UDC 911.9:502.132(477.44-25)
https://doi.org/10.31073/ecobezpeka202507-10

PROTECTING URBAN BIODIVERSITY BY DEVELOPING URBAN ECO-NETWORKS

Radomska M. M., Huz V. V.
State University «Kyiv Aviation Institute»
L. Huzar Ave., 1, Kyiv, 03058
m.m.radomskaya@gmail.com,
6856368@stud.kai.edu.ua

This paper presents an analysis of the current issues of biodiversity conservation in urban areas with a primary focus on the development of eco-networks. Artificial structures span through and beyond cities, creating obstacles to the mobility, reproduction, and survival of the animals. Urban biodiversity is crucial for the functioning of an ecosystem. Thus, its degradation imposes risks to the well-being of the citizens. The purpose of this research is to analyze the current trends in eco-networks development in cities around the world and take into account their specific features while adapting this experience to the Ukrainian condition. Eco-networks of five cities outside the European continent, as well as preliminary designs made for four Ukrainian cities, were studied and generalized to formulate an efficient protection strategy for biodiversity in Ukrainian cities. The majority of the used research works were built on spatial analysis, aided by GIS, and spatial parameters synthesis. A major issue for the functional ability of the urban eco-networks is a lack of connectivity, which is managed differently in the studied cases, with the key differences being: the use of barren lands, constructing green roofs and small squares, legal land withdrawal from the practical use or the addition of wildlife safety parameters to the patches of urban agricultural lands. It is shown that Ukrainian cities have begun working on assessing their eco-networks and determining hotspots for connectivity. The practical part of the work involved developing an eco corridors project for the city of Kyiv. The analysis of the most important threats to biodiversity on the city grounds was conducted, and core areas were defined. Four corridors, as well as additional elements of green infrastructure to fill the available gaps, were offered based on a spatial analysis. Additionally, the prospects of expanding green areas in northern districts of Kyiv were considered and implemented in the general eco-network structure.

Keywords: fragmentation, eco corridors, urban environment.

Introduction

An ecological network is created with interconnected natural areas that together form a functional system, providing the conditions for organisms to exist and benefit the environment. The central aim of creating eco-networks is to conserve biodiversity and support its vital functions so that essential ecosystem processes are not disrupted. Integrity, continuity, and diversity of habitats are crucial for the environmental balance and the resilience of an ecosystem.

Urbanization and drastic changes in land use over the past centuries have led to the reduction and fragmentation of natural habitats worldwide. This poses a long-term threat to biodiversity. Conservation success depends on preserving a stable landscape to guarantee regular gene flow and movement between populations. However, man-made structures have turned into artificial barriers, jeopardizing wildlife population survival. The fact that cities are still a part of animal habitats and so they must provide conditions for safe movement has already been established in the science of biodiversity conservation, but unfortunately, it is still not being recognized in either the theory or practice of urban planning and design.

Ensuring the coherence of ecological networks and addressing threatening barriers is crucial for supporting the survival of species, typical to natural and semi-natural habitats.

This research aims to analyze the available experience of developing ecological networks in cities around the world, define the principles of creating one, and apply this knowledge in the city of Kyiv.

Analysis of the current level of urban eco-networks development

Since the 1980s, environmental research has focused on the tasks of building and expanding ecological networks [1]. Identifying, designating, and protecting ecological networks helps to maintain biodiversity and reduce isolation in fragmented landscapes, which constantly expand due to human habitation.

The concept of greenway and green space planning has been forming for over a century. Early examples were built on the natural wilderness areas, such as the Adirondack Park Region Concept in the United States have laid a general foundation for modern greenway planning [2]. Later, it became clear that special measures must be taken to maintain, enhance, or restore connectivity between protected areas [3]. Throughout the 20th century, cities started to invest efforts to preserve their greenery and expand it. Later researchers have demonstrated that urban environments are too fragmented to provide a reliable foundation for urban biodiversity conservation without connectivity and even the best parks and wilderness areas separated by human interventions gradually degrade and lose their resilience [4].

An eco-network includes a core zone, a buffer zone, and corridors. These are essential elements and eco-networks can function properly only if they are present and interact properly [5]. Core areas, whether legally protected or managed with conservation-oriented approaches, act as focal points for biodiversity conservation efforts. They provide crucial habitats and resources for various species and ensure the ecosystem is balanced. Buffer zones surrounding these core areas protect them from negative effects and mitigate pressure from human activity in the area. They also work as transitional zones where conservation areas and commercial areas can gradually change from one to another. The ecological corridors provide connectivity, enabling wildlife interaction on an individual level as well as the exchange of genetic material, essential for the species' survival and ecosystem resilience. These areas must be sufficiently large and diverse to accommodate species with different biology, living needs, and behavior.

However, forming any or even all elements of an eco-network in cities can be compromised by construction and transport limitations. Creating ecological networks within cities worldwide represents a paradigm shift in urban planning and environmental management. Therefore, it is necessary to look for or develop special approaches to accommodate the needs of ecological connectivity within cities. The following cities represent successful compromises between urban development and habitat conservation, developed using various methods of spatial analysis.

Fuzhou City in China faced challenges due to intensive growth. The idea there was focused on transforming barren land into parkland to bolster connectivity within Fuzhou City's ecological network [6]. Additionally, key barriers within the network were identified, and opportunities for ecological restoration were explored. Findings showed that developing bare land into an ecological source yielded better results than converting existing land into woodland. Currently, Fuzhou City's ecological network comprises 44 source sites and 92 corridors, providing a robust framework for biodiversity conservation in the urban landscape. Thus, transforming 30% of barren land patches into green spaces or parks proved to be the most impactful strategy for enhancing connectivity within Fuzhou City's ecological networks.

For Tabriz, Iran there was a comprehensive framework developed. It was based on the analysis of land use changes spanning from 1984 to 2020, using a thorough examination of multi-temporal satellite images and landscape metrics as a source [7]. This approach aimed to evaluate the current ecological connectivity of the study area and propose optimal corridors for a minimal cost. Furthermore, the evaluation of ecological connectivity in the Tabriz landscape using Cohesion and IIC indices revealed an increasing uniformity of developed lands and the fragmentation of ecological spaces. This gradual transformation progressively dominated the Tabriz landscape, while green areas have become increasingly disjointed.

The areas with the highest population density were identified and cost-effective corridors were then created using graph theory to connect these key areas with consideration to ecological spaces such as farmlands, green spaces, and water bodies, as well as unoccupied lands within the city. However, it is essential to acknowledge that this project primarily focused on the historical and current state of the city, which may have entailed certain limitations and uncertainties, warranting further investigation.

The analysis of ecological networks based on ground cover and urban habitat maps was also performed in Suwon, South Korea [8]. The priority areas for protection were identified, and an ecological network was established by integrating results from both maps. Discrepancies were observed between the two maps, particularly concerning water bodies, agricultural lands, bare areas, and forests. While the urban habitat map highlighted high connectivity for water bodies and agriculture, the ground cover map showed elevated connectivity for forests, bare lands, and wetlands. In particular, it was noted that different types of green areas varied in their level of contribution. Mountain forests and remnant forest areas were well protected but lacked connectivity with other areas. Streams and linear patches significantly enhanced connectivity due to their branching structure. Additional contribution was made by agricultural areas, which were not inhabited on a regular basis, but provided ways of transition and connectivity. The combination of this aspects was used to build a functional eco-network, where the most vulnerable sections were defined and protected.

Harbin, China, has a total of 198 ecological areas that span over 65 thousand ha [9]. However, older districts like Daowai, Xiangfang, and Nangang have small, fragmented patches with high internal porosity, necessitating urgent measures to establish an ecological network for integration. At the same time, newer districts like Songbei, Hulan, and Acheng show a stronger ecological foundation. The ecological network in the study area includes 119 ecological zones with certain protected status and 142 ecological corridors. The best level of connectivity is common for watersheds and areas of green fields, while woodlands are fewer and some remain isolated. Ecological corridors, especially in Hulan, Xiangfang, and Nangang, face challenges due to urban construction, while Songbei and Acheng districts have more established corridors. Optimization of the ecological network was built on the edge-adding strategy from complex network theory, optimized for the given purpose. By implementing this modified strategy researchers were able to develop 43 ecological corridors, resulting in a more resilient and interference-resistant network.

Bogotá, Colombia, has conceptualized and embraced the Environmental Enhancement Plan (EEP) as a network of green and blue infrastructures aimed at safeguarding and restoring the essential ecological processes [10]. This initiative seeks to enhance the well-being of Bogotá's population by protecting various types of natural and semi-natural spaces, including protected areas, metropolitan parks, and ecological corridors. The EEP serves multiple purposes, including recreation, urban enhancement, risk prevention, and runoff control. A particular attention is given to the hills surrounding the eastern part of the city, known as the «Cerros Orientales de Bogotá». It is protected as an official reserve, serving as an ecological corridor. Despite the legal protection status, urban growth has already started to spread in that area. In response, a court order issued by the state of Colombia mandated the establishment of an adequate strip of land to maintain a socio-ecological corridor aimed at fostering citizen engagement with the hills. The same area serves as an ecological corridor through the city. This decision was aimed at resolving a social issue but it has successfully accommodated a solution to an ecological problem, which is interconnected in essence.

Urban eco-networks have shown to be successful because of the alternative green infrastructure: research conducted in Beijing and Wuhan demonstrates the efficiency of such strategies as green roofs and forest conversion in enhancing urban connectivity [11].

In Ukraine, attempts to develop urban eco-networks have been made in the past. In particular, the structural elements and potential additions to provide better connectivity for the ecological network of the city of Kremenchuk were offered [12]. Similarly, the quantitative and qualitative indicators of the natural reserve fund of the city of Khmelnytsky were studied, and the core elements of the network were defined [13]. A serious problem for the given city eco-network was noted: the low protected status of the core areas and the absence of connective areas.

In the structure of the city of Vinnytsia, 25 biocentres of the local ecological network were singled out.

They represent the city's different landscape types, mostly distinguished by the terrain. An important feature found in most of them is their quasi-natural status, where rare species of living organisms and plant associations are frequently seen [14].

The city of Ternopil has been studied to identify the core areas of green infrastructure, and the prospects of their expansion and conservation were established [15]. Even though the research wasn't made specifically for an eco-network, the results can be efficiently used for working out a viable plan for one.

The insights from the aforementioned examples can be used to develop the eco-networks of Ukrainian cities. The information from these studies will provide a range of important benefits to potential projects beyond protecting biodiversity, such as:

- Urban ecological networks serve as vital providers of ecosystem services and improve the well-being of the residents.
- Green spaces of ecological networks can mitigate the urban heat island effect and enhance urban climate resilience.
- Urban ecological networks significantly contribute to the improvement of air and water quality, which is essential for the health and well-being of urban residents.
- Green plants reduce the carbon footprint, regulate surface runoff, and reduce the risk of flooding and water pollution.
- By integrating green spaces and natural habitats into urban planning and development, cities can improve environmental sustainability, mitigate climate change impacts, and create healthier and more livable urban environments for present and future generations.

Methodology of eco-network development

Creating an ecological network poses a number of challenges that need to be effectively addressed. The main task is to choose the most effective strategy for integrating green spaces into the urban environment and combining them into a continuous network.

Such work usually begins with a thorough analysis of the urban landscape, a study of existing green areas, and the identification of potential areas for creating new eco-networks. Collecting detailed data on the health of the ecosystem, target species and the needs of residents is mandatory, as is identifying opportunities for the preservation and development of natural spaces.

An important aspect of this process is collecting the information and taking into consideration the requirements of all stakeholders. It is important for the successful development of an ecological network to establish several alternative routes, which ensures the selection of the optimal path through comparison.

The structure of an ecological network in the city is a key element for creating sustainable and ecologically balanced urban environments. Taking into account the diversity of urban landscapes and the needs of residents, the ecological network should have a flexible and adaptive structure.

There is a range of approaches to the process of creating an eco-network structure, which have proved to be efficient, including soil cover assessment, wildlife assessment, species habitat assessment, node analysis, connectivity analysis, network creation, etc. GIS applications provide reliable tools for exploring ecological networks and estimating connectivity between habitat patches. Multiple indices were developed to asses the connectivity within urban networks, aiding researches in choosing the most beneficial yet low-cost options for building eco-networks.

The task of the given research is to conduct a preliminary analysis of connectivity issues within the urban green infrastructure of Kyiv city. For this purpose, a combination of the aforementioned methods was used, primarily relying on Connectivity and Network Analysis to ensure that the ecological network is well-connected and functional in an urban setting.

Recommendations on developing an eco-network in Kyiv

Kyiv, one of the largest cities in Ukraine, faces numerous environmental challenges stemming from intensive urbanization and industrialization. The main environmental threats that affect the functioning of ecological networks in Kyiv include environmental pollution, habitat fragmentation, invasive species, climate change, and overuse of natural resources.

The level of habitat fragmentation in Kyiv is very high in the central area, while its green belt and the Dnieper zone provide massive and reliable connectivity and serve as valuable and resilient core areas. In the other cities, there is a very high porosity, and many of the ecological zones are isolated or poorly connected, limiting the survival potential of species and increasing the risk of extinction. Another considerable threat to biodiversity conservation comes from invasive species. Invasive species typical for Kyiv (e.g. Japanese clover (*Reynoutria japonica*), Marsh acacia (*Impatiens glandulifera*), Ragweed (*Ambrosia artemisiifolia*), Mantegazzi hogweed (*Heracleum mantegazzianum*), Gray mole (*Talpa europaea*), Gray crow (*Corvus cornix*), Brown marble bug (*Halyomorpha halys*), Red fire ant (*Solenopsis invicta*), Black bass (*Micropterus salmoides*), Silver carp (*Hypophthalmichthys molitrix*) possess danger of transforming local ecosystems, making some areas less suitable for econetworks and therefore need consistent control and management [16]. Climate change is exacerbating the environmental threats affecting Kyiv by changing temperature and precipitation patterns.

The environmental situation in Kyiv varies considerably between different districts of the city, depending on the industrial development, green areas and other factors. This complicates the development of eco-network, but places emphasis on some areas, which are more suitable and have more potential (*Desnyanskyi, Dniprovskyi, Holosiivskyi, Sviatoshynskyi districts*).

Kyiv's ecological network consists of various elements that contribute to the conservation of biodiversity, improve environmental quality, and provide places for recreation and leisure for residents. The largest and pivotal elements of eco-network for the city are natural complexes Holosiivskyi Park, Partisan Glory Park, M. Hryshko National Botanical Garden of the National Academy of Sciences of Ukraine, Dnipro river natural complexes and the green belt of the city. In particular, the Dnipro Ecological Corridor, which runs through the city of Kyiv, is an important part of Ukraine's ecological network and is of national and European importance.

The other eco-network elements of the city include a variety of parks with different levels of adaptability for recreational activities, which can reduce their ecological functional ability. An important role is also played by lake systems and small rivers of the city.

Based on an ecological analysis, accounting for such factors as the presence of valuable natural complexes, the level of anthropogenic impact, connectivity with existing natural areas, and the potential for restoring the natural system of eco-corridors was developed for Kyiv city. These corridors' aim is to create an ecological system that will unite existing and new green areas. Within the framework of this research, four main eco-corridors in different parts of the city were identified in Obolon and Desnianskyi districts, as illustrated in Figure 1.

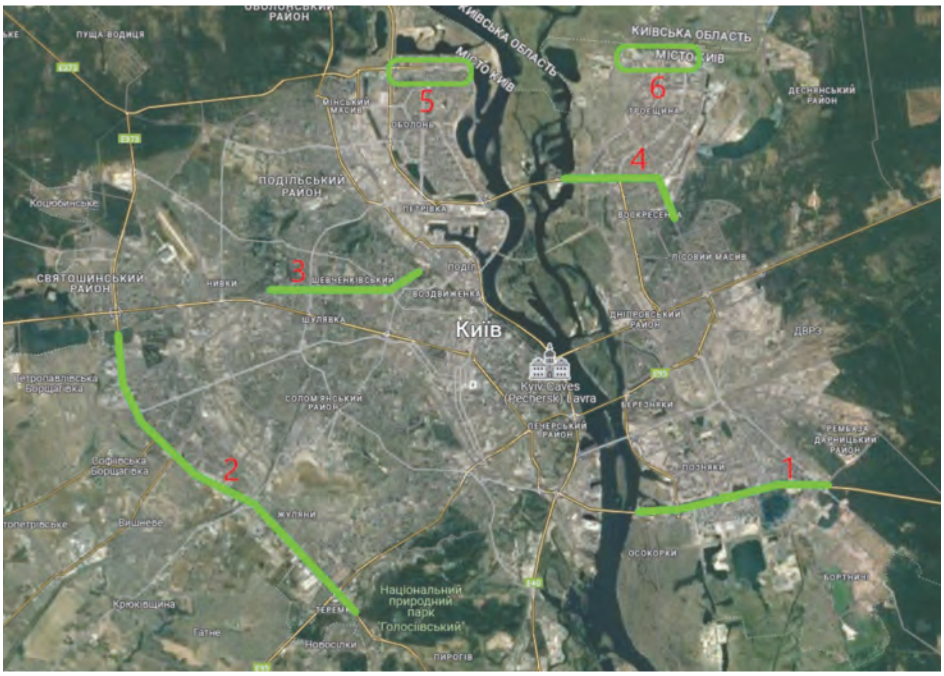

Fig. 1. Eco-network project for the city of Kyiv

Eco-corridor 1 aims to connect the coastal zone of the Dnipro with forests in the Darnytskyi district. The most important existing sites (nodes of the econetwork) for the corridor include: Pozniaky Park; Lake Lebedyne; Lake Vyrlytsia; Lake Pozniaky; Lake Sribnyi Kil. The presence of a large number of lakes was the main reason for creating this eco-corridor, which helps to improve the quality of the environment and ensures the diversity of ecosystems.

If the eco-corridor is established along the Revutskoho Street, Petra Hryhorenko Avenue, Mykola Bazhan Avenue, and the Kharkivske and Boryspil Highway, its potential for environmental enhancement becomes substantial. This route includes diverse urban landscapes, offering opportunities for strategic greening interventions. However, careful planning is required to navigate the challenges posed by infrastructure such as highways and residential complexes.

Eco-corridor 2 serves as a vital link between the forests of the Svyatoshinskyi and Golosiivskyi districts, passing through the Solomianskyi district. The corridor passes along several streets including Sadova, Soborna, Nova, Yabluneva, Zhmerynska, Zodchykh, and Lvivska, encompassing diverse habitats and landmarks such as Zhulyany airport, large commercial buildings, and Sviatoshyn forest. The most important natural sites for the corridor include: Volodymyr Poleutychyi Square; Lake Vira and the park of five benches; Sviatoshynske cemetery; Green spaces near the Capital Market; The alley of the Teremky tract.

An exceptional characteristic of this corridor is its uninterrupted alignment, facilitating extensive greening efforts along its entire length. This uninterrupted pathway presents an opportunity to alleviate the adverse environmental impacts often associated with urbanization. Moreover, its alignment along less densely built areas enable easier connectivity of forests, potentially forming a «Green Ring».

Despite its advantages, the corridor encounters challenges such as railroad tracks, industrial zones, and numerous garages, necessitating careful planning and environmental protection measures. Areas lacking vegetation due to technogenic impact require enhancement through well-designed greening initiatives to improve corridor efficiency and environmental sustainability.

Eco-corridor 3 is designed to establish a vital connection between the Nyvky Park neighborhood and the verdant surroundings of Vozdvyzhenka area. By following the routes of Hlybochytska and Degtyarivska streets predominantly, this corridor aims to achieve a harmonious balance between urban development and the preservation of natural habitats. The most important natural sites for the corridor include: Munich Square; Petro Bolbochan Park; Heydar Aliyev Square; Alley of Luck Park.

An outstanding feature of this eco-corridor is its potential to accommodate a rich diversity of animals and ornamental tree species, providing habitats for many species. However, several challenges, including urban development density, narrow streets, and the prevalence of garages, must be addressed for it to suceed. To optimize the functionality of the eco-corridor, a range of small squares, green roofs and walls could be recommended.

Eco-corridor 4 is meant to provide a continuous green pathway from the Dnipro waterfront to the green areas in the Voskresensky neighbourhood. This corridor will pass through major thoroughfares, including Roman Shukhevych Avenue and Bratyslavska Street, integrating green spaces and facilitating wildlife movement through urban landscapes.

The eco-corridor will begin at the Dnipro waterfront, leveraging the natural riparian habitats, and move through residential and commercial areas, following Roman Shukhevych Avenue and Bratyslavska Street. It will end at the green areas in Voskresensky neighbourhood, connecting various squares and green spaces along the way. The most important natural sites for the corridor include: Monica's Birthday Park; General Vatutin Park; Berizka Recreation Park.

None of the offered corridors has full connectivity, therefore additional elements of green infrastructure were offered for each (Fig. 2). Creating new green spaces and eco-corridors in Obolon and Desnianskyi districts is also necessary to enhance the connectivity in the northern part of the city. This requires detailed design and careful selection of locations. Since these areas are already heavily built up, it is necessary to find optimal locations for creating green areas and in some cases, there is a need to look for alternative nature-based solutions.

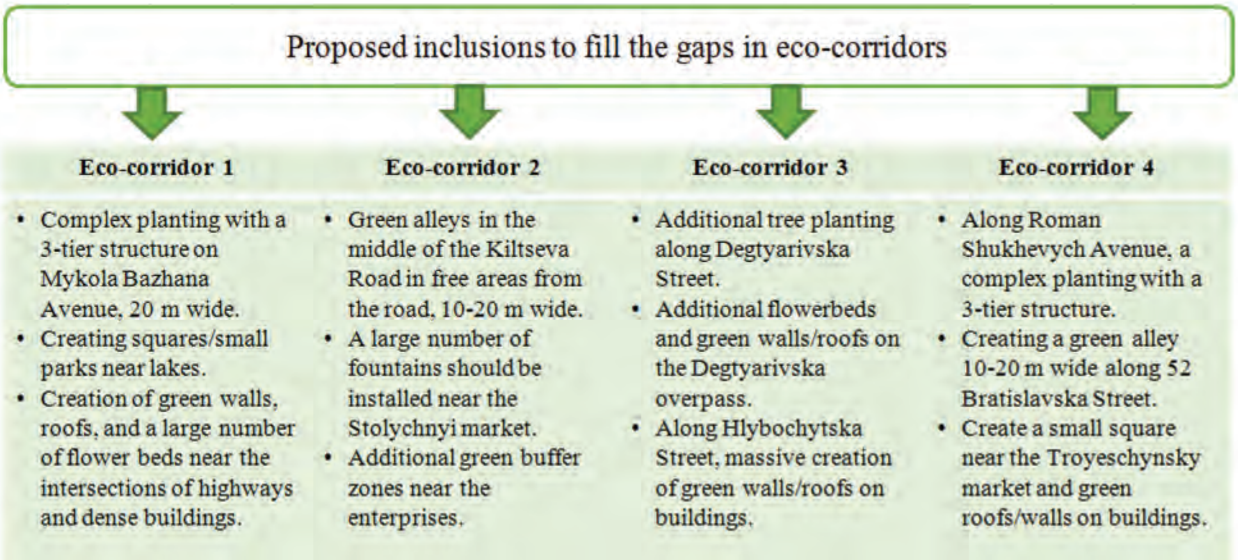

Fig. 2. Proposed inclusions to the eco-corridors

An important condition for the successful development of connectivity is prioritizing the planting of native trees, shrubs, and plants is essential for enhancing the ecological value of the corridor. Native vegetation provides essential habitat and food sources for local wildlife while promoting biodiversity and ecological resilience.

Conclusions

The ecological networks in cities facilitate the migration and dispersal of species, ensure stability of ecosystem services, and preserve unique natural landscapes. They also contribute to mitigation of climate change effects, improve the quality of water and air resources, and maintain the recreational and aesthetic value of the territory. Experience from cities around the world offers diverse approaches to planning and building eco-networks successfully.

The ecological network development for Kyiv is of utmost importance for improving the environmental situation and the quality of life of its residents. Known for its rich green infrastructure, Kyiv ecosystems experience considerable pressure from anthropogenic impacts and growing fragmentation.

Four key eco-corridors were defined for the city to connect green areas with each other. Optimal sites for creating new green areas have been identified in Obolon and Desnianskyi districts, which are intensively built up and require the integration of new green areas to form an ecological network. Suggested solutions also include a number of small-scale activities, such as ponds, green roofs and walls, squares, as well as more complicated structures, such as 3-tier plant association (grass cover, bushes, trees of the lower tier).

Successful implementation of these projects will contribute to the preservation and restoration of Kyiv's natural complexes, strengthening the city's environmental sustainability, improving air and water quality, and creating more comfortable living conditions for residents.

References

1. Ings, T. C., & Hawes, J. E. (2018). The history of ecological networks. Ecological Networks in the Tropics: An Integrative Overview of Species Interactions from Some of the Most Species-Rich Habitats on Earth, 15-28. https://doi.org/10.1007/978-3-319-68228-0_2

2. Hilty, J.*, Worboys, G.L., Keeley, A.*, Woodley, S.*, Lausche, B., Locke, H., Carr, M., Pulsford I., Pittock, J., White, J.W., Theobald, D.M., Levine, J., Reuling, M., Watson, J.E.M., Ament, R., and Tabor, G.M.* (2020). Guidelines for conserving connectivity through ecological networks and corridors. Best Practice Protected Area Guidelines Series No. 30.

Gland, Switzerland: IUCN. https://doi.org/10.2305/IUCN.CH.2020.PAG.30.en

3. Tabor, G. (2019).'Ecological connectivity: A bridge to preserving biodiversity'. In Frontiers 2018/19: Emerging Issues of Environmental Concern. Nairobi: United Nations Environment Programme. Pp. 24-37. ISBN: 978-92-807-3737-0

4. Theodorou, P. (2022). The effects of urbanisation on ecological interactions. Current Opinion in Insect Science, 52, 100922. https://doi.org/10.1016/j.cois.2022.100922

5. Hudzevych, A. V., Nikitchenko, L. O., Hudzevych, L. S., Bronnikova, L. F., & Demets, R. O. (2021). Approaches to organize the econetwork of the Transnistria region in the conditions of urban landscape. Journal of Geology, Geography and Geoecology, 30(3), 449-459. https://doi.org/https://doi.org/10.15421/112141

6. Huang, B.-X., Chiou, S.-C., & Li, W.-Y. (2021). Landscape Pattern and Ecological Network Structure in Urban Green Space Planning: A Case Study of Fuzhou City. Land, 10(8), 769. https://doi.org/10.3390/land10080769

7. Mahmoudzadeh, H., Masoudi, H., Jafari, F., Khorshiddoost, A. M., Abedini, A., & Mosavi, A. (2022). Ecological networks and corridors development in urban areas: An example of Tabriz, Iran. Frontiers in Environmental Science, 10, 969266. https://doi.org/10.3389/fenvs.2022.969266

8. Kim, D., Shin, W., Choi, H., Kim, J., & Song, Y. (2020). Estimation of ecological connectivity in a city based on land cover and urban habitat maps. Sustainability, 12(22), 9529. https://doi.org/10.3390/su12229529

9. Song, S., Xu, D., Hu, S., & Shi, M. (2021). Ecological Network Optimization in Urban Central District Based on Complex Network Theory: A Case Study with the Urban Central District of Harbin. International Journal of Environmental Research and Public Health, 18(4), 1427. https://doi.org/10.3390/ijerph18041427

10. Quimbayo Ruiz, G.A. (2018). People and urban nature: the environmentalization of social movements in Bogota. Journal of political ecology: case studies in history and society. 25, 525-547. https://doi.org/10.2458/v25i1.23096

11. Joshi, M., Rivière, L., Mahy, G., & Teller, J. (2021). Effectiveness of Green Roofs in Strengthening Ecological Network. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 46. 51–54, https://doi.org/10.5194/isprs-archives-XLVI-4-W1-2021-51-2021.

12. Galchenko, N.P., Mudrak, O.V. (2021). Biodiversity centers as structural elements of the ecological network of the city of Kremenchuk. Ecologically balanced development of society: state, problems, prospects: scientific and methodological publication. – Vinnytsia: KZVO «Vinnytsia Academy of Continuing Education», 2021. P. 23-28.

13. Kazimirova L. P., Mironova N. G., Mateyuk O. P., Ilyinsky S. V. Nature Reserve Fund and Ecological Network of the City of Khmelnytsky and Their Role in Preserving Biotic and Landscape Diversity. Scientific Reports of the National University of Sciences of Ukraine, 4 (98). http://dx.doi.org/10.31548/dopovidi2022.04.004

14. Denisyk, G. I., Yatsentiuk, Y. V., Vorovka, V. P., & Volovyk, V. N. (2021). Biocenters of the ecological network of the city of Vinnytsia. Bulletin of the V. N. Karazin Kharkiv National University. Series «Geology. Geography. Ecology», (54). P. 267-277. https://doi.org/10.26565/2410-7360-2021-54-20

15. Kuzyk, I. R., & Tsaryk, L. P. (2020). Geoecological assessment of the structure of the complex green zone of the city of Ternopil and its optimization. Man and Environment. Problems of Neoecology, (34), 8-18. https://doi.org/10.26565/1992-4224-2020-34-01

16. Koniakin, S. M., Burda, R. I., & Budzhak, V. V. (2024). The dynamics of the taxonomic composition of the alien fraction of the urban flora in the Kyiv urban area, Ukraine. Environmental & Socio-economic Studies, 12(2), 62-82. https://doi.org/10.2478/environ-2024-0013

UDC 504.06:631.41:662.75
https://doi.org/10.31073/ecobezpeka202507-11

IMPACT OF SPACE LAUNCHES ON THE ENVIRONMENT

Kotsiubynskyi A. O., Hrytsulyak H. M.,
Yatsyshyn T. M. Lynnyk D. O.,
Ivano-Frankivsk National University of Oil and Gas

In the past, the environmental impact of the space industry has been overlooked. The main reason for this is the small number of large rocket launches per year. But today, the dynamics of growth in the number of launches is impressive - from 114 in 2018 to 222 space launch attempts (211 of which were successful) in 2023. The aim of the study is to assess the impact of space launches on the environment. Each launch of a large rocket brings not only great benefits, both scientific and practical, but also a significant amount of emissions. At the same time, different types of rockets have different environmental impacts. In addition to the impact of spent rocket stages and debris falling into remote areas, oceans, or densely populated areas, there is a negative impact on the atmosphere. All rockets use fossil fuels and emit carbon dioxide and water. But some types of engines are more environmentally acceptable than others. Current research shows that kerosene-fueled rockets and some types of hybrid engines emit significant amounts of black carbon. At the same time, the amount of black carbon emitted by such rockets is already comparable to the amount of soot emitted by the entire aviation industry. Rocket fuel residues contain toxic compounds that have a negative impact on the environment. Therefore, the development of environmentally friendly fuels, such as methane or hydrogen, is becoming increasingly important. Another type of impact on the atmosphere is the destruction of the ozone layer. High temperatures during rocket flight lead to the formation of large amounts of nitrogen oxides, which can destroy ozone in the stratosphere. The destruction of the ozone layer is a global environmental problem with serious consequences for the environment. The current state of the industry does not have a large-scale impact on climate change. However, looking to the future, the dynamics of the growth in the number of launches indicates the need for environmental regulation.

Keywords: Environment, ozone layer, emissions, air pollution, rocket engine

Problem statement

The space industry is one of the fastest growing industries in the world today. Revenue from this industry is projected to grow from $350 billion in 2019 to over $1 trillion and is expected to reach $2.7 trillion by 2045 [18].

This huge demand is due to many factors: lower launch costs due to commercialization, increasing dependence on satellite technology for GPS, surveillance, and broadband internet. The issue of the militarization of space remains open. In this regard, new space launch and rocket production centers are emerging around the world. In addition, 2021 can be considered the beginning of commercial spaceflight and space tourism [5]. Thus, the space industry is growing rapidly, but it also has a significant impact on the environment.

As the number of rocket launches grows annually, there is a need to adapt the regulatory system as the industry is subject to change. An increase in the number of launches can lead to an increase in negative environmental impact, in particular, even a small increase in the number of launches compared to current levels can have serious environmental consequences [6]. At the same time, the CEO of SpaceX said that the ultimate goal of Starship development is to launch up to three times a day, which is equivalent to about 1000 flights a year. Therefore, regulatory authorities should anticipate the negative consequences of such a number of launches and take appropriate action. The purpose our work is an analysis of the assessment of the possible negative impact of space launches on the environment.

Analysis of the latest research and publications

Space rocket launches have a significant impact on the environment in several key ways:

During rocket launches, various chemicals are released into the atmosphere, including aluminum oxide, hydrogen chloride, soot, and other compounds, depending on the type of fuel. These emissions can cause acid rain, increase the concentration of suspended particles in the air, and change weather conditions in the areas surrounding the launch sites. Particularly dangerous are soot emissions in the upper atmosphere, as they can persist for several years and have a significant greenhouse effect that is hundreds of times greater than the impact of similar emissions on the earth's surface.

Some combustion products of rocket fuel, such as nitrogen oxides and chlorine, can interact with the ozone layer, causing its destruction. This increases the level of ultraviolet radiation reaching the Earth's surface and can negatively affect human health and ecosystems.

In the areas where separating parts of missiles fall, soil contamination with rocket fuel residues and structural fragments is observed. This can lead to the accumulation of toxic substances in the soil, which can be absorbed by plants and, ultimately, by animals and humans. In addition, mechanical contamination by solid fragments can reduce crop yields [2].

Rocket fragments and inoperable satellites left in orbit create space debris that poses a threat to existing spacecraft and future missions. With the increasing number of launches, this problem is becoming more and more urgent. As of 2023, there are more than 23,000 objects of space debris larger than a softball in Earth's orbit, as well as more than 100 trillion untraceable smaller particles.

The use of nuclear power sources on spacecraft carries the risk of radioactive contamination in the event of accidents or uncontrolled reentry of such vehicles to Earth. This can cause significant damage to both the environment and human health [3].

The growing intensity of space activities requires the development and implementation of international standards and measures aimed at minimizing the negative impact on the environment. This includes the use of environmentally friendly fuels, the development of technologies to reduce space debris, and effective management of the life cycle of spacecraft. It is also necessary to systematically monitor and assess environmental risks associated with space activities to ensure sustainable development and environmental protection.

Analysis of the latest research and publications

A thorough analysis of scientific articles, technical reports and reviews covering the impact of various types of rocket fuel on the atmosphere, soil, water resources and the ozone layer was conducted. The main focus was on research on pollutant emissions, mechanisms of ozone depletion, and accumulation of toxic substances in soil and water. The sources used include the works of the authors [1, 2, 7, 8, 11, 16, 17].

The types of rocket fuel were systematized and classified, including solid, liquid, hybrid, and hydrogen. Each type of fuel was evaluated in terms of its chemical

To quantify the impact of launches, data on the number of launches in 2019 and associated emissions (H_2O, CO_2, NO_x, Al_2O_3, Cl_2) were used. The modeling results obtained from previous studies [15,12], made it possible to assess how emissions from launches affect the ozone layer and global climate.

The impact of chemical fuel residues and mechanical debris in the areas where rocket parts fall on soils and water bodies was analyzed. Particular attention is paid to spaceports in Kazakhstan, the United States, French Guiana, and other regions with high launch activity.

An analysis of the amount of space debris generated over the period 1957-2019 was carried out. The data was obtained from international databases and compared between the leading countries in terms of the number of launches [17].

Best practices and strategies for reducing the environmental impact of rocket launches, including the use of «green» hydrogen, the development of biofuels.

Determining the goals of the article (task statement)

The aim of the study is to assess the environmental impact of space launches.

Summary of the main research material

In just 40 years, rocket and space activities have created serious problems by polluting the earth's surface, atmosphere, and near-Earth space [17]. In this regard, it becomes extremely important to objectively assess all areas of negative impact of rocket and space activities.

The first obvious pollutant is space debris. Table 1 shows the countries that have been most active in space activities. Between 1957 and 2019, 5912 launches were carried out. The most active suppliers of space debris are Russia, the United States, and China, which account for 90.5% of all space debris [17].

Another environmental impact factor is emissions from rocket engines. Although modern engines

Table 1

Amount of space debris for the period from 1957 to 2019 by country

№	Countries, regions	Number of polluting objects space
1	Russia	6075
2	USA	4867
3	China	3623
4	Europe	367
5	India	174
6	Japan	183
7	Other countries	605
	Total:	**16094**

Table 2

Types of rocket engines in use today

Engine type	Fuel	Advantages	Disadvantages
Liquid rocket engines	Liquid fuel (hydrogen, oxygen, kerosene, liquid nitrogen) and oxidizer	High traction, high efficiency, possibility of adjustment of traction	Complexity, high cost
Solid rocket engines	Solid fuel (based on polyurethane or nitrocellulose)	Simplicity, reliability, low cost	Low traction, inability to adjust traction
Hybrid rocket engines	Liquid fuel and solid oxidizer	Combines the advantages of RRD and TRTD: high traction, reliability, adjustable traction	Complexity, high cost
Nuclear rocket engines	Nuclear fuel (uranium rod)	Potentially the highest thrust, the ability to fly long distances	Very difficult, expensive, dangerous, ethical issues

are capable of operating with high efficiency in converting fuel energy into thrust, they are extremely inefficient from an environmental point of view [9]. Toxic rocket fuel has a catastrophic impact on the environment. It pollutes the upper atmosphere, where the accumulation of combustion by-products leads to the loss of the ozone layer [3]. Table 2 shows the different types of engines in use today.

Most of the air pollution comes from the propellant and oxidizer used in the various stages of a rocket launch. The four main classes of rocket fuel that are most commonly used include kerosene, hyperbolic fuel, liquid hydrogen (cryogenic), and solid fuel [14]. The combustion of these fuels releases various pollutants into the atmosphere, such as water vapor, nitrogen oxides, black carbon, and particulate matter. It is important to note that these pollutants also contribute to the depletion of the ozone layer through gas-phase reactions or activation of chlorine in the atmosphere [13].

Figure 1 shows the locations of all 127 documented rocket launches in 2019, dominated by China (34 launches), Kazakhstan (22), Russia (22), and US-led launches in the United States (21) and New Zealand (6). Others include launches by the European Space Agency (ESA) from French Guiana (9), Iran (5), and launches in India (6) and Japan (2) by their respective space agencie. Shares by weight of the four main fuels (kerosene, hypergolic, liquid hydrogen, and solid propellants) used in each country [15].

Solid propellants dominate launches from Japan, India, and French Guiana. Hypergolic fuels are typical for China, Kazakhstan, and Iran. Kerosene is the dominant fuel for launches in New Zealand, Russia, and the United States. The total amount of rocket fuel used in 2019 was 32 Gg and included 45% kerosene, 32% hypergolic, 14% solid and 8% liquid hydrogen [10].

Figure 2 shows the mass of each pollutant emitted in 2019 within the model's altitude range. This includes the combustion of fuel in the booster and first stage of the rocket, as well as from re-entry heating. The relative mass of each emitted component is the same for each month. Emissions from the booster and first stage of the rocket, which occur within the altitude limits of GEOS-Chem, account for the majority of total emissions from all stages: 80% for NOx, 94% for Al_2O_3 and HCl + Cl, 84% for H_2O and

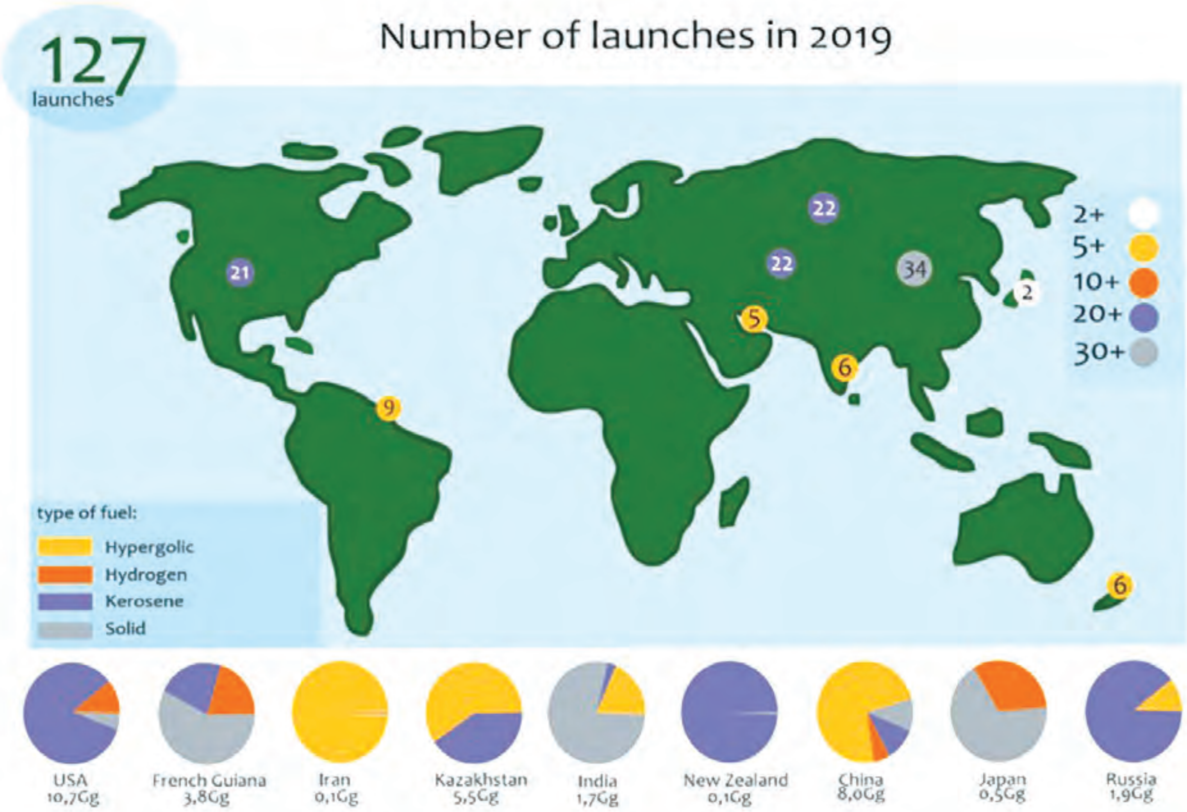

Figure 1. Locations of rocket launches in 2019 and pie charts.

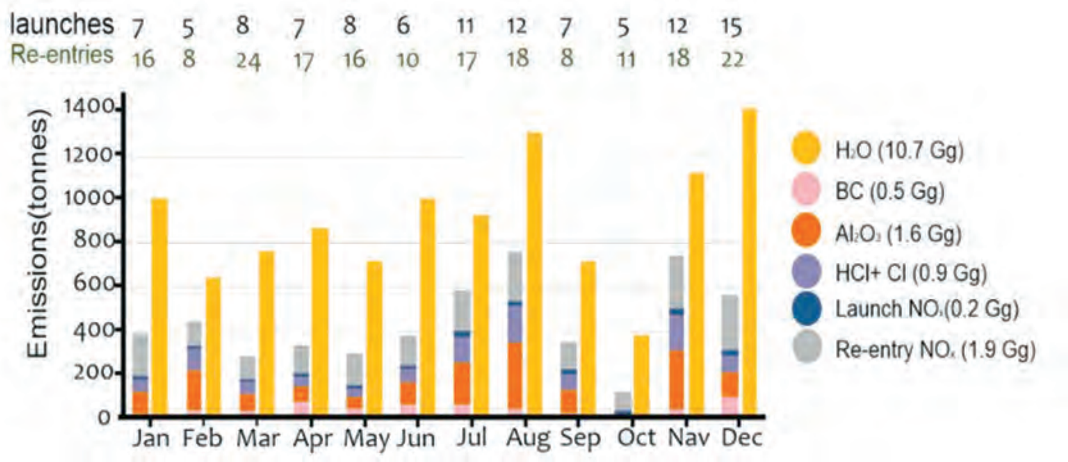

Figure 2. Mass of pollutants emitted in 2019 in the world

79% for BC. The amount of emissions above 15 km is 78%-79% for H_2O and BC, and 68%-69% for Cl and Al_2O_3 [12].

Different types of fuels have different environmental impacts, depending on their chemical composition and combustion processes.

Solid propellants, which are commonly used in rockets, have a significant negative impact on the environment. Its combustion is accompanied by emissions of greenhouse gases such as CO_2 and particulate matter, and emissions of nitrogen oxides (NOx) and chlorine oxides (HCl) contribute to the destruction of the ozone layer and the formation of acid rain [7].

Liquid fuels, such as kerosene, jet fuel, or liquid hydrogen, have a lower environmental impact. It produces fewer greenhouse gases than solid fuels, but it can still pollute the atmosphere with particulate matter. There is also a risk of liquid fuel leakage, which can lead to serious soil and water pollution [1].

Hybrid fuels, which combine elements of solid and liquid fuels, have a lower environmental impact because they produce fewer greenhouse gases and particulate matter. However, chemical washout from rocket launch sites, noise, and debris from launches can still have a negative impact on the environment [8].

Hydrogen is considered to be one of the most environmentally friendly rocket fuels because it does not generate greenhouse gases during combustion. However, hydrogen production can have a negative impact on the environment, depending on the method used. Speaking of green hydrogen, it is the only type of fuel that has an environmental perspective [16].

While solid propellants are efficient for certain types of rockets due to their stability and high energy density, their combustion significantly contributes to environmental degradation. Besides the direct emission of greenhouse gases (GHG) such as CO_2, the particulate matter released during combustion can contribute to air pollution and climate change. Nitrogen oxides (NO_x) and chlorine-based compounds like HCl from solid propellants are particularly damaging to the ozone layer, accelerating its depletion. The accumulation of these pollutants can also lead to regional ecological disturbances, including acidification of soils and water bodies.

Liquid fuels, including kerosene and liquid hydrogen, are widely used due to their relatively lower GHG emissions compared to solid fuels. However, the environmental risks associated with liquid fuels primarily stem from their handling and storage. Leakage of these fuels into the environment can lead to soil contamination and water pollution, severely impacting local ecosystems. For instance, kerosene spillages can destroy vegetation and aquatic life due to its toxicity. Moreover, while liquid hydrogen combustion produces water vapor, its production process, often reliant on fossil fuels, can result in significant GHG emissions unless green hydrogen methods are employed.Hybrid rocket fuels, which utilize a combination of solid and liquid components, represent a middle ground in terms of environmental impact. These fuels offer reduced GHG emissions compared to solid fuels and generate less particulate matter. Despite this advantage, the environmental consequences of hybrid fuel usage are not entirely negligible. Noise pollution from launches, chemical runoff from fueling stations, and debris from rocket components can disrupt local biodiversity and ecosystems near launch sites [9].

Hydrogen, especially green hydrogen derived from renewable energy sources, holds great promise as a sustainable rocket fuel. During combustion, hydrogen produces only water vapor, making it a clean alternative to traditional fuels. However, the environmental footprint of hydrogen depends heavily on its production method.

Conventional hydrogen production through steam methane reforming generates considerable CO_2 emissions unless carbon capture technologies are employed. On the other hand, green hydrogen, produced through electrolysis powered by renewable energy, offers a truly sustainable and environmentally friendly option. Nonetheless, challenges such as storage, transportation, and the high cost of production need to be addressed for broader adoption in the aerospace industry.

Regardless of the type of fuel used, space launches have several secondary environmental impacts. These include: the intense heat generated during launches can damage nearby vegetation and soil, while shock waves can disrupt wildlife and ecosystems; residual fuels and oxidizers can contaminate soil and water around launch sites; the proliferation of space debris from launches poses a long-term challenge, not only for future space missions but also for atmospheric re-entry, which can release toxic substances; rocket launches generate extreme levels of noise, which can disrupt human and animal populations in the vicinity.

Future Directions to mitigate the environmental impacts of rocket launches, research and development efforts are focusing on: developing cleaner fuels, such as bio-derived rocket fuels or advanced forms of green hydrogen; improving the efficiency of rocket engines to minimize fuel consumption and emissions; implementing stricter environmental regulations for rocket manufacturing, fuel production, and launch site management; investing in technologies to capture and neutralize emissions at launch sites; designing reusable rockets to reduce waste and debris associated with single-use components.

The transition toward more sustainable space exploration practices is critical to balancing humanity's scientific ambitions with the responsibility to protect Earth's environment.

Destruction of the ozone layer and its connection with the flight of large rockets. The Earth's ozone layer, located in the stratosphere, protects us from the sun's harmful ultraviolet (UV) radiation. This layer consists of ozone (O_3), which is destroyed by active catalysts such as nitrogen oxides (NOx), chlorine oxides (Clx), bromine oxides (Brx), and hydroxyl radicals (OH) [11]. The exhaust gases from rocket launches, regardless of the type of fuel (Fig. 2), contain NOx, OH and H_2O, which also destroy ozone. Ozone loss can be localized, within the exhaust plume, or global, reducing the ozone concentration in the entire ozone layer [17].

In general, the impact of different catalysts on ozone depletion can be distinguished. NOx: Catalytically destroys ozone molecules in the stratosphere. Sources: launch vehicles (mainly Russian and Chinese), airplanes (UDMH/N2O4). Impact: 10 Proton launches: 0.00012% annual ozone reduction. Actual losses (2000-2009): 0,00016%. Largest contributors: Russian and Chinese missiles. Contribution of the US Air Force: insignificant (0.0000005%) [2].

Clx: Catalytically destroy ozone molecules in the stratosphere. Sources: Solid rocket engines (mostly perchlorate-based). Impact: 816 tons of Clx annually: 0.052% of annual ozone decrease at 60°N, 0.017% at 30°N. Actual losses (over 20 years): 0.14%. Largest contributor: US missiles (23.5% over 20 years). Contribution of the US Air Force after 2003: 5,4%. Future projections: 0.0004(3) % annual ozone decrease [1]. Al_2O_3: Photochemical process: Al_2O_3 reacts with chlorine to form Clx. Sources: Solid rocket engines. Impact: 1120 tons of Al_2O_3 annually: 0.004% annual ozone depletion. Actual losses (over 10 years): 0.004%. Contribution of the US Air Force: 0,0005% (2006-2008) [14]. H_2O: Negligible impact, indirectly through NOx. Sources: launch vehicles (mainly Proton). Impact: 628 tons of H_2O annually: 0.00001% annual ozone reduction. Although the impact of some substances, such as H_2O, may be negligible, the overall impact of rocket launches on the ozone layer needs to be carefully studied and monitored. [2].

Conclusions and prospects for further research. Space exploration has become a milestone in human history, providing access to satellite maps, television, and other technologies that are now an integral part of our lives. However, the development of the space industry has significant environmental consequences that require immediate attention. Every space launch is accompanied by emissions of pollutants that have a negative impact on the environment, including ozone depletion, climate change, acid rain, and an increase in space debris.

Research shows that the growing number of space launches increases emissions of black carbon, nitrogen oxides, water vapor, and other pollutants that contribute to ozone depletion and global climate change. Particularly dangerous are solid fuel and kerosene rockets, which produce high levels of pollution and have a significant impact on the environment. In addition, the accumulation of space debris poses additional risks to the Earth's ecosystem and the functioning of spacecraft.

Ozone depletion and climate change pose a serious threat to human life on Earth. The consequences of these phenomena can be unpredictable, including an increase in the level of ultraviolet radiation, which negatively affects human health, agriculture and ecosystems in general. Therefore, there is an urgent need to develop strategies aimed at reducing the negative impact of space activities.

The main measures to minimize environmental risks are: development of more environmentally friendly rocket engines, in particular based on «green» hydrogen, which does not produce greenhouse gases; reducing the frequency of launches by optimizing launches and commercializing space technologies; implementing strict regulatory standards to limit emissions and monitor their environmental impact; investing in research into methods to restore the ozone layer and combat climate change.

Sustainable development of the space industry is possible only if environmentally friendly approaches are integrated into all aspects of its operation. Implementation of such measures will not only minimize the environmental impact of space launches, but will also help preserve the Earth's ecosystem for future generations.

References

1. Casiano M. J., Hulka J. R., Yang V. Liquid-Propellant Rocket Engine Throttling: A Comprehensive Review // Journal of Propulsion and Power. 2010. Vol. 26, No. 5. P. 897–923. DOI: 10.2514/1.49791.

2. Dallas J. A., Raval S., Gaitan J. A., Saydam S., Dempster A. G. The Environmental Impact of Emissions from Space Launches: A Comprehensive Review // Journal of Cleaner Production. 2020. Vol. 255. P. 120209. DOI: 10.1016/j.jclepro.2020.120209.

3. Emrich Jr W. J. Principles of Nuclear Rocket Propulsion. Elsevier, 2023. DOI: 10.1016/C2015-0-06198-0.

4. Glibovytska N. I., Yatsyshyn T. M., Gritsylak G. M. Application of Environmental Biomonitoring in Environmental Risk Management of the Fuel and Energy Complex // IOP Conference Series: Earth and Environmental Science. 2020. Vol. 1254, No. 1. P. 012111. DOI: 10.1088/1755-1315/1254/1/012111.

5. Go H., Kang M. Metaverse Tourism for Sustainable Tourism Development: Tourism Agenda 2030 // Tourism Review. 2023. Vol. 78, No. 2. P. 381–394. DOI: 10.1108/TR-03-2022-0123.

6. Grewal S. S. Towards a Martian Vernacular: Closed-Worlds and Infrastructures of Social Connectivity : Doctoral dissertation. Carleton University, 2022. DOI: 10.22215/etd/2022-14512.

7. Kalyon D. M., Yaras P., Aral B., Yilmazer U. Rheological Behavior of a Concentrated Suspension: A Solid Rocket Fuel Simulant // Journal of Rheology. 1993. Vol. 37, No. 1. P. 35–53. DOI: 10.1122/1.550401.

8. Karabeyoglu M., Cantwell B., Altman D. Development and Testing of Paraffin-Based Hybrid Rocket Fuels // 37th Joint Propulsion Conference and Exhibit. 2001. P. 4503. DOI: 10.2514/6.2001-4503.

9. Kushnirenko A. G., Stamov L. I., Tyurenkova V. V., Smirnova M. N., Mikhalchenko E. V. Three-Dimensional Numerical Modeling of a Rocket Engine with Solid Fuel // Acta Astronautica. 2021. Vol. 181. P. 544–551. DOI: 10.1016/j.actaastro.2021.01.011.

10. Pang F., Qin Y., Li H., Teng Y., Gong Q., Wang S. Study on Impact Resistance of Composite Rocket Launcher // Reviews on Advanced Materials Science. 2021. Vol. 60, No. 1. P. 615–630. DOI: 10.1515/rams-2021-0045.

11. Parson E. A. Protecting the Ozone Layer: Science and Strategy. Oxford: Oxford University Press, 2003. DOI: 10.1093/0195155491.001.0001.

12. Popp P. J., Ridley B. A., Neuman J. A., Avallone L. M., Toohey D. W., Zittel P. F., Danilin M. Y. The Emission and Chemistry of Reactive Nitrogen Species in the Plume of an Athena II Solid-Fuel Rocket Motor // Geophysical Research Letters. 2002. Vol. 29, No. 18. P. 34-1. DOI: 10.1029/2002GL014810.

13. Ross M., Toohey D., Peinemann M., Ross P. Limits on the Space Launch Market Related to Strato-

spheric Ozone Depletion // Astropolitics. 2009. Vol. 7, No. 1. P. 50–82. DOI: 10.1080/14777620902768867.

14. Ross M., Vedda J. The Policy and Science of Rocket Emissions. Center for Space and Policy Strategy, 2018. DOI: 10.13140/RG.2.2.36492.62088.

15. Ryan R. G., Marais E. A., Balhatchet C. J., Eastham S. D. Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate // Earth's Future. 2022. Vol. 10, No. 6. P. e2021EF002612. DOI: 10.1029/2021EF002612.

16. Silvera I. F., Cole J. W. Metallic Hydrogen: The Most Powerful Rocket Fuel Yet to Exist // Journal of Physics: Conference Series. 2010. Vol. 215, No. 1. P. 012194. DOI: 10.1088/1742-6596/215/1/012194.

17. Sirieys E., Gentgen C., Jain A., Milton J., Weck O. Space Sustainability Isn't Just About Space Debris: On the Atmospheric Impact of Space Launches // MIT Science Policy Review. 2022. Vol. 3. P. 143–151. DOI: 10.38105/spr.15.1.

18. Spector S., Higham J. E., Gössling S. Extraterrestrial Transitions: Desirable Transport Futures on Earth and in Outer Space // Energy Research & Social Science. 2020. Vol. 68. P. 101541. DOI: 10.1016/j.erss.2020.101541.

19. Yatsyshyn T. Global climate changes: factors of intensification and methods of their detection // Book of Abstracts of the 6th KGK Space Resources Conference, May 15-16, 2023. Krakow: AGH University of Krakow, 2023. P. 32. URL: http://www.kgk.agh.edu.pl/wp-content/uploads/2023/06/KGK2023-Book-of-abstracts.pdf.