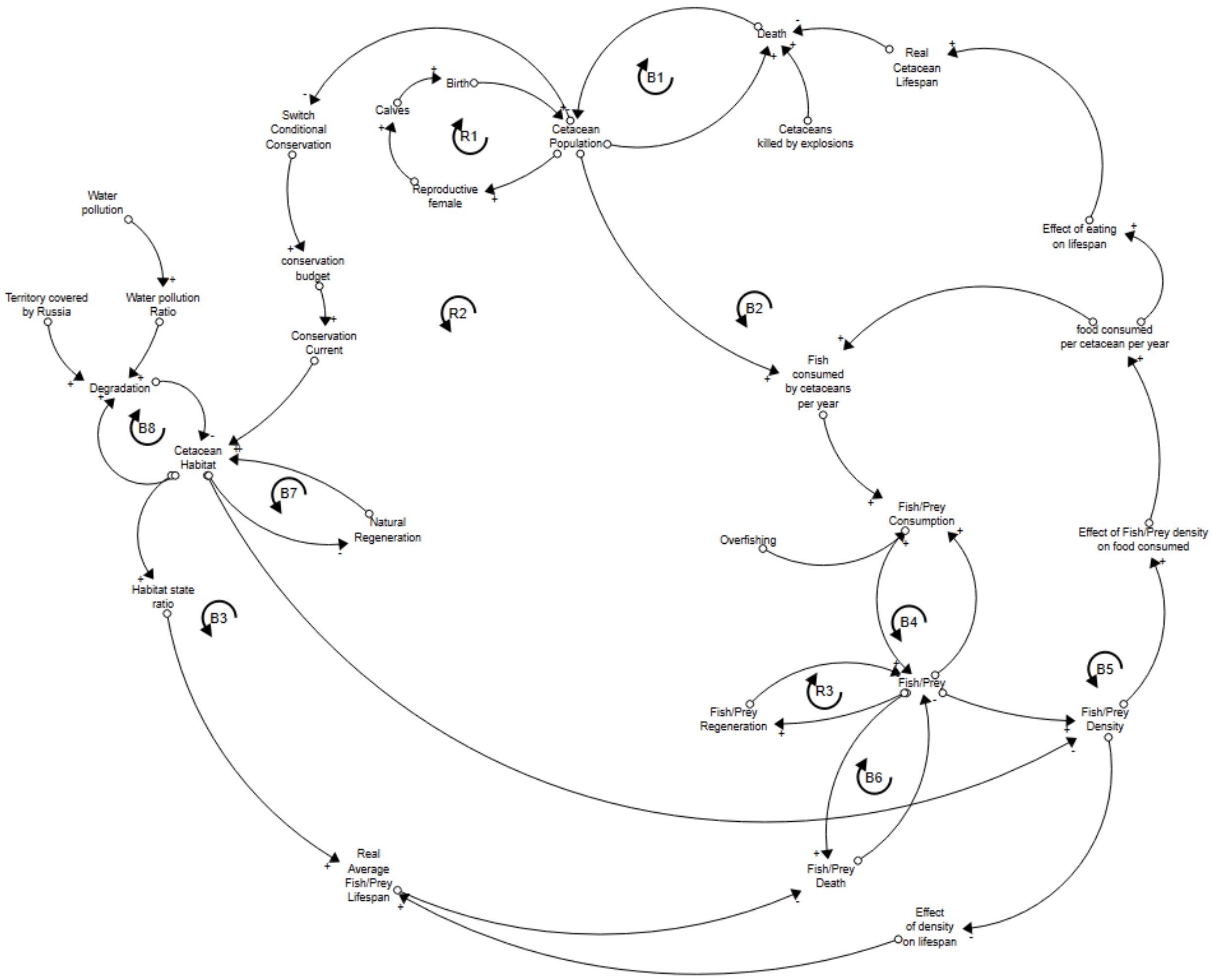

Image 4 - Feedback Loop Diagram

R1 Cetaceans' birth feedback loop:

Cetacean Population →(+) Reproductive female → (+) Calves → (+) Birth→ (+) Cetacean Population.

This reinforcing feedback loop represents the relationship between the cetacean population and the number of calves that are born and survive. The greater the number of cetaceans, the more potentially reproductive female cetacean there are that can give birth to young and ensure the survival of a greater number of calves. It is important to remember that only one young can be born at a time (WDC, 1987), so the more reproductive females there are, the greater the number of young that will survive which means more cetaceans in the population.

B1 Cetaceans' death feedback loop:

Cetacean Population → (+) Death → (-) Cetacean Population.

This balancing feedback loop shows the relation between the cetacean population and death. The greater number of cetaceans means more possible deaths. More possible deaths negatively impact the number of individuals in the population. Moreover, the number of deaths is also replenished with marine mammals that died as a result of the explosions. I include in the number of marine mammals killed by the explosions animals that were directly killed by the explosions and deafened, which also is equal to death. However, the number of cetaceans that died as a result of the explosions may be much higher, as not all animals beached on the shore, as noted by ecologist Ivan Rusev (Gembarska, L. 2023, Ecopolitic).

B2 Cetaceans' population and Fish consumption feedback loop:

Cetacean Population → (+) Fish consumed by cetaceans per year → (+) Fish/Prey Consumption → (-) Fish/Prey → (+) Fish/Prey Density → (+) Effect of Fish/Prey Density on food consumed → (+) food consumed per cetacean per year → (+) Effect of eating on lifespan → (+) Real Cetacean Lifespan → (-) Death → (-) Cetacean Population.

The balancing loop depicts the connection between and the number of fish they consume. If there is a huge number of cetaceans they consume more fish per year, furthermore it leads to an increase in fish consumption in general. Moreover, fish consumption is also affected by overfishing and it has a negative impact on the number of fish (Notarbartartolo di Sciara G. 2002, pp.107-108). If the amount of fish decreases, fish density also goes down, which means that cetaceans won't be able to feed themselves properly. It leads to a decrease in lifespan. Furthermore, shorter cetaceans' lifespan results in a greater number of cetaceans' death. More deaths – population decline.

R2 Cetaceans' population, Habitat and fish density feedback loop:

Cetacean Population → (-) Switch Conditional Conservation → (+) conservation budget → (+) Conservation Current → (+) Cetacean Habitat → (-) Fish/Prey density → (+) Effect of Fish/Prey density on food consumed → (+) food consumed per cetacean per year → (+) Effect of eating on Lifespan → Real Cetacean Lifespan(+) → (-) Death → (-) Cetacean Population.

The reinforcing loop represents the part of the policy included. I assume that when the number of cetaceans in the population reaches the point of half of its initial amount the conservation measures for habitat should be implemented. However, if the area of the habitat is wider it means that prey density is going to be lower, furthermore, it means that it would be harder for cetaceans to hunt. This would negatively impact their lifespan (Hin, V., J. Harwood, and A. M. de Roos. 2019, pp. 1-3), leading to death increase and a decline in the population.

B3 Cetacean Population, the state of the Habitat and the amount of fish feedback loop:

Cetacean Population → (-) Switch Conditional Conservation → (+) conservation budget → (+) Conservation Current → (+) Cetacean Habitat → (+) Habitat state ratio → (+) Real average Fish/Prey Lifespan → (-) Fish/Prey Death → (-) Fish/Prey → (+) Fish/Prey Density → (+) Effect of Fish/Prey density on food consumed → (+) food consumed per cetacean per year → (+) Effect of eating on Lifespan →(Real Cetacean Lifespan) → (-) Death → (-) Cetacean Population.

This balancing loop represents the connection between the state of the habitat, the amount of fish, and the cetaceans' population. When the state of the habitat is not acceptable for living it leads to a decline in the amount of prey, which means less fish for cetaceans (Chu EW, Karr JR. 2016, p.4). Less prey – harder to feed, furthermore, cetaceans' lifespan is shorter, and it increases the number of cetaceans' deaths.

B4 The amount of fish and its consumption feedback loop:

Fish/Prey → (+) Fish/Prey Consumption → (-) Fish/Prey.

This balancing loop shows the connection between the consumption of fish and the amount of fish by itself. If there is more fish it means a bigger amount of it will be consumed, as for predators it would be easier to hunt, and a larger amount could be overfished (described in B2 and B3). Therefore, if more fish are consumed less fish is left.

B5 The fish density and fish consumption feedback loop:

Fish/Prey density → (+) Effect of Fish/Prey density on food consumed → (+) food consumed per cetacean per year → (+) Fish consumed by cetaceans per year → (+) Fish/Prey Consumption → (-) Fish/Prey → (+) Fish/Prey density.

The balancing loop depicts the connection between fish density and fish consumption. When the density of prey in the chosen area is increasing it becomes easier for cetaceans to hunt (Introductory Biology (CK-12), 2023, p. 397). It means that cetaceans will be able to consume more fish which leads to an increase in general fish consumption. More fish consumed – fewer fish are left in the chosen area.

B6 The amount of fish and its natural death feedback loop:

Fish/Prey → (+) Fish/Prey death → (-) Fish/Prey.

This balancing feedback loop shows the relation between the amount of fish and its natural death. A greater number of fish means more possible deaths. More possible deaths negatively impact the amount of prey in the area.

R3 The amount of fish and its regeneration feedback loop:

Fish/Prey → (+) Fish/Prey Regeneration → (+) Fish/Prey.

The reinforcing loop shows the link between the amount of prey and its natural regeneration process. If there is more fish it means more fish can be born, which leads to an increase in fish population.

B7 Cetaceans' habitat and its natural regeneration feedback loop:

Cetacean Habitat → (-) Natural Regeneration → (+) Cetacean Habitat.

This balancing feedback loop represents the relation between habitat and its regeneration. As far as the habitat is a limited territory the regeneration process takes place when the area is getting damaged. The more damage – the more space for regeneration.

B8 Cetaceans' habitat and its degradation feedback loop:

Cetacean Habitat → (+) Degradation → (-) Cetacean Habitat.

The balancing feedback loop describes the connection between the habitat and its degradation process. The bigger territory is acceptable for a living – the more territory is going to degrade following natural processes. However, the degradation process is accelerated by yearly pollution (NOAA, 2020) and by military activity (NRC Research Press, 2015). The more territory degrades – the less territory is acceptable for a living (Science Advances, 2015).

3.3 Model Structure Overview.

This sub-section will describe the main model working principles (*Image 5*).

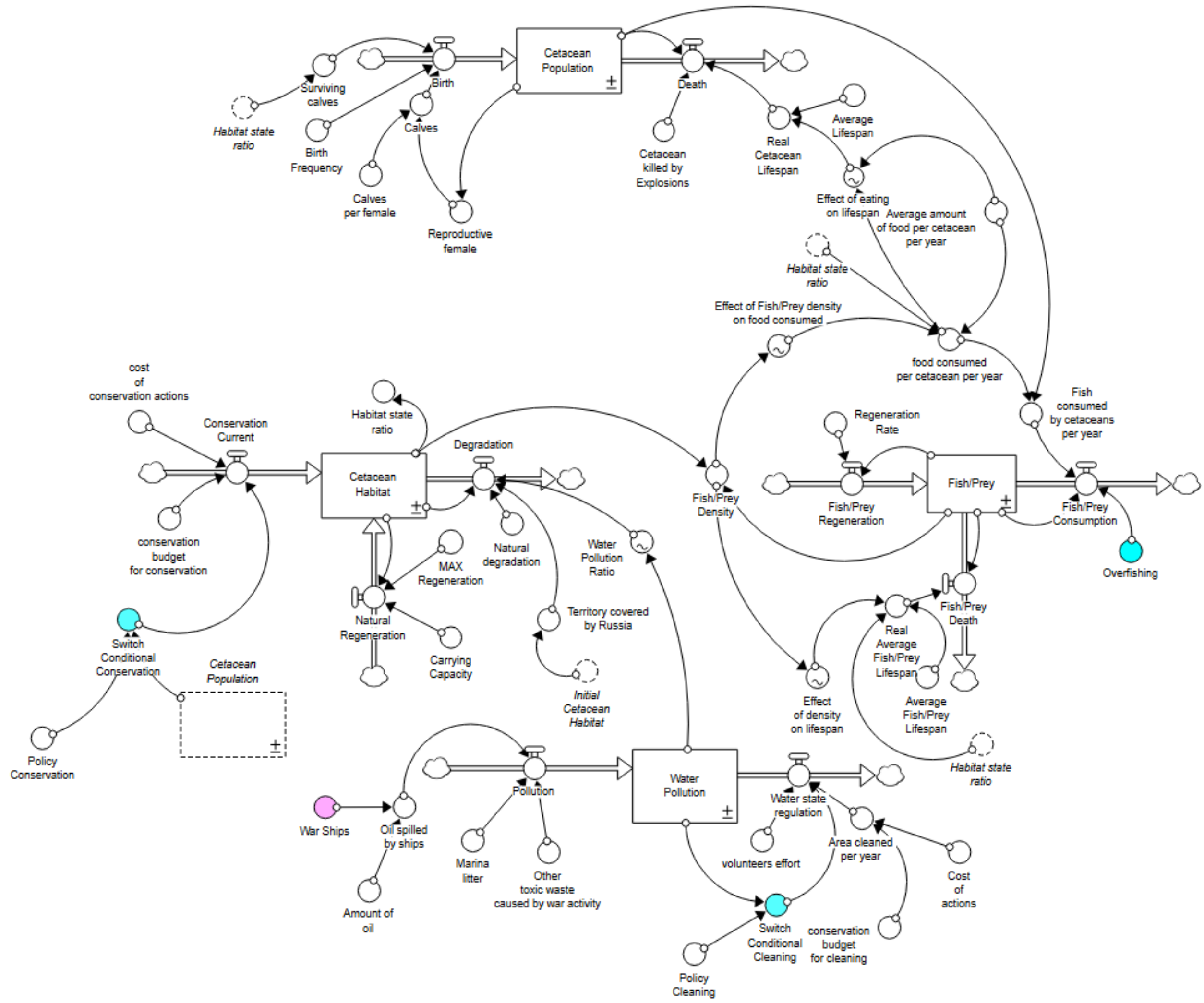

Image 5 – The Full Model Structure

The time period from 2019 to 2069 was selected for the model run. This time frame was chosen to show the state of the population before a full-scale invasion, and because most of the initial data was collected from 2019 materials. Also, Ukrainian scientists believe that it is possible to restore the population to the pre-war state in 30-50 years, as already mentioned in this work.

When calculating the birth rate, the following factors are taken into account: cetaceans can give birth on average once every 2-3 years, in a state of stress this happens even less often. Therefore, it is believed that during the period of military activity in the Black Sea territory cetaceans can give birth once in 5 years, as Professor Rusev I. states in the interview (Nazarchuk I., 2022).

When calculating mortality, the number of cetaceans directly killed by explosions is considered. However, at the time of writing this paper, scientists believe that this number is much higher. The model assumes that military activity will cease in 2025, so the number of cetaceans dying from explosions every year until 2025 is constant. After the cessation of activities that harm the environment, it is accepted that cetaceans still die, due to the demining process, which includes possible explosions. However, cetaceans no longer die in such large numbers, only 0.1% of the initial value of cetaceans killed by explosions.

The relationship between the population of cetaceans and the number of fish, which is their prey, is built on the basis of the already studied Predator-Prey model (*Image 2*).

An important detail in the observation of the dynamics of a suitable environment is its degradation. Degradation is caused by the state of the water polluted by marine debris, as well as military actions. As already mentioned earlier, the influence of military activity will cease from 2025, therefore, after that, the part of the natural environment that was occupied will not experience a sharp negative impact. Also, the environment will theoretically become less polluted from the movement of warships, which also reduces the negative impact on the suitable environment after 2025. Nevertheless, water pollution accelerates the process of environmental degradation. That is why to this parameter is paid careful attention in the Scenarios Analysis section

3.4 Model Boundaries.

There are several significant boundaries in the model, but these boundaries did not prevent achieving a realistic representation of cetacean population dynamics in the Black Sea. One of the main limitations is the difficulty of obtaining specific data on the amount of toxic and plastic waste entering the sea annually since the Black Sea washes the shores of several countries. The lack of specific numerical meanings of pollution required the use of logical assumptions in order to calculate the possible water pollution.

In addition, an important obstacle is that a large part of the Black Sea is occupied territory, which makes it difficult for scientists to assess the full extent of the environmental damage. This is a limitation in access to data and the possibility of conducting research in the relevant areas.

The boundaries of the model are the difficulty of obtaining specific data on the pollution and possible restoration of the state of the Black Sea, as well as the limited access to the occupied territories. The model was created with these limitations taken into account and contains logical assumptions that allow us to get closer to the real dynamics of the cetacean population in the Black Sea.

3.5 Model assumption.

There are several logical assumptions in the model, the application of which was necessary to reproduce realistic behavior.

Assumptions were made in the part of the model that concerns the representation of the dynamics of the natural environment of cetaceans. The assumption about the percentage of natural degradation of the environment was introduced based on the fact that the environment also degrades annually due to the depletion of available resources. An assumption was also made about the percentage of fish recovery. This assumption is generalized since the focus of the study is the population size of cetaceans. However, the assumption is no less important, because, with the help of this assumption, it was possible to replicate the plausible behavior of the interaction of cetaceans with prey.

Next are assumptions about the cost of effort to restore a unit of habitat and the cost of cleaning water from a unit of marine debris. The overall annual budget is also subject to correction and may be edited according to actual data. However, in this model, the value of this parameter is approximate.

Also, taking into account military activity in the waters of the Black Sea, I assume that the occupied territory will be more negatively affected than other territories.

The behavior of the graphic functions is based on the studied Predator-Prey model.

IV. MODEL VALIDATION.

4.1 Calibration.

During the entire model-building process, calibration was carried out to ensure realistic model results. Calibration involved constantly checking and tuning model parameters based on new data and information in news and articles. At the initial modeling stage, some variables were based on logical assumptions, but later materials were found that confirmed the values of these variables. This required additional model calibration to reproduce the exact dynamics of the system. The results of the analysis of the article "Overfishing Statistics – Global Status of Fishery Resources!" were especially important. (Bryant, M. 2023, WorldAnimalFoundation). The changes to the overfishing parameter significantly affected the behavior of the entire system (IMAGE). In addition, after the addition of parameters that determine the price of conservative actions, calibration was necessary to reproduce the logical dynamics of the population.

4.2 Unit Dimension Test.

All variables used in the model correspond to real units of measurement. All single parameter has their own meaning connected to real life. There are no variables in the model that adjust the equations taking into account the dimension. This meets the dimensional test requirements for the model (Forrester W. J., Senge M. P., 1980, pp. 215-216).

4.3 Behavior Replication and Structural Test.

As mentioned earlier, the Predator-Prey model was used as the main reference for building the model. Real data corresponding to the present were also used during construction. The behavior of the model is completely predictable and coincides with the materials that were used for the study.

4.4 Extreme Condition Test.

For the extreme conditions test, I chose to test such parameter as Initial Cetacean Habitat. In "real world" situations the reduction of acceptable for a cetacean's living territory leads to a collapse in the population.

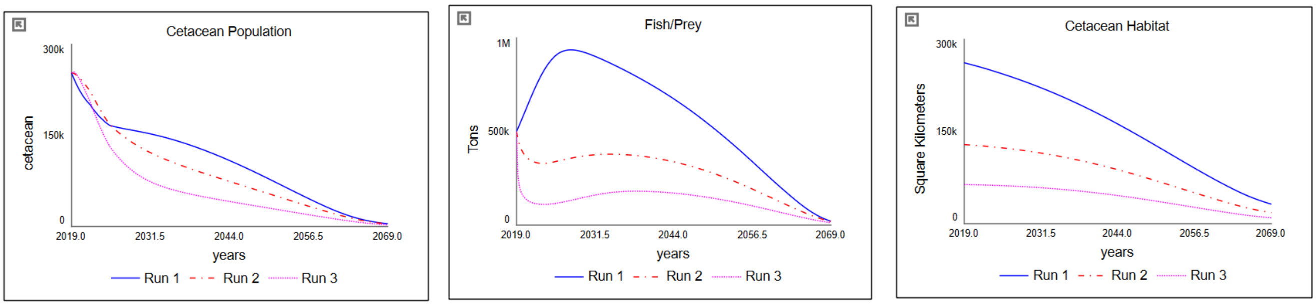

Image 6 - Extreme Conditions Test

Firstly, I reduced the value of the Initial Cetacean Habitat two times and then repeated that action. As expected, the model replicates the dynamics of the cetaceans' population correctly (*Image 6*). The number of cetaceans is decreasing even faster according to habitat loss (Walsh P. M, 2016).

4.5 Parameter Test.

Almost all parameters and connections correspond to "real-world" meanings and are taken from the reviewed previously literature as it should be according to Forrester W. J., Senge M. P., 1980. Several parameters are based on assumptions; however, the assumptions were made referring to the previously studied models. It was done in order to replicate the necessary dynamics that make sense in realistic conditions.

4.6 Integration Error Test.

The test was conducted in order to find out whether the dynamic of the model is sensitive to changes in the integration method. "The results of the model should never be a function of the choice of integration method or integration interval" (Martinez-Moyano J., I., 2018, p. 267).

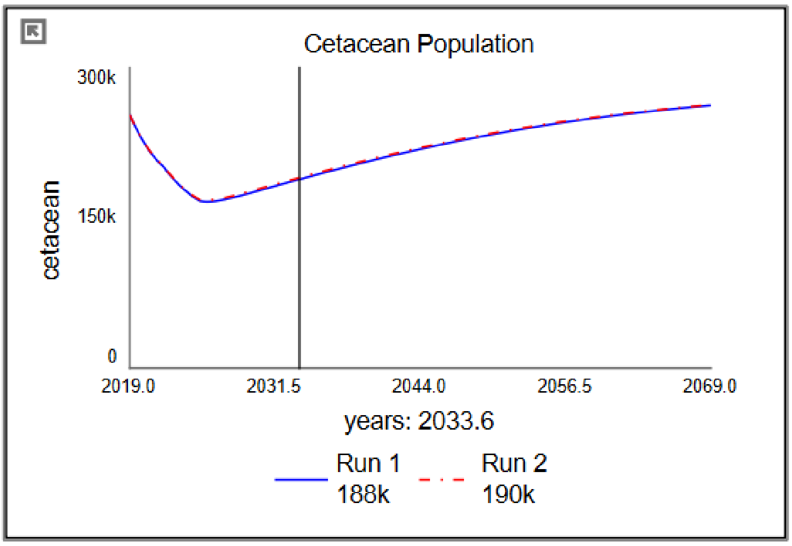

Image 7 - Integration Error Test

The model was built using the Euler integration method. When the integration method was changed to Runge-Kutta 4, almost no changes occurred, except for a slight difference in the population of cetaceans, which subsequently leveled off *(Image 7).*

4.7 Sensitivity Tests.

The Sensitivity tests were made in order to gain a deeper understanding of the overall dynamics of the model. This test made it possible to discover how changing the values of certain parameters affects the behavior of the system. The sensitivity Tests built confidence in the model by identifying and observing the leverage points – those variables that have the greatest impact on the dynamics of the system (Breierova L., Choudhari M., 1996, p.47).

In my model, the main variables that are the subject of this study are cetacean populations, their habitat, and the amount of prey in their habitat. These variables define the main dynamics of the system I am observing. In addition, I pay attention to the lifespan of cetaceans, as this allows me to reveal the sensitivity of the model to changes in individual parameters that affect the life extension of these marine mammals. These four main variables are the basis for analyzing and understanding the impact of various factors on the cetacean system and its environment.

Parameter testing was performed using Uniform Distribution $\pm$ 25% for the initial value of tested parameters. Moreover, in this section, I present the parameters to which the model was most sensitive to changes (all other parameters, as well as the testing of graphic functions, are in APPENDIX A).

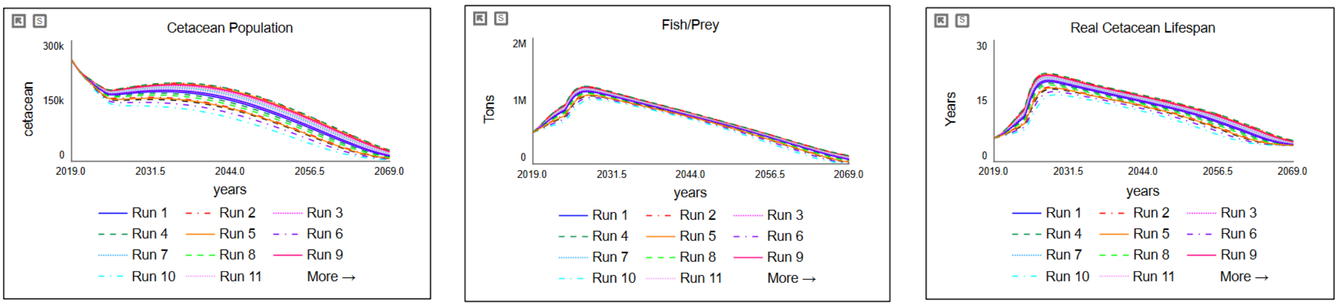

Image 8 - Sensitivity analysis - The change in Average Fish/Prey Lifespan

Image 8 shows how sensitive are Cetacean Population and Real Cetacean Lifespan, Fish/Prey. Even small changes in estimated average prey life affect the number of cetaceans. If prey lifespan increases, this leads to an increase in prey populations as more prey is available for cetaceans to feed on. This can increase their chances of survival and provide them with enough food to feed. However, if the lifespan of prey is reduced, this may lead to a decrease in the amount of food available for dolphins. This can cause a shortage of food, worsening the condition of the dolphins and reducing their survival (this connection is shown in the previous section in the description of the B3 feedback loop). The dolphin population may decrease due to a decrease in prey and an insufficient food base.

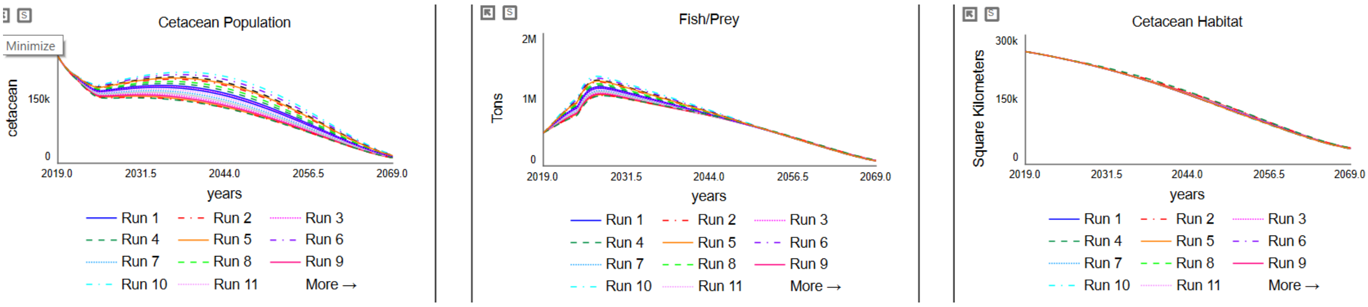

Image 9 - Sensitivity analysis - The change in Average amount of food per cetacean per year

Image 9 depicts how the cetaceans' population and the amount of prey is sensitive to the change in the amount of food per cetacean. However, cetaceans' habitat is not that sensitive to those changes. This sensitivity test helped to make sure in the correctness of links between cetaceans' population and its prey.

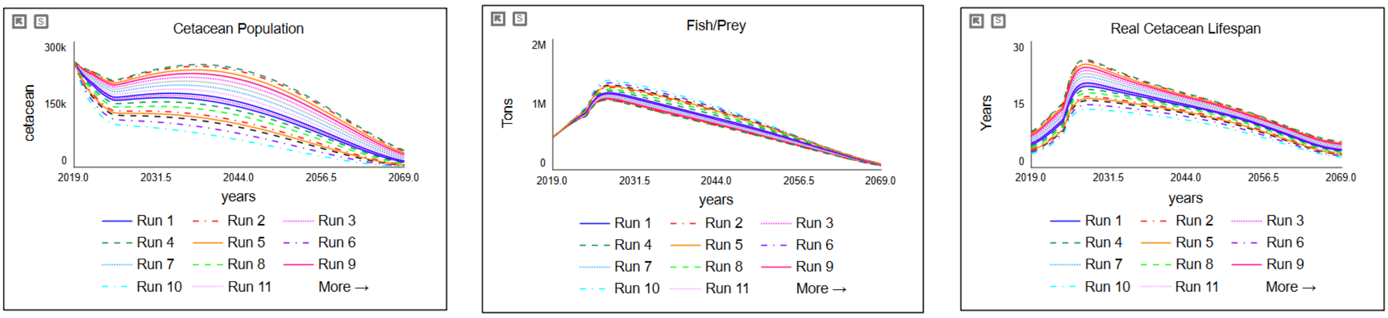

Image 10 - Sensitivity analysis - The changes in Average Lifespan

Image 10 shows the impact of changes in the average cetacean lifespan and how the main parameters are sensitive to it. In fact, based on the loops description in the previous section it becomes obvious that with a longer lifespan, the cetaceans have higher chances to increase their population. If to continue this research this observation could be taken into consideration as a subject of conservation of population measures. The research can be more focused on direct factors that influence the average lifespan of cetaceans.

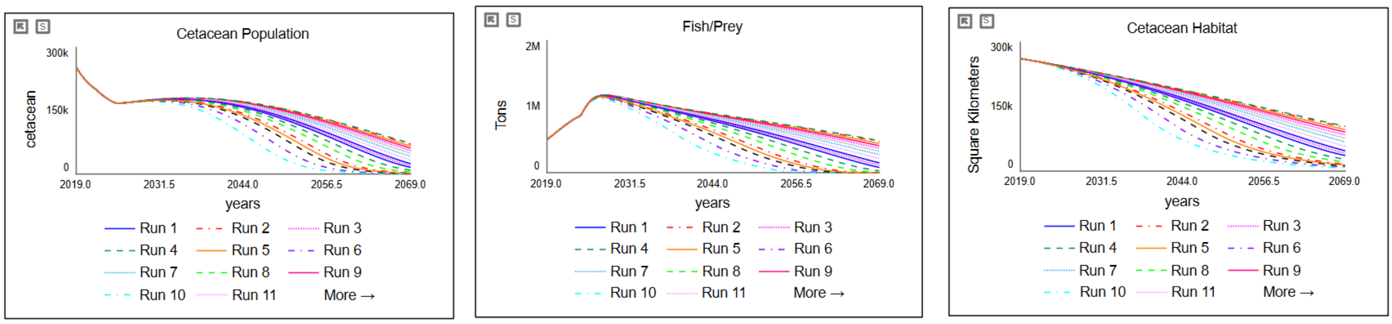

Image 11 - Sensitivity analysis - The changes in Initial Water Pollution

Image 11 represents that all main parameters are highly sensitive to the changes in Initial Water Pollution. With higher water pollution the cetaceans' habitat degrades faster. This observation helped to come up with one of the policies which is described in the next section. The conservation measures should be focused on the regulation of the water state as it directly impacts the cetaceans' and their prey population. Focusing efforts on reducing pollution and improving water quality can contribute to the conservation and recovery of cetacean populations and the balanced functioning of the marine ecosystem.

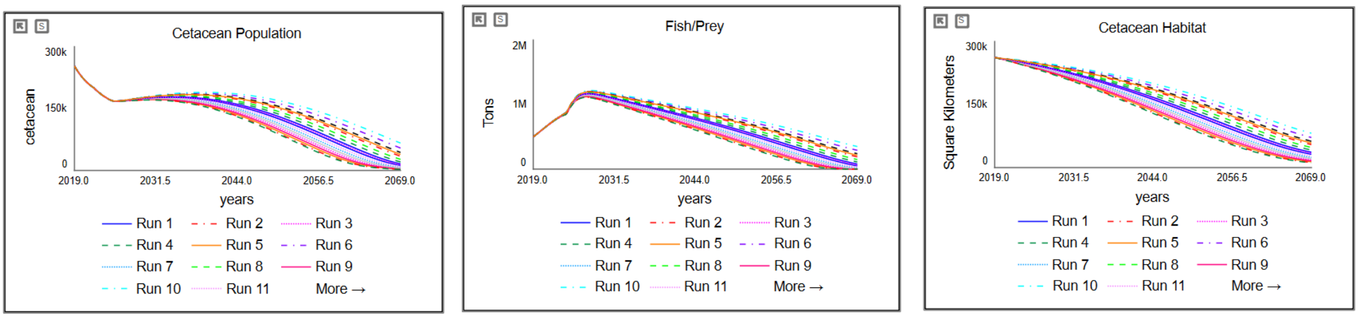

Image 12 - Sensitivity analysis - The changes in Natural Degradation

Image 12 represents the sensitive connection between natural habitat degradation and process and main model parameters. The parameter is assumed as far as there is a lack of data on how many percents of habitat is depredating on its own. This also can be taken into account while doing further research. The model could be expanded by including the various of factors that impact the natural degradation process. Based on the sensitivity test the appropriate value for this parameter was chosen for the purpose of representation of expected model dynamics.

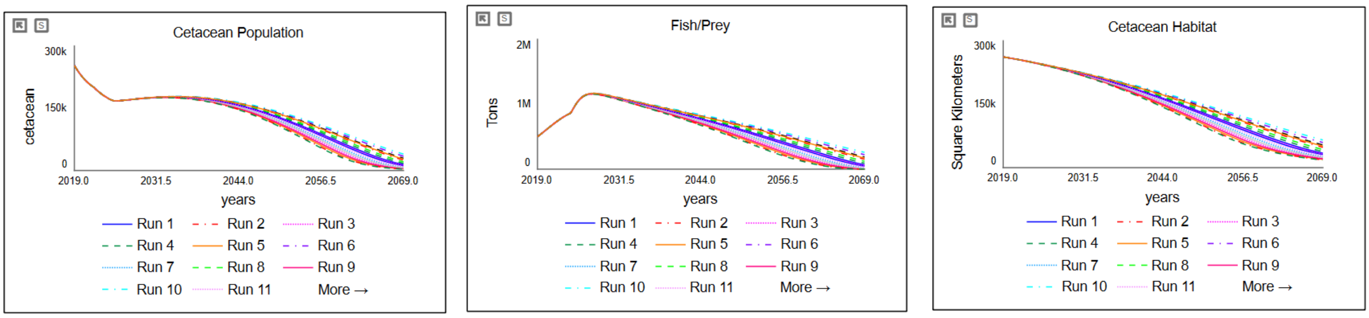

Image 13 - Sensitivity analysis - The change in Marine Litter

Image 13 shows how the main parameters are sensitive to changes in marine litter. This parameter is important in the context of developing possible policies related to the investigated problem. Considering the further expansion of the study, it is recommended to pay close attention to this parameter, since its value is approximate and needs a deeper analysis. Continuation of the research and deeper investigation of this parameter will allow obtaining more accurate results and take into account its influence on the model's dynamics. This will contribute to the development of more effective policies and management strategies aimed at reducing litter and improving the state of the marine environment.

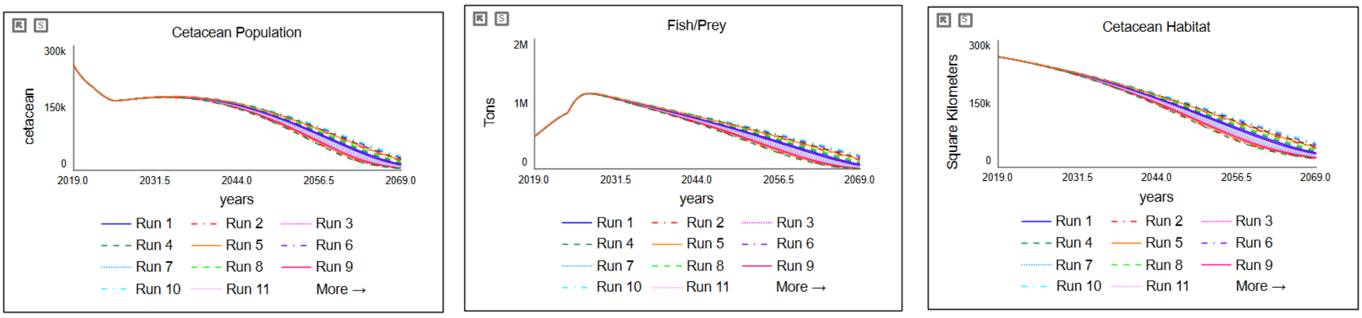

Image 14 - Sensitivity analysis - The changes in Other toxic waste caused by war activity

Image 14 shows how the system dynamics is sensitive to changes in the toxic waste caused by military activity. The damage from naval activity in the Black Sea waters can be fully estimated after the liberation of the sea area. As is visible from image 11, the impact of the toxic waste is guaranteed for a long-term perspective. The value of the parameter is assumed as there are boundaries with getting precise information. However, the model still replicates the expected behavior.

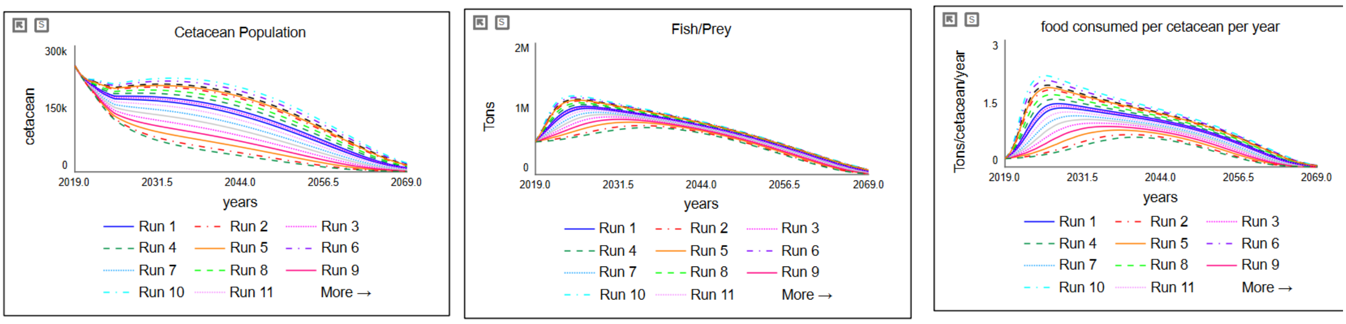

Image 15 - Sensitivity analysis - The changes in Overfishing

Image 15 represents the impact of changes in overfishing and how the dynamics of the system is sensitive to it. The main variables were found to be very sensitive to changes in overfishing. This observation served as the basis for the development of one of the policies, which recommends the implementation of mandatory measures in the future. As the percentage of overfishing increases, cetacean populations decline rapidly, which can lead to catastrophic consequences for the entire ecosystem. This highlights the importance of taking effective measures to reduce overfishing and conserve fish resources. The development and implementation of policies aimed at the balanced management of fish stocks is a necessary task for preserving the ecological balance and ensuring the sustainable functioning of the system.

In general, the model is sensitive to changes in parameters, the values of which are the average accepted norm in the model. The behavior of the model is completely predictable when changing these parameters, which confirms the correctness of the constructed system, and which means the model reacts according to the rules and relationships established in it. This allows for different scenarios and experiments to study the effect of different factors on the system in further research. Changes in the parameters allow you to predict the behavior of the model in different conditions and use it for analysis and decision-making.

V. SCENARIO ANALYSIS.

5.1 Baseline scenario.

This subsection considers the baseline scenario of the model, where the behavior of the system is observed without taking into account possible future measures that could positively affect its dynamics. In this scenario, only the natural evolution of the system and certain impacts that are already occurring are considered. Keeping in mind the initial factors, the model does not have a state of equilibrium (all values of the variables are described in the APPENDIX B).

In the base scenario, military activity ceases in 2025, which means a reduction in the impact of this factor on the dynamics of the system. Naval military activity on the Black Sea territory begins in 2022, which is taken into account in the model as a new factor that can affect the state and interaction of marine organisms.

This basic scenario allows you to observe the natural dynamics of the system and evaluate its changes in the context of already existing factors. The study of such a scenario is an important basis for further analysis and comparison with other scenarios, where additional impacts and measures aimed at improving the dynamics of the system will be taken into account.

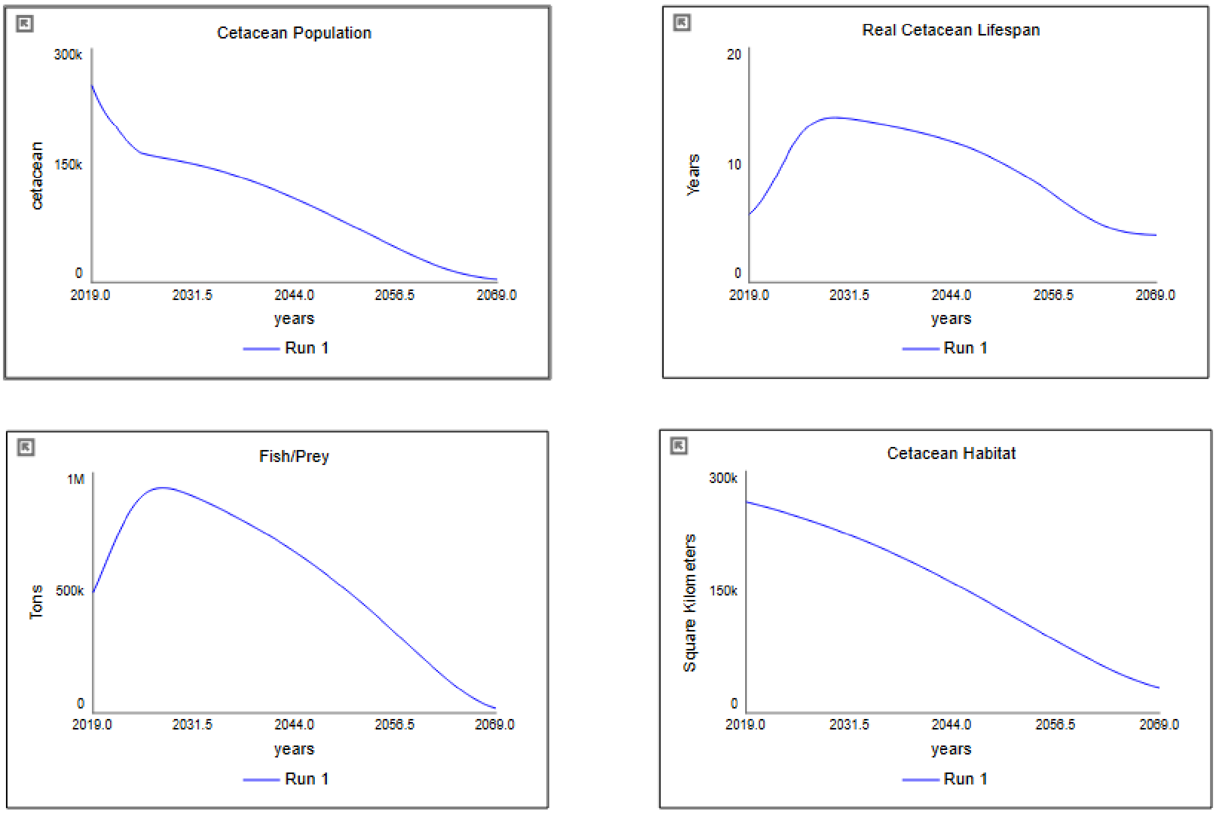

Image 16 – Baseline Scenario

As can be observed from *Image 16*, with the beginning of the invasion, the cetacean population decreases dramatically due to the negative impact of military activity, however, after excluding the negative impact of naval activity, there is still a moderate decrease in the population, although not as drastic as at the initial stage. This is explained by the fact that the state of the natural habitat is still not satisfactory for the habitat of these marine mammals. The state of the environment includes water quality and favorable conditions for living.

The impact of military activity has long-lasting consequences, such as water pollution and environmental destruction, the condition of which affects the lifespan of cetacean even after the activity itself has ceased.

The population can recover to the pre-war state, but this requires further measures to improve the natural environment and ensure optimal conditions for the habitat of these marine mammals.

5.2 Overfishing decrease Scenario.

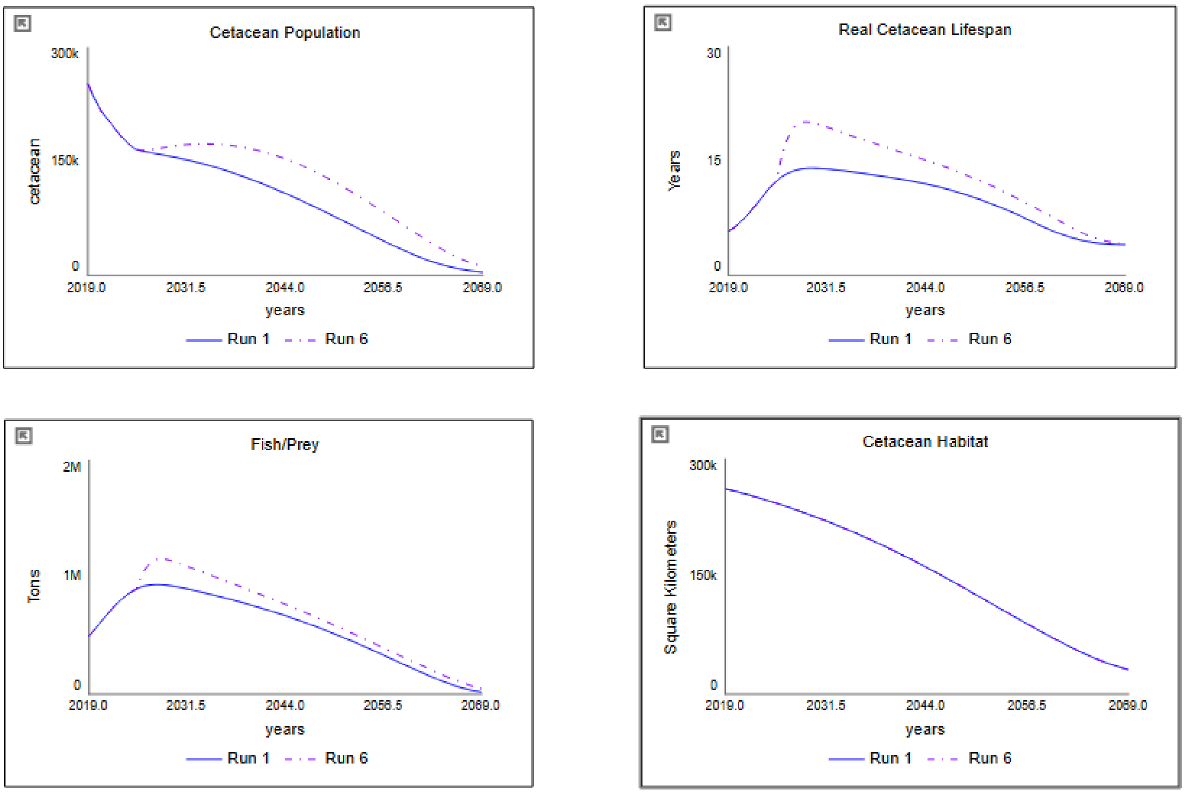

Image 17 – Overfishing Decrease Scenario

One of the most negative factors that directly affect the population of cetaceans in the Black Sea is overfishing. For this scenario, after the end of naval activity, it is proposed to reduce overfishing to at least 17%, as it is accepted that it is practically impossible to completely stop overfishing. There is still a decrease in the main indicators (*Image 18*), which is explained by the lack of actions aimed at environmental conservation.

5.3 Habitat Conservation Scenario 1.

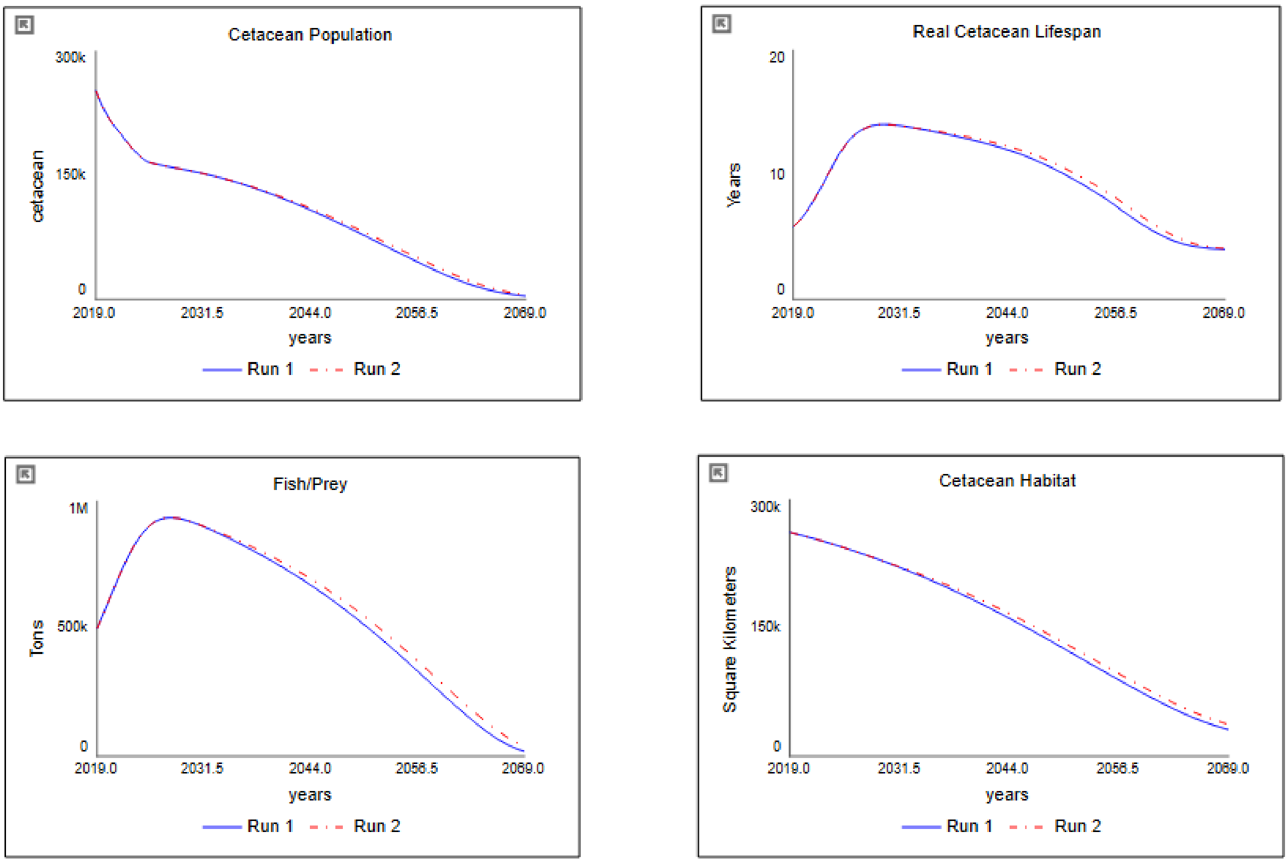

Image 18 – Habitat Conservation Scenario 1

The first scenario, aimed at the conservation of the environment, is the following: when the initial number of cetaceans reaches a quantitative value that is less than 50%, measures are applied to re-establish the habitat. As can be seen from *Image 18*, positive changes in the main parameters are still present, but they do not reach satisfactory values. The population of cetaceans is still moderately declining.

This is explained by the fact that the restoration of the environment requires more intensive actions. Despite the implementation of measures to restore the environment, there are other factors, such as water pollution, which continue affecting the cetacean population and preventing it from fully recovering.

Despite slight positive changes in the first scenario, additional measures and efforts are needed to achieve satisfactory values of these parameters and their stabilization.

5.4 Habitat Conservation Scenario 2.

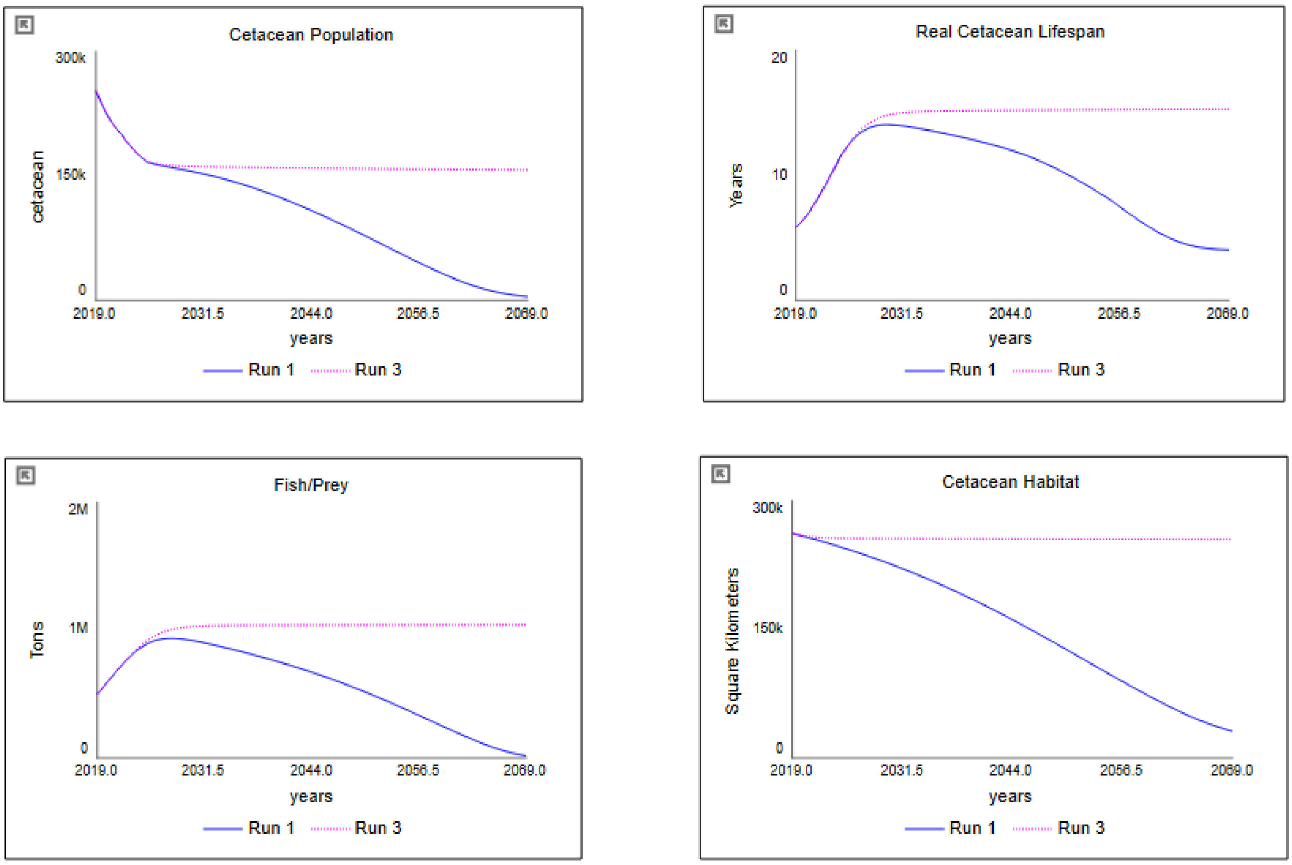

Image 19 - Habitat Conservation Scenario 2

The second scenario is aimed at the regulation of the state of the waters of the Black Sea. Conservation actions are directly aimed at cleaning the water from marine debris in conjunction with the first scenario. Conservation actions now include both cleaning the water of plastic and toxic waste that enters the Black Sea every year, as well as physical restoration of the environment, i.e. ensuring ecological safety and maintaining ecological balance, according to the Cabinet of Ministers' of Ukraine "Resolution On Amendments to the Marine Doctrine", 2018 year.

From *Image 19*, it can be observed that stabilization of the main indicators of the model was achieved, however, the value of the cetacean population is still not satisfactory, which is explained by the direct lack of prey in the habitat territory.

5.5 The Complete Conservation Scenario.

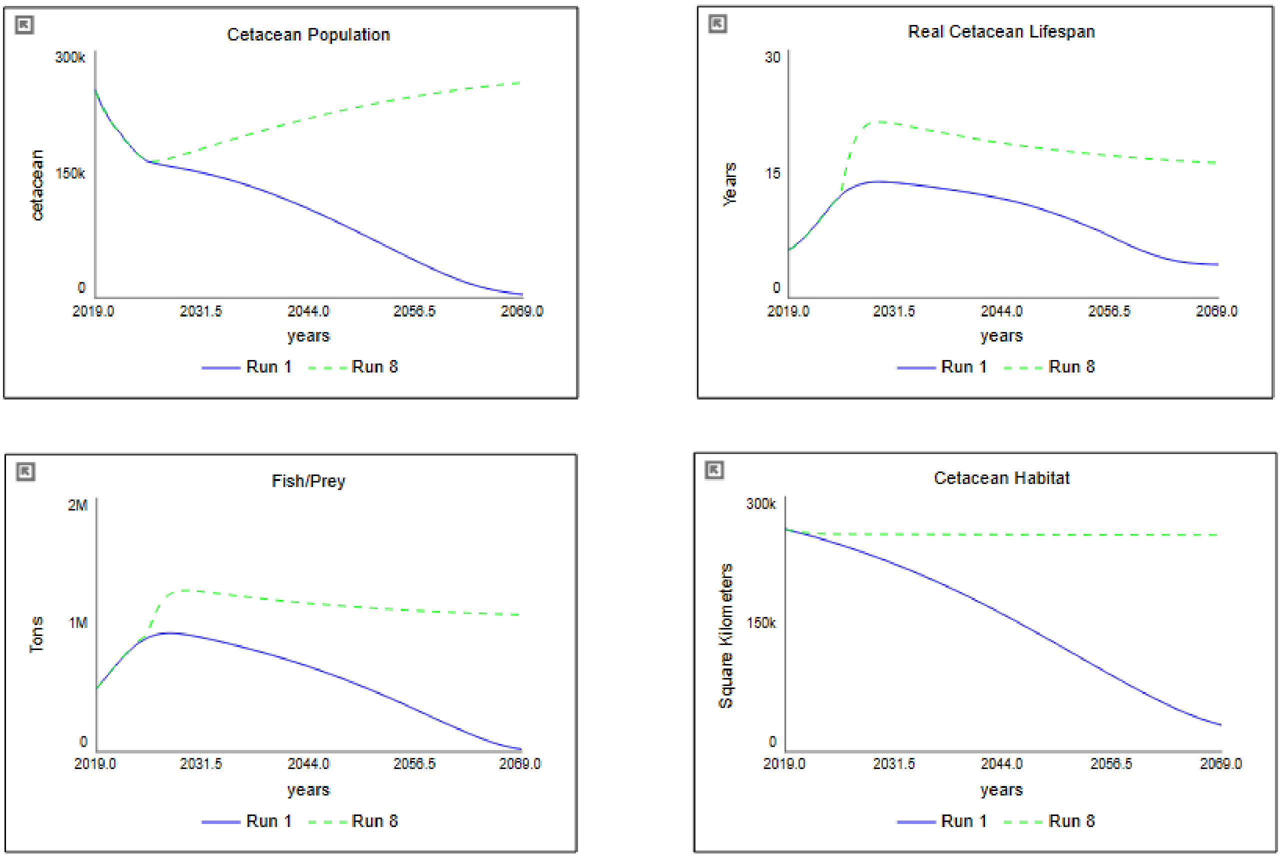

Image 20 – The Complete Conservation Scenario

Image 20 represents the development of the behavior of the main indicators taking into account all possible conservation measures. In this scenario, the following are considered: the restoration of the natural habitat of cetaceans occurs when the population of cetaceans triggers a critical point - 50% of the initial value; water purification occurs when the amount of marine debris exceeds the mark of 10% of the initial value; the level of overfishing is halved from the initial value.

Then it is possible to observe the correspondence of the cetacean population dynamics to the calculations of Ukrainian scientists. In particular, the population of the Black Sea cetaceans can be completely restored to the pre-war state approximately 50 years after the invasion.

5.6 Summary of Scenarios Results.

The research of different possible scenarios is extremely important for future decision-makers in the field of cetacean conservation. Representation of the baseline scenario is quite important, as it allows getting an understanding of the current situation and predicting the possible dynamics of the number of cetaceans in the Black Sea.

From the studies, the most desirable scenario is the one aimed at combining several measures: cleaning the waters of the Black Sea, preserving the natural cetaceans' habitat, and reducing overfishing. Following this scenario, it becomes possible to achieve a full recovery of the cetacean population to its initial pre-war level.

The results show that the recovery of the cetacean population to its original level is realistic, provided that the necessary measures are taken and followed. As the research shows, it is possible to re-establish the population to its initial value (as of the 2019 year) with the implementation and observance of the necessary decisions. However, it means that more efforts and restrictions must be maintained to preserve the fauna and flora of the Black Sea than before the invasion.

Therefore, the research confirms that with the right measures of conservation and preservation of the environment, it is possible to restore the population of cetaceans to the state that existed before the naval activity.

VI. DISCUSSION.

As this study shows, the current situation on the territory of the Black Sea needs intervention. The marine environment is not favorable for the development of the cetacean population, which endangers the entire ecosystem. Disruption of the ecosystem is an indicator of the beginning of global negative irreversible changes (Chu EW, Karr JR., 2017).

The study describes the present causal relationships, which are described in the third section. The state of the environment affects the availability of prey, which directly affects the lifespan of cetaceans. If the environment is polluted or constantly degraded, this can limit the growth of cetacean populations and lead to a decrease in their numbers.

Of course, in view of the sixth section, the following environmental conservation policy becomes apparent. Conservation actions should be aimed at cleaning the waters of the Black Sea and at overfishing, as it leads to difficulties in feeding for cetaceans.

The model depicts the behavior of the total population of 3 species of cetaceans. However, it can also be used to reproduce the behavior of each species individually, taking into account changes in the following variables: average lifespan, the amount of food that each species consumes on average, the area of territory in which a particular species is mostly present, and the amount of prey present in the selected territory.

The model is representative and shows exactly where actions should be directed but does not give specific instructions on how to implement them more effectively. With the possibility of further research, I would pay more attention to the detailed modeling of the environment itself, considering all possible factors of influence.

Understanding of the processes of environmental regeneration and degradation can provide a basis for the development of specific measures aimed at improving conditions for cetaceans and ensuring a stable ecosystem in the Black Sea. It is also advisable to consider the following factors for environmental research: water quality (pollution, level of chemicals, temperature, etc.); study of the amount of annual pollution of the Black Sea in different regions, not only from Ukraine; availability and distribution of prey (fish, squid, other food sources); climatic conditions; geographical features that can affect the ecosystem of the Black Sea; and special attention should be focused on the study of the distribution of cetaceans in the Black Sea and the trajectory of their movement during the year, which affects their reproductive processes. Taking into consideration these factors, it will be possible to reproduce the most realistic dynamics not only of the behavior of the cetacean population but also of the natural environment overall. Moreover, with future access to data and the ability of interview conducting it is possible to avoid approximate values and assumptions, which will allow building confidence in the expended model.

The use of the System Dynamics Approach to model the problem of conservation of cetacean populations in the Black Sea has several advantages. This allows you to understand the complex interrelationships in the system, predict its development, take into account the complexity of the problem, and test different strategies, which was successfully performed during this study. Modeling using system dynamics is also conducive to communicating with stakeholders and involving them in the decision-making process.

VII. CONCLUSIONS.

The System Dynamics approach in this study was cricial in understanding the interactions present in the system. The obtained results are clear and understandable for an audience that has not previously worked with System Dynamics. This facilitates possible future collaboration with stakeholders that can directly contribute to the development and implementation of effective marine conservation strategies.

The study showed that the state of the natural environment affects the population of cetaceans. An unfavorable state of the environment can threaten the entire ecosystem. An important task is the implementation of measures aimed at cleaning the waters of the environment, as well as at reducyion of overfishing. Thanks to these actions, it becomes possible to re-establish the cetacean population to its pre-war state.

Modeling results showed that effective implementation and strict adherence to conservation measures contribute to the full recovery of the population of these marine mammals.

Further research should be aimed at detailing the modeling of the natural environment of Black Sea cetaceans, taking into account all possible factors of impact.

Preservation of the population of cetaceans in the Black Sea is an integral part of preserving the ecological sustainability of the region. They play a key role in regulating the ecosystem and ensuring a balance in the distribution of fish resources. The loss of these marine mammals could have serious consequences for the ecology and natural resources of the Black Sea (Albouy C. et al, 2020), as well as affect the lives of people who depend on these resources. Therefore, the preservation of the cetacean population is an important task to ensure sustainable and stable future recovery and development of the region.

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APPENDIX A: SENSITIVITY ANALYSIS

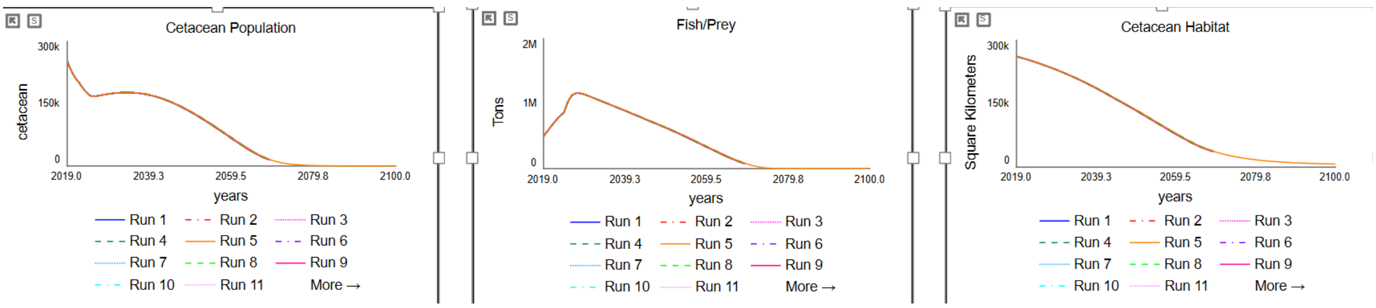

Image 21 - Sensitivity analysis - The change in Amount of oil

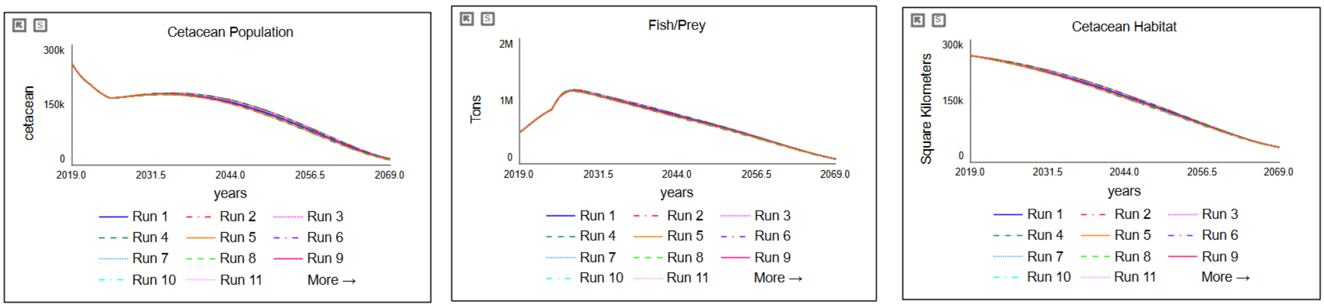

Image 22 - Sensitivity analysis - The change in Carrying Capacity

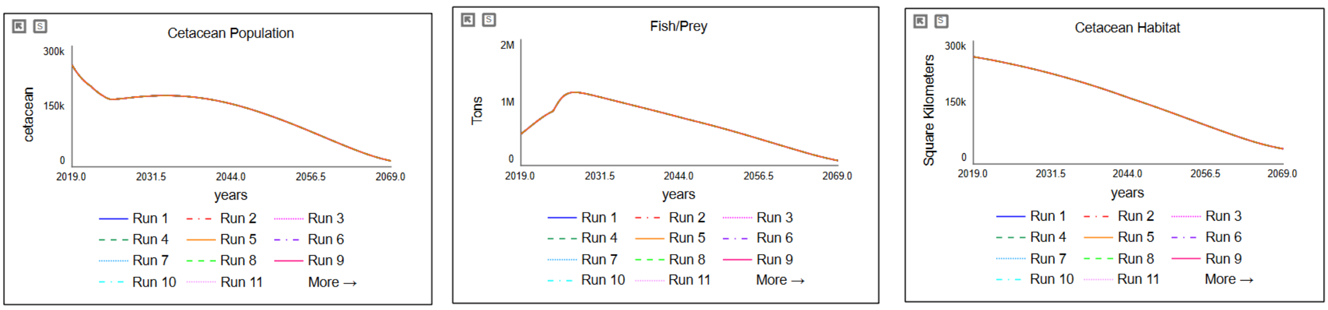

Image 23 - Sensitivity analysis - The change in Cost of Actions

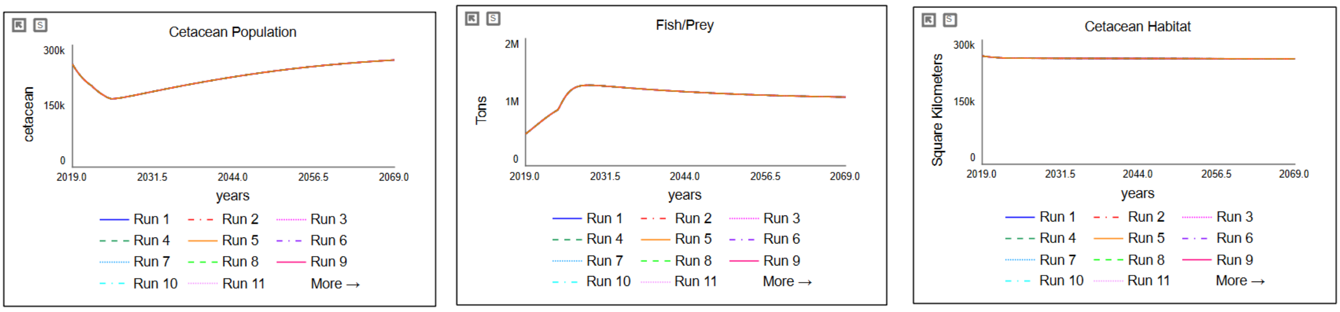

Image 24 - Sensitivity analysis - The change in The Cost of Conservation Actions

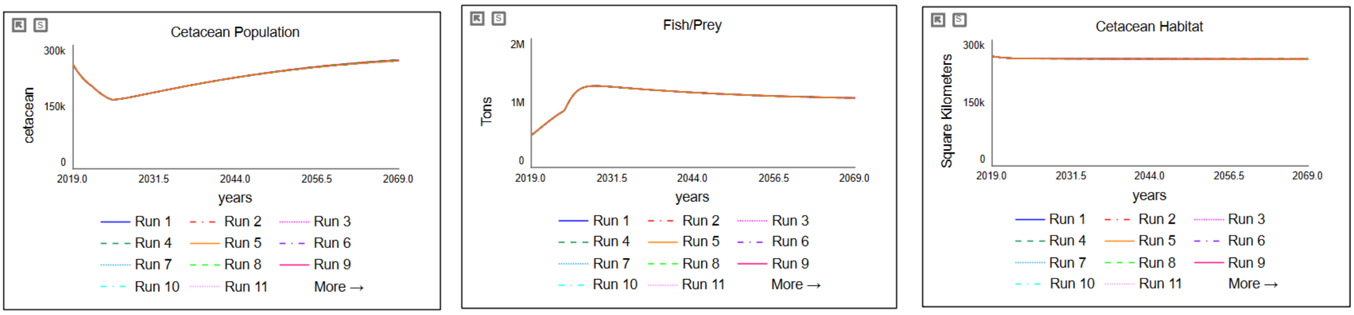

Image 25 - Sensitivity analysis - The change in MAX Regeneration

The model behavior tuned out not being sensitive to the changes in parameters mentioned above. It could occur because of the lack of the necessary data.

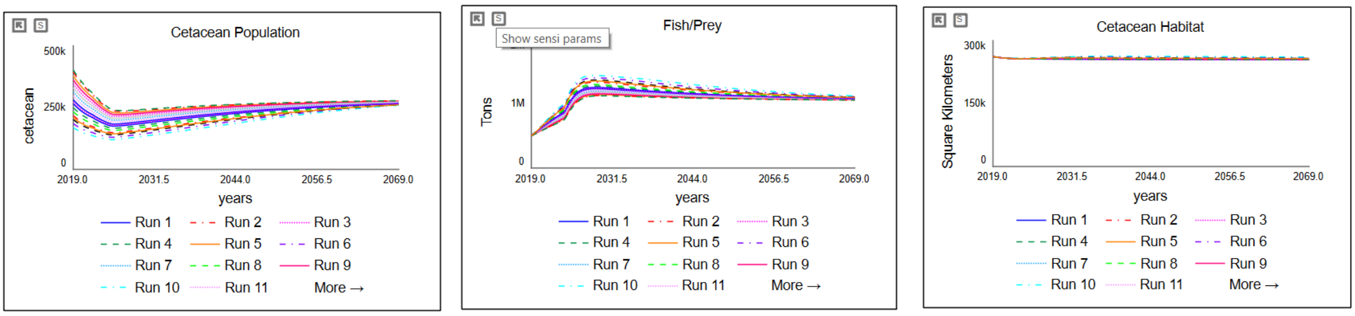

Image 26 - Sensitivity analysis - The change in Initial Cetacean Population

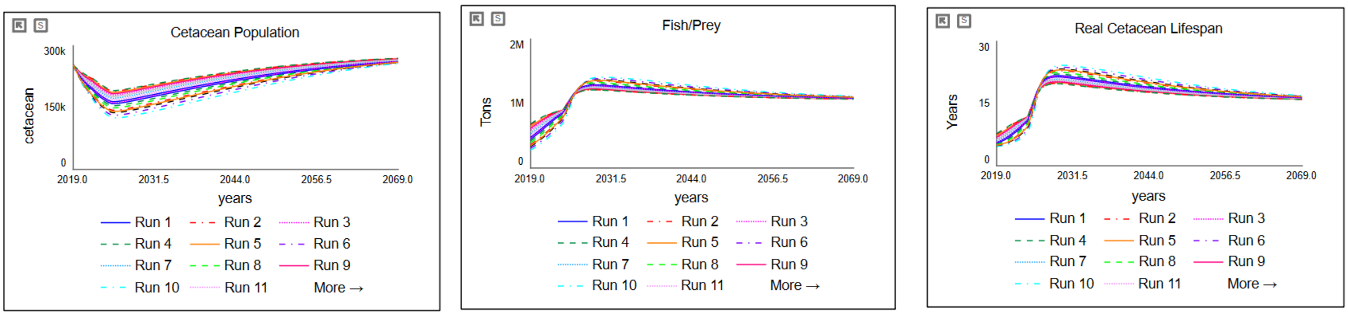

Image 27 - Sensitivity analysis - The change in Initial Fish/Prey

The sensitivity of the model to changes in parameters which represent the initial value is expected. Moreover, the connection between changes and result is linear.

Also, the model was tested on sensitivity to graphical functions. Even a slight change in any of those can lead the model to unpredictable behavior. That is why there is a need in further research with the aim to avoid such kind of uncertainty.

APPENDIX B: DOCUMENTATION

Total	Count	Including Array Elements
Variables	58	58
Sectors	1	
Stocks	4	4
Flows	10	10
Converters	44	44
Constants	21	21
Equations	33	33
Graphicals	4	4

	Equation	Properties	Units	Documentation	Annotation
Top-Level Model:					
Cetacean_Habitat(t)	Cetacean_Habitat(t - dt) + (Conservation_Current + Natural_Regeneration - Degradation) * dt	INIT Cetacean_Habitat = Initial_Cetacean_Habitat	Square Kilometers	The cetacean habitat stock refers to the spatial extent of suitable habitat for cetaceans, measured in square kilometers. It represents the available area where these marine mammals can find the resources and conditions necessary for their survival and well-being.	
Cetacean_Population(t)	Cetacean_Population(t - dt) + (Birth - Death) * dt	INIT Cetacean_Population = Initial_Cetacean_population	cetacean	The cetacean population includes three species: bottlenose dolphins (Tursiops truncatus), common dolphins	

				(Delphinus delphis), and harbour porpoises (Phocoena phocoena). The initial number is approximately estimated as 253000 in 2019 year in the Black Sea waters.	
"Fish/Prey"(t)	"Fish/Prey"(t - dt) + ("Fish/Prey_Regeneration" - "Fish/Prey_Consumption" - "Fish/Prey_Death") * dt	INIT "Fish/Prey" = Initial_FishPrey	Tons	The fish/prey population in the Black sea waters area refers to the total count of fish/prey tons present.	
Water_Pollution (t)	Water_Pollution(t - dt) + (Pollution - Water_state_regulation) * dt	INIT Water_Pollution = Initial_Water_Pollution	Tons	The amount of pollution present in the Black Sea.	
Birth	Calves*Surviving_calves /Birth_Frequency		cetacean/year	The amount of potentially survived calves per year. Taking into consideration the fact that cetaceans can give birth once in 3-5 years, depending on stress and other factors. That is why at the beginning birth is given once in 5 years.	UNIFLOW
Conservation_Current	(conservation_budget_for_conservation/cost_of_conservation_actions)*Switch_Conditional_Conservation		Square Kilometers/ year	The number of possibly reestablished safe square kilometers of the cetaceans'	UNIFLOW

				habitat area per year.	
Death	Cetacean_Population / Real_Cetacean_Lifespan +Cetacean_killed_by_Explosions		cetacean/year	The number of cetaceans cetaceans that can potentially die per year.	UNIFLOW
Degradation	IF TIME<2024 AND TIME>=2022 THEN (0.75*Cetacean_Habitat)*Natural_degradation*Water_Pollution_Ratio++Territory_covered_by_Russia*Natural_degradation*(Water_Pollution_Ratio*1.35) ELSE Cetacean_Habitat*Natural_degradation*Water_Pollution_Ratio		Square Kilometers/year	The number of square kilometers of the habitat of the marina mammals is degradating or simply destroyed with the impact of pollution as a .	UNIFLOW
"Fish/Prey_Consumption"	Fish_consumed_by_cetaceans_per_year +Overfishing*"Fish/Prey"		Tons/years	The number of fish consumed and overfished in tons per year.	UNIFLOW
"Fish/Prey_Death"	MIN(("Fish/Prey" / MAX("Real_Average_Fish/Prey_Lifespan", 0.0000001)), "Fish/Prey" / DT)		Tons/years		UNIFLOW
"Fish/Prey_Regeneration"	Regeneration_Rate*"Fish/Prey"		Tons/years	The natural regeneration (birth process) of prey. The number of tons gotten per year.	UNIFLOW
Natural_Regeneration	MAX(MAX_Regeneration*(Cetacean_Habitat/Carrying_Capacity)*(1-Cetacean_Habitat/Carrying_Capacity), 0)		Square Kilometers/year	The natural regeneration process is described as the number of square kilometers per year. If the habitat reaches the initial value it means that the are is fully recovered, that is	UNIFLOW

				why the process of natural regeneration is not active anymore.	
Pollution	Oil_spilled_by_ships+Marina_litter+Other_toxic_waste_caused_by_war_activity		Tons/years	The amount of garbage (oil spills included) that goes to the Black Sea waters yearly.	UNIFLOW
Water_state_regulation	(Switch_Conditional_Cleaning*Area_cleaned_per_year) +volunteers_effort		Tons/years	The amount of garbage that should be successfully taken from Black Sea waters per year.	UNIFLOW
Amount_of_oil	0.5		Tons/ship/year	The amount of oil pollution caused by a single warship per year.	
Area_cleaned_per_year	conservation_budget_for_cleaning/Cost_of_actions		Tons/year		
Average_amount_of_food_per_cetacean_per_year	3.53		Tons/cetacean/year	The calculated average amount of food the cetacean consumes per year.	
"Average_Fish/Prey_Lifespan"	10		Years	This average number of years fish/prey lives.	
Average_Lifespan	20		Years	The average calculated number of years cetacean lives (taking into consideration the lifespan of each of three cetacean specie in the Black Sea waters.	

				Bottlenose Dolphin: 30 years. Common Dolphin: 20 years. Harbour Porpoise: 10 years.	
Birth_Frequency	IF TIME<2025 AND TIME>=2022 THEN 5 ELSE 3		year	The cetaceans in general can give birth once in 2-3 years, in the condition of stress it happens more rare: once in 5 year.	
Calves	Calves_per_female*Reproductive_female		cetacean	The number of calves that can be reached in perfect non-realistic conditions.	
Calves_per_female	1		cetacean/cetacean	The reproductive cetacean can give birth only to one calf.	
Carrying_Capacity	260000		square kilometer	The limitation till the cetceans' habitat can possibly be naturally restored.	
Cetacean_killed_by_Explosions	IF TIME>=2025 THEN PULSE(0.5, 2024.5, 1) ELSE PULSE(500, 2022, 1)		cetacean/year	The approximate number of killed cetaceans by explosions or impact of explosions during the first year (Feb, 2022 - Jan, 2023) of the full-scale invasion. The number is different in different articles, as researchers	

				can not fully estimate this number as the war is still continuing. I assumed that even after the war there will be cases of rare explosions, as the process of de-mining the territories is difficult and long-lasting	
conservation_budget_for_cleaning	9000000		$/year	Potential Budget which can be allocated for water treatment needs, such as cleaning of the sea area, water, and coastline, and monitoring of the current situation.	
conservation_budget_for_conservation	9000000		$/year	Potential Budget which can be allocated for habitat conservation needs, such as isolation of the territory and keeping it safe, monitoring of the current situation for cetaceans.	
Cost_of_actions	35000		($/tons)	The assumed amount of money is needed for getting rid of a single ton of garbage (including collecting garbage from the water and also	

				recycling waste when possible).	
cost_of_conservation_actions	18000		$/square kilometer	The assumed amount of money is needed for saving needs of the square kilometer of the cetaceans habitat area.	
Effect_of_density_on_lifespan	GRAPH("Fish/Prey_Density") Points: (0.00, 1.000), (1.00, 0.9736), (2.00, 0.924), (3.00, 0.8343), (4.00, 0.6896), (5.00, 0.500), (6.00, 0.3104), (7.00, 0.1657), (8.00, 0.07596), (9.00, 0.02642), (10.00, 0.000)		Dimensionless	This table function describes the relationship between the density of the fish/prey population and the average lifespan. It assumes that a low-density level does not have a significant negative impact on lifespan, while a high-density level significantly reduces lifespan due to the stress of crowding and competition for food resources.	
Effect_of_eating_on_lifespan	GRAPH(food_consumed_per_cetacean_per_year/Average_amount_of_food_per_cetacean_per_year) Points: (0.000, 0.200), (0.121724137931, 0.3998), (0.243448275862, 0.5779), (0.365172413793, 0.7368), (0.486896551724, 0.8785), (0.608620689655,		Dimensionless	The table function depicts the correlation between the amount of fish consumed by a cetacean and its corresponding lifespan. In instances where food availability is ample, it is presumed that the cetacean will	

	1.005), (0.730344827586, 1.118), (0.852068965517, 1.218), (0.973793103448, 1.308), (1.09551724138, 1.388), (1.21724137931, 1.459), (1.33896551724, 1.523), (1.46068965517, 1.579), (1.5824137931, 1.630), (1.70413793103, 1.675), (1.82586206897, 1.715), (1.9475862069, 1.751), (2.06931034483, 1.783), (2.19103448276, 1.812), (2.31275862069, 1.837), (2.43448275862, 1.860), (2.55620689655, 1.880), (2.67793103448, 1.898), (2.79965517241, 1.914), (2.92137931034, 1.928), (3.04310344828, 1.941), (3.16482758621, 1.953), (3.28655172414, 1.963), (3.40827586207, 1.972), (3.530, 1.980)			experience a lifespan equal to or near its average expectancy. However, as fish scarcity arises, the cetacean's lifespan gradually diminishes, with more pronounced reductions occurring when prey shortages become more severe.	
"Effect_of_Fish/ Prey_density_on _food_consumed "	GRAPH("Fish/Prey_Density") Points: (0.00, 0.000), (0.30303030303, 0.003854), (0.606060606061, 0.008848), (0.909090909091, 0.01536), (1.21212121212, 0.0239), (1.51515151515, 0.03511), (1.81818181818, 0.04984), (2.12121212121, 0.0691), (2.42424242424, 0.09417), (2.72727272727, 0.1265), (3.0303030303, 0.1677), (3.33333333333,		Dimensionl ess	The table function illustrates the relationship between fish/prey density and the feeding efficiency of cetaceans. When prey density is low, cetaceans face challenges in locating and capturing their prey, requiring more energy expenditure. Conversely, when fish/prey density is high, cetaceans have an easier time	

	0.2193), (3.63636363636, 0.2826), (3.93939393939, 0.3581), (4.24242424242, 0.4454), (4.54545454545, 0.5427), (4.84848484848, 0.6468), (5.15151515152, 0.7532), (5.45454545455, 0.8573), (5.75757575758, 0.9546), (6.06060606061, 1.042), (6.36363636364, 1.117), (6.66666666667, 1.181), (6.9696969697, 1.232), (7.27272727273, 1.273), (7.57575757576, 1.306), (7.87878787879, 1.331), (8.18181818182, 1.350), (8.48484848485, 1.365), (8.78787878788, 1.376), (9.09090909091, 1.385), (9.39393939394, 1.391), (9.69696969697, 1.396), (10.00, 1.400)			finding and catching fish, leading to improved feeding success and overall thriving.	
Fish_consumed_by_cetaceans_per_year	Cetacean_Population*food_consumed_per_cetacean_per_year		Tons/year	The amount of fish that is consumed every year by the whole population of cetaceans.	
"Fish/Prey_Density"	"Fish/Prey"/Cetacean_Habitat		Tons/Kilometers^2	The fish/prey density is how many tons of possible food is located per square kilometer. The converter is also the main indicator of food availability.	
food_consumed_	Average_amount_of_foo		Tons/cetac	The real amount	

per_cetacean_per_year	d_per_cetacean_per_year *"Effect_of_Fish/Prey_density_on_food_consumed"*Habitat_state_ratio		ean/year	of food cetacean consumes per year depending on food availability.	
Habitat_state_ratio	MIN(Cetacean_Habitat/INIT(Cetacean_Habitat), 1)		Dimensionless	The habitat state ratio reflects the condition of the cetacean habitat area compared to its initial value. A ratio of 1 signifies a healthy habitat, while a lower ratio indicates a decline that can affect cetaceans and their prey population.	
Initial_Cetacean_Habitat	261841		Square Kilometers	The territory on which researchers noticed the marina mammals and assumed it to be their habitat area. (The half of the Black Sea territory).	
Initial_Cetacean_population	253000		cetacean	The number of cetaceans in the Black Sea as of 2019. It is worth noting that even before that, the population was slowly declining.	
Initial_FishPrey	500000		Tons	The initial fish/prey variable represents the initial quantity of fish in the system and is measured in tons.	
Initial_Water_Pollution	1520		Tons	The initial amount of	

				pollution is assumed and based on the information read (it includes plastic garbage, micro plastic, oil spills, and other toxic waste).	
Marina_litter	23.696		Tons/year	The amount of plastic waste entering the water each year.	
MAX_Regeneration	2500		Square Kilometers/ year	The assumed square of the maximum natural regeneration of the habitat area per year.	
Natural_degradation	0.1		Per Year	It s assumed that naturally every year the area of habitat degrades for 10% every year.	
Oil_spilled_by_ships	War_Ships*Amount_of_oil		Tons/year	The oil spilled in the Black Sea waters by ships.	
Other_toxic_waste_caused_by_war_activity	10		Tons/year	Other toxic liquids and micro-plastic which goes to the Black Sea every year.	
Overfishing	IF TIME>=2025 THEN 0.17 ELSE 0.34		per year	The percentage of tons of fish which is overfished every year. However, the meaning is taken from global statistics. In perfect conditions, overfishing is reduced to 17%	

				(half of the initial meaning) per year after the end of the war.	
Policy_Cleaning	0		Dimensionless	The policy is aimed at the reducing of water pollution.	
Policy_Conservation	0		Dimensionless	The policy is aimed at the implementation of conservation actions.	
"Real_Average_Fish/Prey_Lifespan"	Effect_of_density_on_lifespan*"Average_Fish/Prey_Lifespan"*Habitat_state_ratio		Years	The real number of years fish/prey lives, impacted by habitat state and density.	
Real_Cetacean_Lifespan	Average_Lifespan*Effect_of_eating_on_lifespan		Years	It is a real estimated number of years cetaceans can live affected by the food that cetaceans can consume as a main indicator of their well-being.	
Regeneration_Rate	0.7		Per Year	The assumed regeneration rate of the fish (cetaceans' prey) amount in the Black Sea waters	
Reproductive_female	0.5*Cetacean_Population		cetacean	The percentage of reproductive female cetaceans.	
Surviving_calves	0.4*Habitat_state_ratio		Dimensionless	The percentage of surviving cetaceans calves per year. In the Black Sea waters, it is lower 30-40% than the percentage in other waters (60-	

				80%). Moreover, this percentage already includes the fact that cetaceans usually can give birth once in 3-5 years depending on the stress level.	
Switch_Conditional_Cleaning	(IF Water_Pollution >153 THEN 1 ELSE 0)*Policy_Cleaning {0*Water_Pollution}		Dimensionless	This Switch is responsible for providing the budget for water cleaning needs when the amount of garbage is bigger than 10% of the initial pollution value.	
Switch_Conditional_Conservation	{Cetacean_Population*0} (IF Cetacean_Population< 155500 THEN 1 ELSE 0)*Policy_Conservation		Dimensionless	This Switch is responsible for providing the budget for conservation needs when the population of cetaceans drops to the number which is equal to approximately half of the initial cetacean population.	
Territory_covered_by_Russia	IF TIME<2025 AND TIME>=2022 THEN STEP(Initial_Cetacean_Habitat*0.2, 2022) ELSE 0		square kilometer	It is stated that 20% of the Black Sea is taken by Russia. Based on the simple logic, it is assumed that the level of destruction caused there is definitely higher than in other sea areas. (The assumption it is 35% higher water	

				pollution).	
volunteers_effort	IF TIME>2025 AND TIME<2021.9 THEN 5 ELSE 0		tons/year	It is assumed that volunteers could possibly clean and get rid of at least 5 tons of garbage per year.	
War_Ships	IF TIME<2025 AND TIME>=2022 THEN STEP(14, 2022) ELSE 0		ship	The number of Russian warships present in the Black Sea at the moment. (9th of May, 2023). It is assumed that after the predicted end of the war (2024) the warships will be taken from the habitat area.	
Water_Pollution_Ratio	GRAPH(Water_Pollution/INIT(Water_Pollution)) Points: (0.000, 0.000), (0.0689655172414, 0.00193), (0.137931034483, 0.004181), (0.206896551724, 0.006808), (0.275862068966, 0.009872), (0.344827586207, 0.01345), (0.413793103448, 0.01762), (0.48275862069, 0.02248), (0.551724137931, 0.02816), (0.620689655172, 0.03478), (0.689655172414, 0.04251), (0.758620689655, 0.05152), (0.827586206897, 0.06204),		Dimensionless	The water pollution ratio describes the relation between current water pollution and initial water pollution. The lower the ratio, the slower the degradation process is, and vice versa.	

	(0.896551724138, 0.07431), (0.965517241379, 0.08862), (1.03448275862, 0.1053), (1.10344827586, 0.1248), (1.1724137931, 0.1475), (1.24137931034, 0.174), (1.31034482759, 0.205), (1.37931034483, 0.2411), (1.44827586207, 0.2832), (1.51724137931, 0.3323), (1.58620689655, 0.3896), (1.65517241379, 0.4565), (1.72413793103, 0.5345), (1.79310344828, 0.6255), (1.86206896552, 0.7316), (1.93103448276, 0.8555), (2.000, 1.000)				

Run Specs	
Start Time	2019
Stop Time	2069
DT	1/10
Fractional DT	True
Save Interval	0.1
Sim Duration	1.5
Time Units	years
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True

Exhaustive Search Threshold	1000

Custom Unit	Aliases	Equation
Dimensionless	dmnl unitless	1
kilowatt hours per day		kWh/day
kilowatts	kilowatt	kW