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Assessment of Ecosystems Damages Caused by Russian War against Ukraine

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Abstract

The question of the impact of war on ecosystems still remains secondary in the internal and external policy of states, society and the agenda of international organizations. From the point of view of losses in monetary terms, the values of ecosystem damages obtained in the work, which are a consequence of the impact of hostilities on the environment, correspond to the annual budgets of the largest countries in the world or exceed them. The presented calculations significantly exceed the known normative methods, the use of which in the conditions of war is limited in space and time. Objective difficulties associated with the uncertainty of many processes of the development of ecological systems and their reaction to the multifactorial impact of war are also significant limitations. Therefore, as part of the study, a method of assessing the impact of war on the environment is proposed, which is based on the patterns of energy flows in ecosystems from the moment it is binding by producers. This made it possible to take into account in the calculations the principle of functional integrity of the ecological system, according to which the destruction or damage of the components of a functionally whole environment will necessarily cause negative phenomena in the development of ecological systems. The results are presented in the form of real values of ecological losses in energy and monetary equivalents, as consequences of the loss of ecosystem services. As the results of the research show, the minimum amount of damage to ecosystems from Russian tanks is 43,500 USD per day. Environmental damage from Russian fighter jets has been estimated at $1.5 billion per week since the start of the war. Noise from military operations causes losses of at least 2.3 billion US dollars per year. The obtained results create prerequisites for improving the system of ensuring environmental safety at the local, state, and international levels and transferring the obtained solutions into safety-shaping practice.

Keywords

Ecosystem Services, Damage Assessment, Environmental Security, Russia's War against Ukraine

1. Introduction

Explosions, shootings, noise of machinery, fires, hunting, destruction of natural habitats, pollution of the environment—ecosystems suffer from wars no less then human. In order to assess environmental damages from Russia's military invasion to Ukraine, the Ukrainian specialized ministry focused on recording specific (local) facts of negative impact on the environment, referring to appropriate methods. For example, the number of damaged/destroyed landscapes, the volume of damaged/felled forest, the extent of contamination of the territory with waste and hazardous substances, including as a result of accidents at chemical, energy and metallurgical enterprises, oil spills, etc., are estimated. In fact, a component-by-component assessment of the damage to the environment from the war is carried out.

Unfortunately, the ecosystem level and ecosystem services remain underestimated. This could explain by the lack of appropriate methodical background not only in Ukrainian, but also in international practice. The theoretical and applied foundation of ecosystem services evaluation continues to be formed [1].

There is certainly logic in the separate allocation of component and ecosystem units. For example, the human body. A viral or bacterial disease usually causes a failure in the normal functioning of systems and/or organs. Liver disease will cause problems with blood quality, assimilation of nutrients from food, etc. Damage to the skin limits the functionality of the body. The use of alcohol and narcotics causes disorders in the work of the digestive and nervous systems. Many examples can be given, but the essence remains the same: damage to an organ/organs leads to various types of dysfunction of the body in general. From another point of view, a negative impact on the body in general leads to a decrease in its functional properties, or several organs.

By analogy, military actions at the level of ecological systems cause violations of a number of ecosystem services, which, first of all, are a source of key materials and food for humans.

Give one more small explanation of our own thoughts to prove the clarity of the border between the two approaches. Economic activity of a person in accident-free mode is the embodiment of the component impact on the environment. Fishing, mining, logging, etc. are clearly oriented impacts on a specific component of the environment. Depletion of these components leads to failure of other components of the environment and ecosystems in general. Here are some examples. Component-by-component impact, which over time led to a violation of the functional integrity of ecosystems (the list is far from exhaustive).

- overfishing of aquatic biological resources [2]-[6].
- mining [7]-[10].
- damming of rivers to ensure economic and household needs [11]-[15].
- pest control in agriculture using chemical methods [16]-[19].

Regarding war or man-made accidents/catastrophes, it is almost impossible to regulate the negative anthropogenic impact on the environment. In addition, this impact is simultaneous, multidirectional (on all living and non-living environment within reach) and multifactorial (chemical, physical, mechanical, biological).

Military operations in Afghanistan, Libya, Iraq, Syria, Vietnam and many other countries of the world have led to the rapid degradation of ecological systems. It is obvious that the result of irrational behavior of human society and excessive consumption of natural resources is the degradation of ecological systems. And in the case of military operations, environmental degradation occurs quickly, over large areas, and affects all environmental components and ecosystem services [20]-[23].

Accordingly, the period of restoration of ecosystems increases, the quantity and quality of ecosystem services decreases.

In view of the above, there is no doubt about the relevance of determining the amount of damages that are the consequences of the war that Russia has waged against Ukraine.

Within the framework of the article, the disclosure of this issue will consist in the analysis of existing approaches to the assessment of ecosystem damage and the improvement of views on the material and energy value of ecological systems and their services. The main result of the work will be the calculation of environmental damage from the war based on the patterns of energy flows in ecosystems, the assessment of their importance in the economic, ecological and social dimensions. In addition, attention will be paid to the ability of environmental legal systems to objectively assess the real damage caused by military actions to nature. And the study of the experience and possibilities of applying ecological measures to prevent wars, along with the calculations, will contribute to the search for an answer to the question of whether war and the technology involved in it can be environmentally safe.

2. Analysis of Literary Data and Statement of the Problem

Military actions with the use of a large and diverse number of weapons always cause enormous damage to ecological systems [24]-[27]. Based on the analysis of wars in the Balkans and the Middle East [27], in Ukraine [28], it was established that deforestation (34%), soil erosion (23%) and loss of wildlife and biodiversity are the most pronounced environmental consequences of armed conflicts. Similar results can be found in [26], where the conclusions are based on the study of almost 200 cases of armed conflicts around the world. Moreover, the history of armed conflicts shows the absolute indifference of the parties to the issue of environmental protection [26].

At the moment, scientists are united in the need to carry out a quantitative

assessment of the ecosystem damage caused by the war. However, the methods of carrying out relevant work are mostly focused on the components of the environment that are affected, on material losses [24]. While the ecosystem level remains poorly researched. Thus, generalizing works on the impact of war on the environment [29] [30], unfortunately, lack examples of ecosystem assessments.

The reason for this may be the complexity of the analysis and the multifactorial nature of the ecosystem level, objective difficulties in choosing key indicators of the state of the ecosystem. This opinion is confirmed in [31], where the theoretical models of damage calculation created by the authors included both environmental and socio-economic factors.

The problem of providing a comprehensive assessment of the impact of war on the environment is strengthened by the fact that the main tools for recording these facts are appropriate video and photo materials of military themes, satellite images [25], and news [24]. Whereas field research, even with the use of drones, is for objective reasons very limited in space, time and capabilities. Therefore, damage assessment is often carried out years after the cessation of hostilities, when it is difficult to establish basic conditions [30].

In view of the above, the proposals regarding the assessment of damage to the environment from wars and their practical application deserve attention.

According to [29], there are currently no international standards for measuring the impact of war on the environment. However, the development of appropriate methods could have significant international applications or help unify current approaches.

In [32] it is stated that a scientific approach is required for the quantitative assessment of ecosystem damage, which is closely consistent with the standard rules of evidence in Western legal systems. In particular, to prevent damage in the future and bring the aggressor to justice, the authors [28] suggest including environmental crimes in the mandate of the International Criminal Court.

It is undeniable that the approach should be scientific and preventive in its foundations [24], because environmental safety and human safety are inextricably linked [33]. However, if binding to legal systems can prevent wars, it is unlikely to objectively assess the corresponding consequences for the environment in view of its component focus. The latter is likened to finding the forest among the trees. It is hardly possible to determine the scale of the forest by looking only at its elements.

Therefore, it is proposed to use the regularities of energy flows in nature as a synthesizing basis for determining the approximate amount of damage from military actions at the ecosystem level. And damage from the pollution of ecosystem components, for example, atmospheric air, should complement them and be an integral part of reparation payments.

It is obvious that during hostilities it is impossible to control the influence of the aggressor on the ecosystems of the occupied territories. Therefore, it is necessary

to consider them as being under constant maximum negative influence, as on the battle line.

3. The Purpose and Objectives of the Research

The purpose of the study is to determine the amount of damage that Russia caused to the environment of Ukraine at the ecosystem level by starting the war. This will provide an opportunity to improve the theoretical and methodological basis for evaluating ecosystem services and justify the approximate amounts of reparation payments that Russia should pay to Ukraine and its partners.

To achieve the goal, the following tasks have been defined:

- analize the problem of assessing ecosystem damage due to the impact of war on the environment and determine ways to solve it.
- calculate the amount of damage to ecological systems from Russian military equipment: tanks, planes, bombing of the territory, etc.
- summarize indicators of negative changes in ecosystems in monetary terms to justify the amount of reparation payments.

4. Methodology, Methods and Materials

The methodological basis of the calculations presented in the work is a systematic approach. Ecological systems are considered as a collection of abiotic and biotic components connected in space and time, which form a self-regulated functional integrity and are connected by flows of matter, energy and information.

Thus, the destruction or damage of the components of a functionally whole environment will necessarily cause negative phenomena in the development of ecological systems (productivity, self-recovery rate, qualitative and quantitative composition, etc. will decrease).

Therefore, the impact of war on ecological systems is defined as the object of research. And the subject is ecosystem damage as a result of the Russian military invasion of Ukraine.

In order to be able to simultaneously work on the determination of damages for different ecosystems (fields, forests, rivers), we will determine the energy intensity of the ecosystem as an indicator of its health (environmental safety).

Below is a general scheme of energy flows in the ecological system (**Figure 1**).

The methodological essence of the calculations presented in the work becomes finally clear (and very simple), if in **Figure 1** component of K_3 is considered a person. If there is trouble in the ecological system, a person (for example, in food, water, recreation, ecologically safe environment, etc.) immediately feels it. The economic complex will have less raw materials to meet the needs of the population. Or the quality of the resources will be lower. Or the ecosystem may disappear altogether, along with all the corresponding benefits (the island of Madagascar, for example, where about 3% of the rainforest once spread there remains).

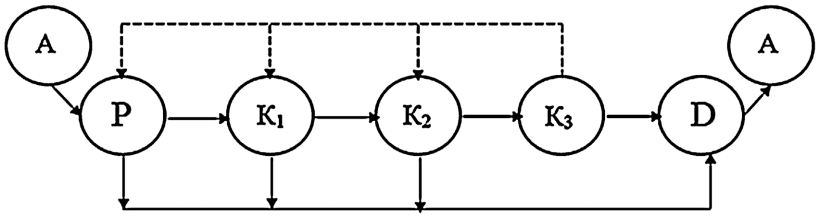

Figure 1. Scheme of matter and energy flows in ecological systems: A—abiotic environment (including solar energy); P—producers; K_1, K_2, K_3—consumers of the first, second and third order, respectively; D—decomposers.

Energy, in contrast to economic or material indicators, is a single matter, the size (or weight) of which is unchanged over time and is formed under the influence of all environmental factors without exception. Strengthening, removing or changing the effect of one or more abiotic factors on the ecosystem will necessarily affect the structure and quantitative indicators of biotic diversity.

According to the well-known ancient Chinese treatise "The Art of War" by Sun Tzu, "military action is expensive". The country that starts war must bear full responsibility for the chaos that it will bring to the environment. Therefore, it will be fair to accept all the negative effects on the environment from Russia as an aggressor country as maximum (operations of engines of tanks, vehicles and other equipment, noise pollution, etc.).

Thus, the basis of the proposed method of assessing ecosystem damage is the patterns of flows of matter and energy in the environment. Quantitative and qualitative analysis of these processes in nature, their comparison with man-made analogues, formalization and generalization of the results in economic, ecological and social dimensions made it possible to solve the research tasks.

The relevant material base of the research is based on data from scientific publications, mass media, regulatory documents, technical literature and other open sources.

5. Research Results

5.1. Damage from the Russian's Tanks

According to information from various sources, at the beginning of the military invasion, Russia concentrated about 1200 tanks near the Ukraine state border [34] [35]. The core of tanks arme consist of the following models: T-72, T-80, T-90. For the most part, they are equipped with V-46 (B-46; here and further in the text Cyrillic abbreviation are also given) and V-84 (B-84) diesel engines in various modifications, and the less part—with gas turbine units.

From the point of view of direct impact on the environment, these engines should be characterized by the fuel consumption indicator. According to information from open sources [36], V-84MS (B-84MC) "eats" 247 grams of fuel per kWh (182 g/h.p.h)[1]. For gas turbine engines of the series GTE-1000T (ГТД-

[1]h.p.h—horse power per hour.

1000T) these values are 30% higher: 230 - 240 g/h.p.h. Engine power of the V-84 MS is 618 kW (840 h.p.).

It is not possible for author to estimate the share of certain engine models in the Russian army, therefore the calculations below are made on the basis of the known fuel consumption indicator of the V-84MS engine.

To calculate the daily damage to the environment of Ukraine from tanks, based on the factor of emissions into the atmospheric air, we will assume that all the tanks concentrated near the border of Ukraine were involved in the war (then why place them there?):

$$1200 \text{ tanks} \times 24 \text{ hours} \times 247 \frac{\text{g}}{\text{kW} \cdot \text{h}} \times 618 \text{ kW} \approx 4.4 \text{ thousand tons of fuel per day}$$

Further, the amount of exhaust gases was determined and appropriate evaluation was carried out (based on the data of clause 4.1.2 (**Table 6**) of the Ukrainian Methodology for calculating emissions of pollutants and greenhouse gases into the air from vehicles [37] (for military equipment, unfortunately, it was not possible to find similar methodologies) and Article 243 of the Tax Code of Ukraine [38] (**Table 1**)).

Table 1. Exhaust gas emissions from 1200 tanks.

Pollutants and greenhouse gases	Specific emissions*, kg/ton	Volume of fuel per day, tons	The amount of emissions, tons	Tax rates for emissions**, UAH/ton	Amount by type, thousand UAH
Carbon monoxide	36.2	4400	159.28	96.99	15.44857
Nitrogen dioxide	31.4	4400	138.16	2574.43	355.6832
Sulfur dioxide	4.3	4400	18.92	2574.43	48.70822
Non-methane volatile organic compounds	8.16	4400	35.904	145.5	5.224032
Methane	0.25	4400	1.1	145.5	0.16005
Nitrous oxide	0.12	4400	0.528	2574.43	1.359299
Soot	3.85	4400	16.94	96.99	1.643011
Carbon dioxide	3138	4400	13,807.2	30	414.216
Benz(a)pyrene	0.03	4400	0.132	3,277,278.63	432.6008

*Are taken from Methodology [37]. **Currently, in Ukrainian legislation, tax rates for atmospheric air pollution are determined only for stationary sources. Therefore, in the absence of similar sources for mobile sources, these are the basis of damage assessment (Article 243 of the Tax Code of Ukraine [38]).

The total amount for all types of emissions was 1.28 million UAH. In currency equivalent, this will amount to 43.5 thousand USD per day (at the exchange rate of 29.45 UAH/USD before the Russian military invasion to Ukraine) or $36.25 from every tank per day.

Having analyzed the dimensions of the T-72 tank (**Figure 2**), it is possible to determine the approximate area of contact of the tank tracks with the ground.

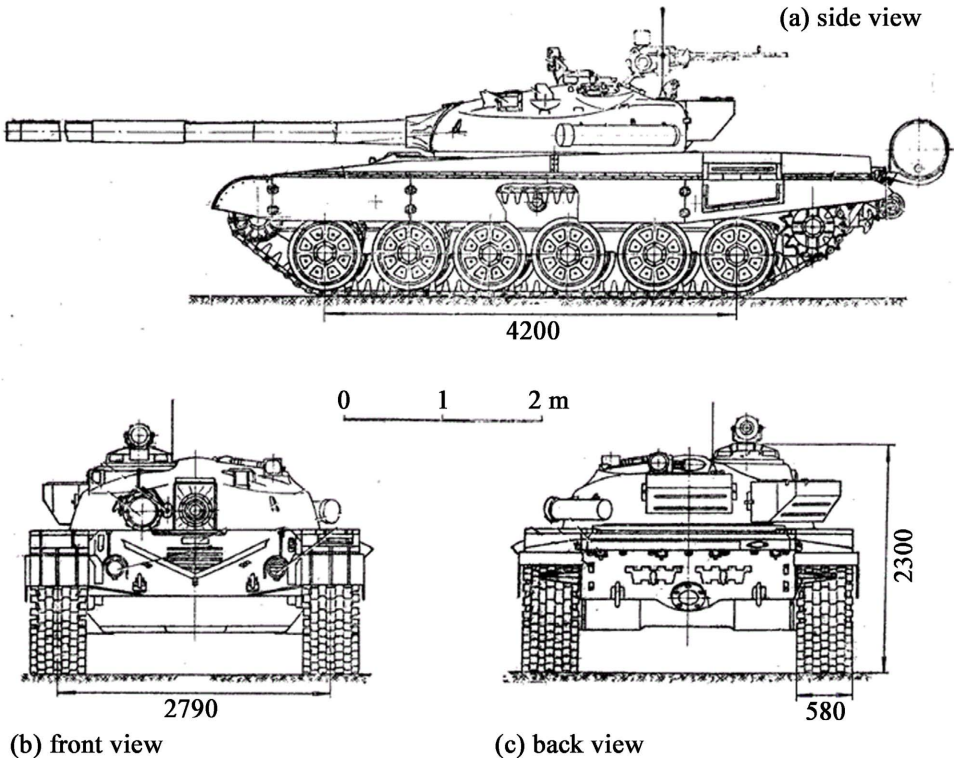

Figure 2. Parameters of the T-72 tank [39].

This value is about 5 m^2 (the length of one caterpillar, which is in contact with the ground, is 4.2 m (Figure 2(a)); the width of one is 0.58 - 0.6 m (Figure 2(b); Figure 2(c)). Thus, 1200 tanks of the Russian Federation destroy and compact 0.6 ha of Ukrainian land just by standing still:

$$1200 \times 5 = 6000 \text{ m}^2$$

It is difficult to determine the amount of soil compacted by tanks without knowing the length of their routes. In this case, it is fair to start from the map presented in Figure 3.

Visually determining the percentage of territories in regions, where combat operations involving Russian ground vehicles are taking place or have taken place (Table 2). This decision does not affect the methods of calculating damages.

Tanks compact the soil very much. The pressure on the soil of the tanks of the previously mentioned models is in the range 0.83 - 1 kg/cm^2 (81.4 - 98.07 kPa). According to the research of Voorhees W. B. [40], a machine weighing 10 tons compacts the soil to a depth of 60 cm. And the weight of one tank is about 40 tons. Obviously, soil compaction is very strong.

Soil compaction causes a decrease in the productivity of plants in ecosystems (including the productivity of agroecosystems). According to many scientists [41]-[43], the productivity (yield) of plants on compacted soils can drop by 40% - 60%. Hence, it is fair to determine the corresponding damage from Russian tanks in Ukraine.

The average plowed land in Ukraine is 54% [44] [45], 78% of which is occupied

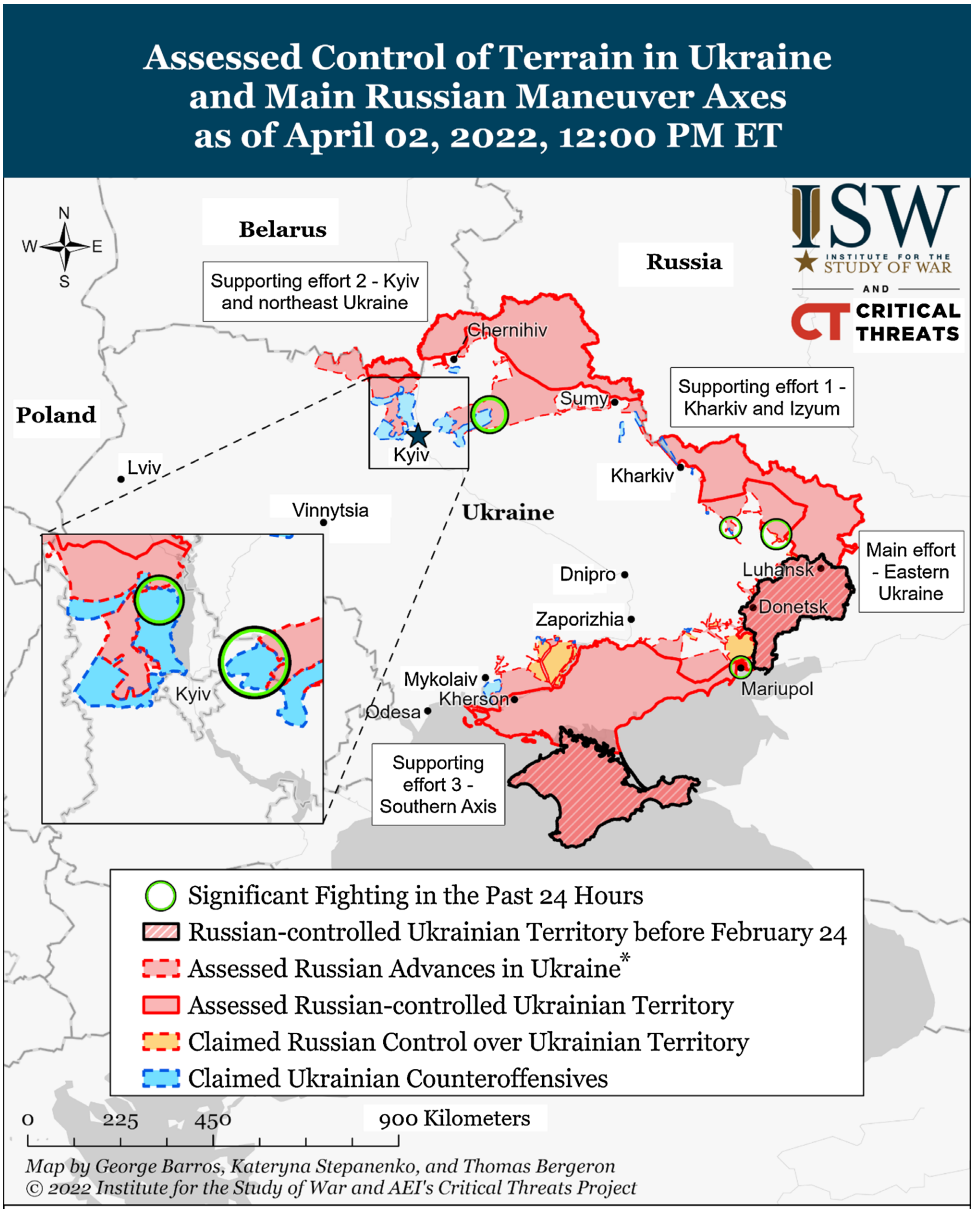

Figure 3. Map of hostilities on the territory of Ukraine as of April 2022.

Table 2. The territory of Ukrainian lands on which hostilities are taking place or have taken place.

Region	Approximate percentage	Area of temporarily occupied lands, km²	Natural area
Zhytomyr	5	1491.6	Mixed forests
Kyiv	20	5626.2	Mixed forests
Chernihiv	80	25,492	Mixed forests

Continued

Sumy	80	19,067.2	Forest steppe
Kharkiv	45	14,136.75	Forest steppe
Luhansk	90	24,015.6	Steppe
Donetsk	80	21,213.6	Steppe
Zaporizhzhya	80	21,744	Steppe
Kherson	90	25,776.9	Steppe
Mykolaiv	15	3689.7	Steppe
Total		**162,253.55**	

by arable fields. For a better perception of the scale of the damage caused, the damage from the tanks will be expressed in terms of the lost winter wheat harvest, the average yield of which in Ukraine is about 4 t/ha (tons per hectare).

$$162253.55\ \text{km}^2 \times 0.54 \times 0.78 = 68341.19\ \text{km}^2 = 6834119\ \text{ha}$$

$$6834119\ \text{ha} \times 4\ \text{t/ha} \approx 27.34 \times 10^6\ \text{tons}$$

Taking into account the results of the above scientific studies, 60% of the potential volume of the harvest will be considered lost:

$$27.34 \times 10^6\ \text{tons} \times 0.6 = 16.404 \times 10^6\ \text{tons}$$

According to the thematic Internet resources, the price for winter wheat of the 2nd class in the ports of Ukraine at the beginning of February was 285 USD per ton. Will use this value to calculate damage from tanks for agroecosystems of Ukraine:

$$16.404 \times 10^6\ \text{tons} \times 285\ \text{USD/ton} \approx 4.5111\ \text{billion USD}$$

Taking into account the conclusions [40] that the soils after powerful compaction are restored within several years, it is fair to increase the specified damages tenfold (taking into account the mass of tanks, unforeseen costs in the future (mining, for example), abandoning areas for development for several years):

$$4.5111 \times 10\ \text{years} \approx 45.111\ \text{billion USD}$$

Now let's define damages for ecological systems that are not agroecosystems. Their share within the territory of Ukraine is, respectively, 46%. And the area of the territory covered by hostilities:

$$162253.55\ \text{km}^2 \times 0.46 = 74636.633 = 7463663.3\ \text{ha}$$

Let's calculate the primary production (from which the food chain of life begins) in these territories, taking into account belonging to natural zones (**Table 2**). Thus, in the zone of mixed forests, this indicator per year is 75 t/ha, in the forest-steppe zone—125 t/ha, in the steppe zone—85 t/ha [46]. As a result, we will get:

Mixed forests:

$$(1491.6+5626.2+25492)\text{km}^2 \times 100 \text{ ha}/\text{km}^2 \times 75 \text{ t/ha} \approx 24.5\times10^6 \text{ tons}$$

Forest steppe:

$$33203.95 \text{ km}^2 \times 100 \text{ ha}/\text{km}^2 \times 125 \text{ t/ha} \approx 41.5\times10^6 \text{ tons}$$

Steppe:

$$96439.8 \text{ km}^2 \times 100 \text{ ha}/\text{km}^2 \times 85 \text{ t/ha} \approx 81.97\times10^6 \text{ tons}$$

The total biomass in the three zones will be 147.97 million tons. Of this amount, we will assume 60% as lost as a result of tanks influence:

$$147.97\times10^6 \text{ tons} \times 0.6 = 88.78\times10^6 \text{ tons}$$

That is, the ecological systems of Ukraine did not receive at least 88.78 million tons of plant biomass in 2022. Accordingly, similar to agrocenoses, it will take time to restore the soil.

According to R. Lindemann's "10% rule", the flow of phytomass in the food chain will have the following form:

88.78 million tons—producers (plants, bushes, trees).

8.878 million tons—consumers of the first order (herbivorous animals; humans).

0.8878 million tons—consumers of the II-th spinning wheel (predators; humans).

0.08878 million tons—third-order consumers (humans).

Thus, the biomass of first-order consumers is equivalent, for example, to the mass of one and a half million savannah elephants, 250 million adult roe deer or 2 billion adult broiler chickens.

It is impossible to determine the species of all representatives of the animal and plant world, in order to clarify the amount of damage from this biomass. One thing is obvious—human and ecological systems are experiencing a huge energy deficit.

In order to establish the minimum amount of damage caused to the environment, we will use the indicators of the flow of matter and energy in the process of photosynthesis:

$$6CO_2 + 6H_2O + E_{Sun} = C_6H_{12}O_6 + 6O_2$$

According to [47], during the year an "average" plant (calculated per kilogram of dry matter) has the following balance of substances (**Table 3**).

Summarizing the information given in **Table 3**, one kilogram of dry phytomass per year binds 170 g of carbon dioxide, 50 g of water, creates 100 g of organic matter and releases into atmosphere 120 g of oxygen.

Thus, it is easy to convert 88.78 million tons of lost plant biomass into energy units, to determine the amount of unbound carbon dioxide (the emissions of which the whole world is trying to reduce) and unreleased oxygen (**Table 4**) per year.

The volume of unfixed energy in plants is equivalent to, for example, 3.6 million

Table 3. Balance of substances during photosynthesis (per 1 kg of dry matter).

A component of photosynthesis	Absorption	Creation	Breath	Biological harvest
Carbon dioxide (CO_2)	500 g	–	330 g	170 g
Water (H_2O)	150 g	–	100 g	50 g
Energy of the Sun	5.4 MJ	–	3.6 MJ	1.8 MJ
Organic matter	–	300 g	200 g	100 g
Oxygen (O_2)	–	350 g	230 g	120 g

Table 4. Lost biological harvest in ecological systems of Ukraine.

A component of photosynthesis	Biological harvest	Lost phytomass	Lost biological harvest	
			Grams	Million tons
Carbon dioxide (CO_2)	170 g		$14.4 \cdot 10^{12}$	14.4
Water (H_2O)	50 g		$4.2 \cdot 10^{12}$	4.2
Energy of the Sun	1.8 MJ	88.78×10^9 kg	159.8×10^9 MJ	
Organic matter	100 g		$8.9 \cdot 10^{12}$	8.9
Oxygen (O_2)	120 g		$10.2 \cdot 10^{12}$	10.2

tons of oil. For example, on April 1, 2022, one barrel (0.1364 tons) of Brent oil cost about 104.38 USD. Using the method of energy analogies, the corresponding annual energy losses of ecosystems can be estimated at the level of 2.7 billion US dollars:

$$\left(159.8\times10^{9}\ \text{MJ}\right)/44000\ \text{MJ/kg} = 3.63\times10^{6}\ \text{kg of oil}$$

$$\left(3.63\times10^{6}\ \text{kg of oil}\right)/136.4\ \text{kg} = 26.6\times10^{3}\ \text{barrels}$$

$$26.6\times10^{3}\ \text{barrels}\times104.38\ \text{USD} \approx 2.8\ \text{million USD}$$

And this is only the energy of chemical bonds in phytomass.

As for vital oxygen, we determine its man-made price and estimated losses for the ecosystem. According to the data of the Advanced Gas Technologies [48], based on an oxygen purity of 95%, geographic location, and associated energy costs, typical operating costs (energy and maintenance) for on-site oxygen production can range from 0.07 to 0.11. USD per m^3. Losses for the year are:

$$\frac{10.2\times10^{9}\ \text{kg}}{1.43\ \text{kg/m}^3}\times0.11\frac{\text{USD}}{\text{m}^3} \approx 784.6\ \text{million USD}$$

According to the data of the International Energy Agency [49], it is most difficult to artificially bind carbon dioxide from atmospheric air. Agency specialists determined the price range of 40 - 120 USD per ton, while Chinese scientists estimated such an ecosystem service at 192 USD/t [50].

Damages for non-sequestration of carbon dioxide at maximum prices:

$$14.4\times10^{6}\ \text{tons}\times192\frac{\text{USD}}{\text{ton}}\approx 2.8\ \text{billion USD}$$

It is important to note that the given calculations of ecosystem damages correspond to results of other scientists, in particular Zhao X. *et al.* [50] and Wu C. *et al.* [51].

As for the binding of atmospheric moisture, the price of such an ecosystem service can be taken at the level of 0.3 USD/liter, taking into account the study Bagheri F. [52], and the price of electricity of 0.05 USD/kWh.

Therefore, estimated losses are (at one liter = one kg):

$$0.3\ \text{USD/kg}\times4.2\times10^{9}\ \text{kg}=1.26\ \text{billion USD}$$

Taking into account the annual growth of phytomass by 10%, the 10-year losses from the disruption of ecosystems will also increase (Table 5).

Table 5. Losses in a 10-year perspective

Year	Phytomass, million tons	Underselection, million tons			Energy of the sun, billion MJ	Damages, billion USD			
		CO_2	O_2	H_2O		CO_2	O_2	H_2O	E_{Sun}*
2022	88.78	14.4	10.2	4.2	159.8	2.8	0.8	1.3	2.8
2023	97.658	16.6	11.7	4.9	175.8	3.2	0.9	1.5	3.1
2024	107.4238	18.3	12.9	5.4	193.4	3.5	1.0	1.6	3.4
2025	118.1662	20.1	14.2	5.9	212.7	3.9	1.1	1.8	3.8
2026	129.9828	22.1	15.6	6.5	234.0	4.2	1.2	1.9	4.2
2027	142.9811	24.3	17.2	7.1	257.4	4.7	1.3	2.1	4.6
2028	157.2792	26.7	18.9	7.9	283.1	5.1	1.5	2.4	5.0
2029	173.0071	29.4	20.8	8.7	311.4	5.6	1.6	2.6	5.5
2030	190.3078	32.4	22.8	9.5	342.6	6.2	1.8	2.9	6.1
2031	209.3386	35.6	25.1	10.5	376.8	6.8	1.9	3.1	6.7
2032	230.2725	39.1	27.6	11.5	414.5	7.5	2.1	3.5	7.4
Total						**53.6**	**15.2**	**24.6**	**0.0527**

*Calculations are presented in oil equivalent.

Damages from tanks in a 10-year perspective for ecosystems already due to the fact of military aggression of the Russian Federation and advancement on the territory of Ukraine amounted to at least **93.45 billion USD**. Although the actual effects of war on ecosystems may be more lasting. According to the conclusions [24], for example, after the end of the war, it may take up to 50 years to destroy all land mines and munitions that have not exploded.

The cumulative damage to ecosystems from 1.200 tanks is shown in Table 6.

During 2022, the minimum total ecosystem losses from the military aggression of the Russian Federation (only from tanks) for Ukraine amount to 138.5 billion

US dollars (this is more than price of 4000 F-16). Russia's continuation of the war against Ukraine will degrade ecosystems every day and will constantly increase the amount of reparations. War is expensive.

Table 6. Generalized damage to the environment from tanks of the Russian Federation

Influence	In 1 day	Year scale
Air pollution with exhaust gases	43,500 USD	15.877 million USD
Agroecosystems	-	45.111 billion USD
Ecosystems and ecosystem services	-	93.45 billion USD

5.2. Damages from the Russian's Fighter Jets

The following models of fighters are currently in service with the Russian Federation: Su-24; Su-25; Su-27; Su-30, Su-34; Su-35; MiG-25; MiG-29; MiG-31 (in cirillic: Cy-24; Cy-25; Cy-27; Cy-30, Cy-34; Cy-35; МіГ-25; МіГ-29; МіГ-31). And according to data from open sources, their number in Russia is 1585 units [53]-[55]. At the beginning of the invasion, about 330 fighters [56] were concentrated near Ukraine barder.

Impact factors of aircraft on the environment are: exhaust gases, noise from flight, noise from the use of rockets, damage to the ground cover by rockets.

Various fire and technical equipment are installed on fighter planes of the Su and MiG types. Below, in order to calculate the damage to the environment (**Table 7**), some of their technical characteristics, which are available in open sources, are summarized.

But the most often Russians use three types of fighters in their military invasion to Ukraine: Su-30, Su-34 and Su-35 [57]. The same scenario they made in Syria [58]. Little bit less using fighter—MiG-31. But it usually works under Russian territory for supersonic cruise missile "dagger" launch in Ukraine. Any way, they produce contamination.

5.2.1. Exhaust Gases

The fuel consumption of R15B-300 (Р15Б-300 in cirillic) engines and its modifications in the maximum (non-afterburner) mode is 1.25 kg/kgf·h.[2] For RD-33 (РД-33), this indicator is 0.77 kg/kgf·h. For D-30F6 - 0.72 kg/kgf·h (Д-30Ф6). AL-21-F3 (АЛ-21-Ф3) - 0.86 kg/kgf·h; R-195 (Р-195) - 0.89 kg/kgf·h; AL-31F (АЛ-31Ф) - 0.75 kg/kgf·h. It is difficult to use these data to calculate the impact on atmospheric air, because they do not take into account the mass of the fighter on which they are installed.

In general, the impact of military equipment on the environment is an unpopular topic, to say the least. There is very little relevant data. It was not possible to find information about emissions of pollutants from fighter jets above in Ukrainian or Russian language.

Therefore, it was decided to rely on information in available foreign scientific

[2]kgf—kilogram-force.

Table 7. Technical and fire equipment of Russia fighter aircraft.

Fighter	Engine	Rockets	Gun	Air bombs	Fuel tank, kg
MiG-25 (supersonic)	2 × ТРДФ Р15БД-300	4 × Р-40 + 4 × Р-60		8 × ФАБ-500	15,000
MiG-29 (supersonic)	2 × РД-33	6 × Р-60/Р-27/Р-73	30 mm	ФАБ-500	3400
MiG-31 (supersonic)	2 × ТРДДФ Д-30Ф-6	4 × Р-33 + 2 × Р-40 + 4 × Р-60	23 mm	ФАБ-500	17,730
Su-24 (supersonic)	2 × ТРДФ АЛ-21-Ф3	2 × Р-60 + 4 × Х-25 or Х-23 + 3 × Х-29 or Х-59 + 6 × С-25 + 2 × Х-58	23 mm	3 × ФАБ/КАБ-1500 or 8 × ФАБ/КАБ-500* or 32 × ОФАБ-100**	9800
Su-25 (subsonic)	2 × ТРД Р-195	11 × Р-60/Х-25/Х-29	30 mm	8 × ФАБ-500 or 32 × ФАБ-100	3000
Su-27 (supersonic)	2 × АЛ-31Ф	10 × Р-27/Р-73/Р-77/С-8/ С-13/С-25/Х-31	30 mm	ФАБ-250/500	9600
Su-30 (supersonic)	2 × ТРДДФ АЛ-31Ф	6 × Р-77/Р-27 + 6 × Р-73	30 mm	8 × ФАБ-500 or 28 × ФАБ-250	9640
Su-34 (based on Su-24)	2 × АЛ-31Ф-М1	6 × Р-77 or 8 × Р-27	30 mm	22 × ФАБ-250	12,100
Su-35 (based on Su-27)	АЛ-31Ф, АЛ-35МЛ	8 × Р-27/Р-77/Р-73/Р-60 + 6 × С-25/Х-29/Х-59/Х-31	30 mm	12 × ФАБ/КАБ-500/250;	11,500

*FAB (in Cyrillic ФАБ)—high-explosive aerial bomb (from Fr. *fougasse*—explosive device). The number after abbreviation means weight of the bomb in kilograms. **КАБ—high-explosive guided aerial bomb; ОФАБ—high-explosive fragmentation aerial bomb.

research. As the calculations will show, such a decision is acceptable, taking into account the technical similarity and temporal compatibility of fighters' generations.

Thus, Polish scientists established [59], that F-16 fighter jet on 91% - 100% engine operation mode emits into the atmosphere 0.3354 g/s of nitrogen oxides, 0.0252 g/s of hydrocarbons, 0.1258 g/s of carbon monoxide and 4359.9 g/s of carbon dioxide with a fuel consumption of 1.71 kg/s. For one kilogram of fuel the following values work:

- NO_x—0.196 g/kg.
- C_xH_y—0.015 g/kg.
- CO—0.074 g/kg.
- CO_2—2549.649 g/kg.

In the study of another large group of scientists [48], it was established that the exhaust gases of fighter jets, for example F-15, also contain 1.94 mg of acetone per 1 kg of burned fuel and about 60 dangerous hydrocarbons. Unfortunately, scientists do not specify the nomenclature of the latter, as well as their specific weight.

Based on the above information, Table 2 presents calculations of fuel consumption of Russian fighters and their foreign counterparts. (Table 8)

Table 8. Fuel consumption of military fighters.

Fighter	Practical range with a FCK*, km	Mass of fuel, kg	Maximum speed, km/h (km/s)	Working combat time, seconds	Fuel consumption, kg/s
MiG-25	1800	15,000	3000	2160	6.94
MiG-29	1430	3400	2450	2101	1.62
MiG-31	2500	17,730	3000	3000	5.91
Su-24	2800	9800	1700	5929	1.65
Su-25	750	3000	950	2842	1.06
Su-27	3500	9600	2500	5040	1.90
Su-34	4000	12,100	2200	6545	1.85
Su-30	3000	9640	2125	5082	1.90
Su-35	3600	11,500	2800	4629	2.48
F-15	2000	6100	2650	2717	2.25
F-16	1300	3250	2410	1964	1.67

*The practical range with a full combat kit (FCK) is the horizontal distance, traveled by the fighter after the use of the available fuel reserve (without taking into account the so-called aeronautical fuel reserve).

As can be seen, 1.67 kg/s was obtained for the F-16, which almost coincides with the fuel consumption given by Merkisz J. *et al.* in [59]. This allows us to assert the correctness of given calculations and collected information. And we can use the specific indicators of emissions of polluting substances from the military aviation of the Russian Federation into the air environment of Ukraine given in [59] [60].

Since we are unable to establish the number of aircraft used by the Russians to attack Ukraine, in order to objectify the calculations of their impact on the atmospheric air, it was decided to determine the arithmetic average of fuel consumption (without taking into account the F-15 and F-16). This figure corresponds to 2.66 kg of fuel in one second and, accordingly, 9576 kg in one hour. On the basis of this information, a calculation was made of losses from atmospheric air pollution by Russian fighter jets in one hour (Table 9).

In the list of substances (Table 9), in accordance with the Ukrainian Methodology [37], sulfur dioxide and soot were added, and the volume of their emission per hour was calculated.

Air pollution losses from the operation of one Russian fighter jet amount to at least 631,654 UAH per day, which is equivalent to 21,412 USD (at the exchange rate of 29.50 UAH/USD). Since a single fighter cannot work 24 hours a day, the indicated amounts of harm are achieved by the work of 21 fighters, on the condition of one sortie per day lasting 1.15 hours.

Since Russia concentrated near the borders of Ukraine and intended to use at least 330 fighter jets, the daily losses from enemy military aircraft due to atmospheric

air pollution should be increased by 15.7 times:

Table 9. Atmospheric air pollution over Ukraine by one Russian plane in one hour.

Substances	Emission from one kg of fuel, g	Fuel consumption, kg/sec	Emission volume, tons per hour	Tax rates for emissions, UAH/t *	The amount of losses per hour, UAH
CO_2	2549.649		24.415439	30	732.4632
CO	0.074		0.000709	96.99	0.068729
NO_x	0.196	2.66	0.001877	2574.43	4.831937
C_xH_y	0.015		0.000144	145.5	0.0209
Acetone	0.00194		0.000019	965.67	0.01794
SO_2	1	9576 kg/h	9.576	2574.43	24652.742
Soot	1		9.576	96.99	928.776
		Total			**26318.92**

*The rates are determined for stationary sources. In the absence of similar ones for mobile vehicles, the ones indicated in Art. 243 of the Tax Code of Ukraine.

$$\frac{330}{21} = 15.714 \approx 15.7 \text{ times}$$

Thus, a horde of 330 fighter jets of the Russian Federation causes damage to the environment every day due to emissions of pollutants in the amount of at least 9.9 million UAH, which is equivalent to 335.6 thousand USD.

5.2.2. Noise from Fighter Jets

According to the conclusions of Sordello R. *et al.* [61], the issue of noise pollution and related harms is poorly researched in the world. And the known results of scientific works are mostly focused on mammals.

According to the results of research by American scientists [62], the level of environmental noise pollution of 60 dB (5 dB more than the norm) causes an increase of epy hypertension cases in the population by approximately 1.4% and cases of coronary heart disease by 1.8%. The researchers estimate that the associated health care costs and lost productivity exceed $3.9 billion per year. That is, noise pollution of the environment has significant economic consequences.

Heart disease caused by exposure to road noise costs the UK an estimated £1.183 billion a year. Noctidial noise delays children's learning, costing an estimated £252 million a year [63].

For threating this problem, British legal system was made the approach to the assessment of noise pollution [64]. And the calculations of harm from the negative impact of noise are made with reference to the household or family ("per household"). In order to apply the given tabular data to assess the impact of Russia's military aggression on the environment, the presented data were graphically and mathematically formalized (**Figure 4**).

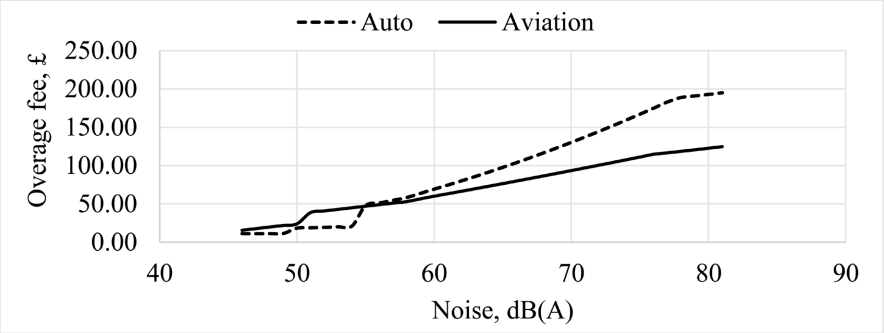

Figure 4. Amount of daytime noise pollution charge, pounds sterling (£)

For vehicles, the mathematical relationship (1) between noise and the corresponding charge is well described by a linear function ($R^2 = 0.98$):

$$y = 5.908x - 280.97 \quad (1)$$

For air transport ($R^2 = 0.99$) (2):

$$y = 3.1982x - 130.76 \quad (2)$$

Noise from fighter jets at night is estimated as follows (**Figure 5**).

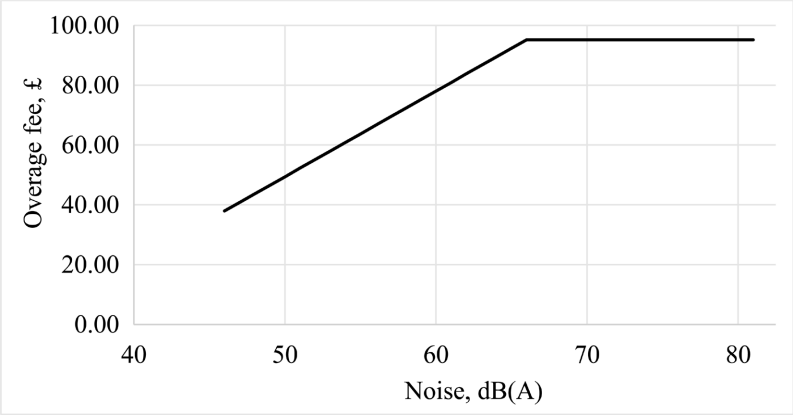

Figure 5. The size of the charge for avianoise pollution at night, pounds sterling (£).

After reaching 66 dB(A), the harm to people helth from the negative impact of noise at night remains the same for both motor vehicles and aviation at £95.15. That is, this level of noise is considered the minimum, at which a person's sleep is definitely disturbed.

As for the reaction of biodiversity on the noise pollution by fighters, the results of the study of the American group of scientists are very indicative [65].

Thus, it was established that the recorded levels of sound (107 ± 5 dB(A)) and sound pressure in the air from airplanes (110 ± 4 dB re 20 μPa rms) exceeded known standards of behavioral and physiological effects on humans, as well as terrestrial birds and mammals. Using a hydrophone installed 1.4 km from the runway, the researchers recorded aircraft noise at 134 ± 3 dB re 1 μPa rms at a depth of 30 m. Such sound levels exceed all known threshold values that cause changes in the behavior of fish, seabirds and mammals [65]. Root-mean-square

(rms) pressure—mean squared sound pressure [66]. Sound levels (dB) in the water environment are reduced to the reference root mean square pressure value of 1 μPa. For the air environment, sound levels are reduced to a sound pressure value of 20 μPa, which is the lower limit of perception by the human ear.

Thus, for further calculation the noise from the fighter in the air will be equal to 112 dB(A), in the water—137 dB re 1 μPa rms (for rivers, Black and Azov seas).

Find the size of the fee for daytime noise pollution, using dependence (2):

$$3.1982 \times 112 - 130.76 = 227.44 \quad £$$

The size of the daily fee for noise pollution in the air environment will be:

$$227.44 + 95.15 = 322.59 \quad £$$

The resulting value corresponds to 419.37 US dollars (1 £ = 1.3 USD).

According to the State Statistics Service of Ukraine [67], the average size of one household within the entire state in 2021 was 2.58 people, *i.e.* 3 people. Will use this value to specify the harm caused by aircraft noise pollution to the environment.

In order to understand the minimal harm for the health of Ukrainians, the data of population by region were used (Table 10).

Table 10. Losses from noise pollution of fighter jets by region.

Region	Population as of February 1, 2022, thousand	Territory covered by hostilities*, km²	Area of the region, km²	Population density, thous. inh. /km²	Number of households affected by noise	Harm to health from noise, million USD
Zhytomyr	1177.6	1491.6	29,832	39	19,626.67	8.2
Kyiv	1794.5	5626.2	28,131	64	119,633.3	50.2
Chernihiv	957.7	25,492	31,865	30	255,386.7	107.1
Sumy	1034.4	19,067.2	23,834	43	275,840	115.7
Kharkiv	2596.3	14,136.75	31,415	83	389,445	163.3
Luhansk	2101.7	24,015.6	26,684	79	630,510	264.4
Donetsk	4056.4	21,213.6	26,517	153	1,081,707	453.6
Zaporizhzhya	1636.3	21,744	27,180	60	436,346.7	183.0
Kherson	1000.4	25,776.9	28,461	35	302,018.1	126.7
Mykolaiv	1090.5	3689.7	24,598	44	54,525	22.9
		Total				**1495.1**

*Approximate percentage of coverage of hostilities based on visual analysis of the map of hostilities and occupied territories.

The resulting amount of harm, about 1.4951 billion dollars, should be interpreted as follows: households located in the territory covered by hostilities were exposed to fighter jet noise of 112 dB(A) at least once during the day and once at night (twice a day). The correctness check of the statement is given below.

For all models of Russian fighter jets, the minimum combat radius is about 500 km. Approximately, at the end of April 2022, the area of the territory of Ukraine, which was covered by hostilities, was 162253.55 km^2.

The wingspan of the mentioned Russian fighters is approximately 14 m. The maximum noise level is obviously under the plane. In the conditions of war, all military maneuvers are carried out as close as possible to the earth's surface—to human settlements and social infrastructure, and habitat of wild animals, respectively. It is difficult to establish fighter flight routes. However, it is possible to calculate the amount of time that Russian fighter jets need to fly over the territory of Ukraine that is covered by hostilities.

The total length of the military route is:

$$\frac{162253.55\ \text{km}^2}{0.028\ \text{km}} = 5794769.643\ \text{km}$$

That is, if to stretch the territory of Ukraine covered by hostilities into a rectangle with a width of 28 m, the length of such a route will be approximately 5.79 million km. The value of 0.028 km in the denominator corresponds to twice the wingspan of the fighter (there and back). In fact, the sound impact of the plane's invasion of Ukraine and its return are taken into account.

According to Table 2, the average maximum speed of Russian fighter jets is 2300 km/h. In order to overcome a combat route of 5.79 million km at maximum speed, it is necessary to spend 2519.46 hours in the air:

$$\frac{5794769.643\ \text{km}}{2300\ \text{km/h}} = 2519.46\ \text{hours}$$

The average working time of the fighter at maximum speed is 1.15 hours (69 minutes), according to Table 2.

At the beginning of the military invasion, if we take the minimum numbers into account, Russia planned to use 330 fighter jets against Ukraine. In the event that the Russian Federation would simultaneously use this entire military supersonic air fleet, it would take one week to cover a route of 5.79 million km, provided that one aircraft makes one sortie per day lasting 1.15 hours:

$$\frac{2519.46\ \text{h}}{330 \times 1.15\ \text{h}} = 6.63889 \approx 6.64\ \text{days}$$

Summarizing the above calculations, a horde of 330 Russian fighter jets, being an active part of the military invasion of Ukraine, causes harm to people's health due to noise pollution in the amount of 1.4951 billion dollars every week. Since it is difficult to establish the real number of Russian fighter jets involved in the war against Ukraine, it was decided to use the value of 330 combat units that Russia mobilized near the Ukrainian borders. After all, why concentrate near the state borders of Ukraine equipment that will not be used?

Noise pollution because of fire equipment of Russian fighters also needs assessment. The sound from bullets, rockets, and bombs also causes disturbance of

animals, changes in their behavior, movement routes, and periods of activity. It is hard to prove on the paper, but I noticed that when Russian fighter jets held on fire our positions, nature were getting silent. There were no birds singing, any sounds or movements from insects or terrestrial animals. Only wind and plants rustling.

The order of opinions regarding other military equipment of the Russian Federation is similar: trucks, artillery, rockets, machine guns, etc. All this creates noise, which strongly affects not only people, but also animals. Therefore, the "noise of war" will be evaluated separately.

5.3.2. Weapon Damage

According to the data in Table 7, fighters are equipped with rapid-fire guns, and can carry bombs, air-to-ground and air-to-air missiles.

As for rapid-fire guns and air-to-air missiles, which are used for targets destruction in the air, it is more appropriate to include this negative effect in the "noise of war" category. Objectively, it is almost impossible to determine the losses from combat operations in the air, as well as their volumes. However, the corresponding noise, chemical and physical negative impacts can be covered by the calculation of damage from air-to-surface missiles. The logic is as follows. The possibility of using types of fire equipment of fighters is limited by the number of hangers on them and their carrying capacity. That is, the same aircraft can be armed with a larger number of light weapons, which are equivalent in weight to a smaller number of more powerful ones. However, both options for fire equipment are possible.

For example, according to Table 7, the Su-24 supersonic fighter can be armed with two R-60 missiles (air-to-air) and four X-25 (air-to-ground) or only three high-explosive aerial bombs of 1500 kg (ФАБ-1500), or eight ФАБ-500.

The vast majority of air-to-ground missiles are used by Russians to destroy armored vehicles, radar stations, surface fleets and other types of military equipment, civil and military transport infrastructure objects.

Aviation bombs (high explosive, guided, incendiary, cluster bombs, etc.) are aimed at destroying both manpower and equipment. Their use is characterized by the radius of a continuous impression. But bombs are far eviller than missiles in terms of destruction. Therefore, the characteristics of the impact of aerial bombs will be used for determining the damage caused to the ecosystems of Ukraine (taking into account the possibility of their transfer by Russian fighter jets).

In Table 11 shows the characteristics of aerial bombs in relation to the area of destruction. The type of bombs that can be used by fighter jets is taken with reference to the data in Table 7.

According to the data in Table 11, the most destructive is the use of ФАБ-250 in the amount of 28 units. In one sortie with a full combat kit, Su-30 can destroy life on an area of 27.5 hectares.

ФАБ-250 is possible on all Russian fighters. Only "light" (attack) MiG-29 and MiG-31 have not been used by Russia in Ukraine for bombing. At the same time, with the understanding that all other models can carry minimum 8 ФАБ-250 each

(especially Su-30, Su-34 and Su-35), further calculations will operate with an area of continuous damage to the ecosystems of 8 hectares (80,000 m^2)—eight sized area of continuous damage for ФАБ-250 (Table 5)—from one aircraft per one sortie.

Table 11. Radius of continuous impact of aerial bombs.

Type of aerial bomb	Radius of continuous damage, m	Area of continuous damage, m^2	Possible to equip a fighter, pieces	Potential area of continuous impression for one flight, m^2
ФАБ-1500*	160	80,384	3	241,152
ФАБ-500	80	20,096	8	160,768
ФАБ-250	56	9847	28	275,716
ФАБ-100	18	1017	32	32,544
КАБ-1500**	140	61,544	3	184,632

*The radius of the solid impression of ФАБ and ОФАБ is approximately the same. But the zone of damage for ОФАБ, due to the fragmentation charge, is much larger. **Guided aerial bombs (КАБ) are capable of penetrating 3 m thick concrete or a 20 m layer of soil.

A horde of Russian fighter jets of 330 units can completely destroy the ecosystems of Ukraine with an area of 2640 hectares (26.4 km^2) in one day of war. Of this territory, 54% (14.26 km^2) is agricultural land (78% (11.12 km^2) of which is arable land), 46% (12.14 km^2) is natural territory.

If we follow the simplest way and rely on Article 52 of the Code of Ukraine on Administrative Offenses, then for spoiling and polluting agricultural and other lands, the maximum prescribed amount of the fine is one hundred tax-free minimums (1,700 UAH). Thus, Russian planes, daily bombarding Ukrainian land with at least eight aerial bombs, cause damages of UAH 4.5 million within 26.4 km^2.

$$1700\ \text{UAH} \times 330 \times 8(\text{FAB}) = 4.49\ \text{million UAH}$$

In currency equivalent, this will amount to 152.5 thousand dollars (at the exchange rate of 29.50 UAH per USD) every day for the bombing of the territory of Ukraine.

If evaluate the impact of the bombings from an ecosystem approach, rather than a regulatory approach, the damage will be much greater. The following assessmrnt, within the limits of the presented materials, will once again prove it.

According to Table 2, since the beginning of the war, approximately 162,253.55 km^2 of the territory of Ukraine (about 27% of its area) have been covered by direct combat operations.

Similarly to the calculations with tanks, it is necessary to separate the regions according to the sign of belonging to natural zones, which differ among themselves in the productivity of the vegetation cover.

Thus, Zhytomyr, Kyiv and Chernihiv regions are included in the zone of mixed forests with an annual phytomass productivity of 75 t/ha. The fighting covered an

area of approximately 32,609.8 km² or 20% of 162,253.55 km². The forest-steppe zone (Sumy and Kharkiv regions) with a productivity of 125 t/ha also accounts for 20%. And for the steppe zone (Mykolaiv, Kherson, Zaporizhzhya, Donetsk and Luhansk regions) - 60% (with a productivity of 85 t/ha). After that we can estimate the damage from bombings and the continuous destruction of the territory.

On an area of 26.4 km², the following volume of phytomass can be produced within one year:

1) mixed forests:

$$2640 \text{ ha} \times 0.2 \times 7.5 \frac{\text{tons}}{\text{ha}} = 3960 \text{ tons}$$

2) forest steppe:

$$2640 \text{ ha} \times 0.2 \times 12.5 \frac{\text{tons}}{\text{ha}} = 6600 \text{ tons}$$

3) steppe:

$$2640 \text{ ha} \times 0.6 \times 8.5 \frac{\text{tons}}{\text{ha}} = 13464 \text{ tons}$$

In total, the amount of phytomass lost as a result of bombing within the year will be 24,024 tons. In this case, let us emphasize that we are talking about lost phytomass after one bombing. And such damage to the soil and plant cover in one day will not be able to recover within one year. Therefore, it will be fair to consider the damage from at least a 10-year perspective (although 1 cm of fertile soil layer is formed for about 100 years [68]-[71]).

By analogy with the damage from tanks defined earlier, we worked with the equation of photosynthesis and the balance of substances.

The lost biological yield in ecosystems was determined due to the destruction of 26.4 km² of territory (Table 12).

Table 12. Lost biological yield in ecological systems of Ukraine after bombings.

A component of photosynthesis	Biological harvest	Lost phytomass	Lost biological harvest	
			Grams	Tons
Carbon dioxide (CO_2)	170 g		2.3×10^9	2300
Water (H_2O)	50 g		0.6×10^9	600
Energy of the Sun	1.8 MJ	13,464 tons	24.2×10^6 MJ	
Organic matter	100 g		$1.3 \cdot 10^9$	1300
Oxygen (O_2)	120 g		$1.6 \cdot 10^9$	1600

The volume of unfixed energy in plants on the territory of 26.4 km² is equivalent to, for example, 500 kg of oil. On April 1, 2022, for example, one barrel (0.1364 tons) of Brent oil cost USD 104.38. Using the method of energy analogies, the corresponding energy losses of ecosystems can be estimated at the level

of 383 USD:

$$\frac{500\text{ kg}}{136.4\text{ kg}}\times 104.38\text{ USD}\approx 383\text{ USD}$$

And this is only the energy of chemical bonds in phytomass.

Damages for non-sequestration of carbon dioxide by phytomass at maximum prices:

$$2288.9\times 10^3\text{ t}\times 192\frac{\text{USD}}{\text{t}}=439.5\text{ th.USD}$$

Losses due to non-production of oxygen:

$$\frac{1615.7\times 10^6\text{ kg}}{1.43\text{ kg}/\text{m}^3}\times 0.11\frac{\text{USD}}{\text{m}^3}=124.3\text{ th.USD}$$

Damages due to non-binding of water:

$$0.3\frac{\text{USD}}{\text{liter}}\times 0.673\times 10^6\text{ liters}=202\text{ th.USD}$$

Damage to ecosystems due to pedosphere destruction and the corresponding biota will have multi-year effect. Taking into account the annual growth of phytomass by 10%, the 10-year damages from the disruption of ecosystems will also increase (Table 13).

Table 13. Losses in a 10-year perspective.

Year	Phytomass, tons	Substance losses, tone			Energy of the sun, TJ	Damages, thousand USD			Energy of the sun*, TJ
		CO_2	O_2	H_2O		CO_2	O_2	H_2O	
2022	13464.0	2288.9	1615.7	673.2	24.2	439.5	124.3	202.0	421.5
2023	14810.4	2517.8	1777.2	740.5	26.7	483.4	136.7	222.2	463.6
2024	16291.4	2769.5	1955.0	814.6	29.3	531.8	150.4	244.4	510.0
2025	17920.6	3046.5	2150.5	896.0	32.3	584.9	165.4	268.8	561.0
2026	19712.6	3351.1	2365.5	985.6	35.5	643.4	182.0	295.7	617.1
2027	21683.9	3686.3	2602.1	1084.2	39.0	707.8	200.2	325.3	678.8
2028	23852.3	4054.9	2862.3	1192.6	42.9	778.5	220.2	357.8	746.7
2029	26237.5	4460.4	3148.5	1311.9	47.2	856.4	242.2	393.6	821.4
2030	28861.3	4906.4	3463.4	1443.1	52.0	942.0	266.4	432.9	903.5
2031	31747.4	5397.1	3809.7	1587.4	57.1	1036.2	293.1	476.2	993.9
2032	34922.1	5936.8	4190.7	1746.1	62.9	1139.9	322.4	523.8	1093.3
		Total				**8143.8**	**2303.1**	**3742.6**	**7810.9**

*Calculations are presented in oil equivalent: the specific heat of combustion of oil is taken to be 43 MJ/kg.

Obtained results should be interpreted next way: in one day of the Russian military invasion to Ukraine, 330 fighter jets (one sortie of one aircraft), whose fire

equipment with aerial bombs is equivalent to eight ФАБ-250, destroyed 26.4 km^2 of Ukrainian ecosystems. The damages from such destruction of the environment and disruption of the ecosystem services flow in one day amount to 765.8 thousand dollars. It should be clearly understood that this is the minimum loss that can be determined at the ecosystem level. And it is obviously five times higher than the amount of damages determined on the basis of Article 52 of the Code of Ukraine on Administrative Offenses.

How to apply the obtained results: every day of the war that Russia started against Ukraine adds 765.8 thousand dollars to the amount of reparations payments. After all, every day Russian fighter jets bomb the territory of Ukraine with aerial bombs, destroying at least 26.4 km^2 of Ukrainian territory with all its landscape and biodiversity.

Summarized minimal damages to the ecosystems of Ukraine from Russian fighter jets are:

1) for waste gases—336.2 thousand dollars (daily).

2) for noise—1.4951 billion dollars (for every 7 days).

3) from fire equipment—765.8 thousand dollars (daily).

And it is obvious that with the increase in the area of the territory covered by hostilities, the losses will increase in direct proportion.

5.3. Influence of "Noise of War" on Ecosystems of Ukraine

Lack of knowledge about the noise impact on the environment during military equipment operation and the use of appropriate fire equipment does not allow assessing the full scale of ecosystem changes as a result of Russia's military invasion of Ukraine. This will be proved in the following calculations. Nevertheless, to solve this issue, we will rely on the current Ukrainian environmental legislation.

To assess damages from noise pollution of terrestrial ecosystems, rivers and seas, we will operate according to the provisions of Article 87 of the Code of Ukraine on Administrative Offenses. Thus, a fine from fifty to seventy of tax-free minimum incomes[3] of citizens is provided for violation of the requirements for protection of the habitat and migration routes, resettlement, acclimatization and crossing of wild animals or failure to take measures to prevent the death of wild animals, deterioration of their habitat and migration conditions. It will be fair to operate in further evaluations with a maximum for one person (a Russian soldier)—40.32 USD.

The Law of Ukraine "On the Animal World" establishes a period of silence from April 1 to June 15 every year. This measure is carried out in order to protect habitats, breeding conditions and migration routes of wild animals. According to Article 39, at this time it is prohibited to carry out works and activities that are a source of increased noise and disturbance (firing, carrying out explosive works, fireworks, sanitary felling of the forest, using motor small vessels, holding rallies and other competitions on vehicles).

[3]Tax-free minimum incomes = 17 UAH (≈ 0.576 (USD) before invasion).

War is the personification of "restlessness" and is accompanied by all actions prohibited by Ukrainian legislation in relation to wild animals. Therefore, it is fair to consider February 24, 2022, as the day of violation of the silence regime.

According to the data on the number of Russian troops that started the war against Ukraine, determine the amount of damage to the ecosystem due to noise pollution (Table 14).

Table 14. The damage to the ecosystem is due to noise pollution.

The source of noise pollution	Amount	Damage for "restlessness", USD
Soldiers	140,000	5,644,800
Tracks	4000 [72]	161,280
Light vehicles	>1000	40,320
Tanks	1300	52,416
Airplanes	330	13,305
Helicopters	240	9677
Cruise missiles*	5000 [73]	201,600
Artillery	1800	72,576
Armored combat vehicle	2900	116,928
Reactive volley fire systems	>100	4032
Navy**	227 [74]	9153
Total		**6,326,087**

*The amount that Russia released on the territory of Ukraine on February 23, 2023. **Data on the size of the Russian Black Sea Fleet at the end of 2019 were used.

Explain the calculations. It's easiest with soldiers: 140,000 people, having invaded Ukraine, are daily causing damages in the amount of:

$$140000 \times 40.32 \text{ USD} = 5644800 \text{ USD}$$

At least one person is responsible for the control of a truck, passenger car, tank, airplane, helicopter, artillery installation, armored combat vehicle, reactive volley fire system, combat ship. In fact, one unit of equipment can be equated to one person, which is a source of anxiety in the environment, because every day Russian military equipment either drives, or rolls, or shoots.

Total daily damages for violation of Ukrainian legislation, in terms of negative noise impact on biodiversity, are $6.3 million (at the rate of 29.50 UAH/dollar).

Now prove that even this amount is very detached from reality.

As an example, consider beekeeping. Against the background of explosions, the work of enemy artillery, aviation, infantry, and the work of Ukrainian army to protect against aggression, apiaries and natural habitats are destroyed, bee families are greatly disoriented or die. As a result, they use much more energy for protection,

exploration, self-regulation than collecting honey (pollinating flowers, gardens, fields) and developing their own family.

According to the Ministry of Agriculture of Ukraine, it is known that in 2013, for example, 73,713 tons of honey were produced in Ukraine (these are only official data), which in terms of money (at the price of 40 UAH/kg for 2013) is approximately 2.9 billion hryvnias or 0.2% of the nominal GDP of the country in the same year. These are direct revenues from the rational use of the living component of the ecosystem.

In terms of the production of sunflower products, Ukraine occupies a leading position in the world. However, it is known that 99% of this crop is pollinated by bees and hornets. The sunflower harvest in 2013, according to the State Statistics Committee of Ukraine, amounted to 11,051 thousand tons. The official price for this crop, according to the Ministry of Agriculture of Ukraine, in the same year was 3315 UAH/ton. After conducting simple calculations, we see that the income from the sale of these products amounted to 36.6 UAH billion, which is about 2.5% of the country's nominal GDP. These are incomplete indirect income from the living component of the ecosystem for Ukraine. All in total is about 3% of Ukraine's GDP in the same year.

In 2020, for comparison, this figure was 3.8%. According to the State Statistics Committee of Ukraine, with the official production of 68 thousand tons of honey, 81.1 thousand tons worth $139.4 million were exported. About 13.11 million tons of sunflower were collected, the price of which was about 450 dollars per ton (total 5.9 billion dollars).

Ukraine's economy and world's ecosystem are losing incredible benefits just from the Russians' destruction of apiaries and natural habitats of bees. Not to mention other biodiversity that has been adversely affected by the war.

Summarizing damages for violation of Article 39 of the Law of Ukraine "On the Animal World" in accordance with the provisions of Article 87 of the Code of Ukraine on Administrative Offenses, the sum of damages for the year is:

$$365 \times 6.3 = 2299.5 \text{ USD millions}$$

The share of this amount in the nominal GDP of Ukraine in 2020 is at the level of 1.5%. However, only bees, as an example given earlier, provided at least 3.8% of GDP in the same year. Even if to take corrections for the dollar exchange rate, inflation and other conversion-time factors, the compared values are very different!

Ecosystems remain underestimated both in Ukraine and in the world.

After the end of the war, "detached from reality" fines for violations of environmental legislation should be increased. Calculations proved this demonstrably.

Since it is impossible to assess the full negative impact of the noise of war on animals and plants (by species) at this stage of human development (due to the insufficient study of this issue), it is proposed to take as a basis the amount of damages based on the rates of the "quiet season" and, if possible, to supplement his (as was shown on the example of bees).

For the period of the war, the violation of the "season of silence" had started from the beginning of the war and should be included in the relevant period every day until its end. After all, the noise of war has a negative effect not only on the reproductive activity of the biota (which is mainly what the "quiet season" is aimed at), but also on its migration routes, mass grazing, rest, efficiency and the possibility of hunting. Every day of war undoubtedly disrupts the normal development of biodiversity.

6. Discussion of the Results

Summarizing the obtained results, it can be argued that they confirm and complement the conclusions of other scientists about the negative impact of war on ecosystems. The novelty of the conducted research lies in the choice of the level of the evaluation object. This led to a certain difference in the choice of methods, construction and interpretation of calculations. The use of patterns of energy flows in ecosystems made it possible to clarify the magnitude of the negative impact of war on the environment. Therefore, from a practical point of view, the numerical solutions obtained in the work can be considered complex. The environmental damage shown in Table 12, for example, covers the loss of forests and some ecosystem services: sequestration of carbon dioxide, release of oxygen, production of organic matter.

Another important aspect of the practical significance of this work is to highlight the inability of environmental legal systems to objectively assess real environmental damage. This gap between the regulatory and ecosystem approach is clearly visible if you compare the data in Table 14 with Table 5 and Table 10.

The obtained results of the war's impact on the environment significantly refine the known analogues, exceeding them. In particular, the estimates calculated by the experts of the Kyiv School of Economics [75] are 30 times less than those calculated in this work in terms of forest loss. As for air pollution, the factor of exhaust gas emissions from military equipment remains underestimated at a staggering $28 billion.

In work [24], for example, the authors estimated the damage to the environment at the level of a modest 56 billion dollars. It is obvious that these values are significantly less than those substantiated in the work.

At the same time, the research that was conducted revealed some limitations and weaknesses of the proposed "energy flow" method of damage calculations.

An objective limitation of the proposed solutions is that the proposed method of assessing environmental damage from the war does not specify the importance of the lost ecosystem components. This would make it possible to specify damages and reparations in a larger direction. When, on the basis of calculations, we come to the conversion of biomass flows by the energy chain, probably the losses from the loss of red-listed animals will be greater than, for example, broiler chickens. The author, considering every living being equally valuable in nature in principle, suggests using such an assessment only in cases of regional limitation of armed

conflicts. That is, in the conditions after the end of the war, when populations and groups will be able to recover at the expense of the resources of neighboring ecosystems.

It is also worth noting the limitations that determine the dynamics of the assessment. In cases of resolved armed conflicts, the final value of the damage from the war on the environment can be obtained only after its completion.

Another limitation is the secrecy of data on the technical characteristics of military equipment. In this regard, the calculations given for damage caused by atmospheric air pollution should be considered minimal since the composition and amount of exhaust gases can be affirmatively classified as unstudied.

However, the author considers these questions to be clarifying and such that they do not fundamentally affect the results of the evaluation, although they require additional research.

The weakness of the practical application of specified damage estimates is the prevention of wars. The results of losses are directly proportional to the scale. At the stage of formation of the aggressor's intentions, the complexity of the assessment is caused by the uncertainty of the scale. As a result, "not big enough" arguments may not influence the decision to launch a military invasion. As a solution to this issue, deterrence reparation payments should include damages calculated for the entire territory of the country that is being attacked. In addition, adjacent ecosystems should be added to the objects of influence, and a complex set of ecosystems should be considered (for example, in the context of assessing the integrity of biodiversity migration routes).

In general, according to the author, the results obtained create prerequisites for improving the system of ensuring environmental safety at the local, state, and international levels and transferring the obtained numerical solutions into the relevant safety-forming practice.

7. Conclusions

War is a tragedy for the environment. The work-based decisions regarding the assessment of its impact on ecosystems, based on the study of energy flows, confirm this without appeal. The comprehensiveness and multifaceted nature of the negative impact of hostilities on ecosystems will probably never be determined in absolute terms. But even the given calculations of losses proved that it is millions of dollars every day, millions of tons of organic matter every year. At the same time, it should be understood that the provided estimates are incomplete due to the lack of data on the number of certain military equipment and its functional characteristics. Therefore, it is quite fair to consider the amount of damages received to be minimal.

The main results of the study are as follows.

1) The investigation of the problem of assessing the war's impact on the environment allows us to assert the established global practice of ignoring the value of ecological systems and their importance for humanity's development during all

phases of military operations. In addition, the underestimation of ecosystems by legal systems is measured by at least tenfold categories in comparison with the appropriate damage calculations given in the work.

2) During the year of the war, only Russian tanks caused damage to the environment in the amount of about 138.5 billion dollars. Among the evaluated impact factors, exhaust gases, land compaction and disturbance of vegetation cover were evaluated. Only fighter jets caused losses of almost 79 billion dollars due to the emissions of exhaust gases, noise, and bombings. And the negative impact of the general noise of hostilities amounted to about 2.3 billion dollars. The total amount of losses based on only these components is already comparable to the state budget of Russia for a year.

3) Another influential aspect that is not considered in the article is the defense side of the war. After all, the given calculations of environmental damage were made for Russia, the aggressor. Ukraine has to use a huge amount of resources to defend its own borders, as a result of which environmental pollution also occurs. Ukraine's partners spend resources. This also has an impact on the environment that cannot be neglected. Perhaps the approach "the force of action is equal to the force of counteraction" will allow at least an approximate understanding of the order of damage to the environment in general in any war. If we use the values obtained in the work, then the minimum is at the level of 440 billion dollars, taking into account the defense side. And the responsibility for these damages must undoubtedly be placed on the aggressor, and in the context of the topic of the article on Russia.

Use of Artificial Intelligence

The author confirms that he did not use artificial intelligence technologies when creating the presented work.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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