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THE IMPACT OF FOREST FIRES IN THE CONTEXT OF CLIMATE CHANGE: AN INTERDISCIPLINARY ANALYSIS

The object of the study is forest fires as a complex natural and social phenomenon that encompasses ecological, climatic, technological and management aspects of their occurrence, spread and consequences for ecosystems and society. Forest ecosystems are a complex natural system that plays a key role in economic activity, biodiversity conservation, climate regulation and the carbon cycle. One of the most problematic areas is the increasing frequency and scale of forest fires caused by both natural and anthropogenic factors, as well as the lack of an integrated approach to analyzing, forecasting and managing this phenomenon. The study used the method of an interdisciplinary literature review with a focus on key concepts: "forest fires", "fire spread", "anthropogenic impact", "modelling", "carbon cycle", "environmental consequences". The analysis of publications and clustering of topics in a term-oriented environment to identify structural links between scientific areas made it possible to obtain a qualitative typology of approaches to the study of forest fires, which includes: analysis of natural and social determinants, modelling of fire spread, assessment of environmental damage, impact on climate processes and development of prevention systems. This is due to the fact that the proposed approach covers a wide range of risk factors, allows for ecosystem specificity and emphasizes the need for interdisciplinary management. This makes it possible to develop effective strategies for climate change adaptation, increase ecosystem resilience and improve fire prevention systems. The proposed structure of the review provides a holistic view of the problem and identifies priorities for further research in the field of environmental safety and natural resource management.

Keywords: *forest fires, ecosystem, climate change, modelling, management, anthropogenic factors.*

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1. Introduction

Forests are important natural resources that contribute to economic activity and have a significant impact on climate regulation and the carbon footprint cycle. In recent decades, fires in natural ecosystems, including forests and rangelands, have become a significant threat. The study of fires in natural ecosystems requires an integrated approach that includes analysis of natural and anthropogenic factors, modelling of fire spread, assessment of consequences and development of prevention measures. The methodology should take into account the multifactorial nature of the process of fire occurrence and spread, as well as the specifics of ecosystems.

The geography of wildfire research is extremely wide, covering all corners of the world United States [1], Spain [2, 3], California [4, 5], India [6–8], Portugal [9], Central Himalayas [10], Nepal [11], Northern Thailand [12], Bangladesh [13], Iran [14], Jasper Park Canada [15, 16], Eastern Serbia, Latvia [17, 18], Southern Sweden, Australia [19], Brazil [20].

The problem of forest fires is attracting the attention of scientists in many countries, which indicates its relevance at the global level. In the United States [1], wildfires are seen as a result of climate change and human activity that threatens the sustainable management of forest ecosystems. The authors have developed a system for inventorying emissions from wildfires in the United States, which allows for an accurate assessment of carbon emissions. This is important for the fight against climate change. In Spain [2, 3], the emphasis is on changing the structure of land use and its impact on the frequency of fires. A study [2] showed that the composition of tree species affects the degree of damage to forests during fires. Species diversity reduces vulnerability. In the Mediterranean forests, the recurrence of fires is due to post-fire vegetation dynamics and the location of the areas [3]. In the state of California [4, 5], there is a link between urbanization, droughts, and a sharp increase in fire danger. A comparison of fire and mechanical forest management showed that they support different parts of bird populations, which is important for biodiversity conservation [4]. Predictability of conifer recovery after severe fires in dry forests has been revealed [5]. Indian studies [6–8] highlight shortcomings in the early warning and response system. The frequency of fires affects the structure of tropical deciduous forests in Central India, which can alter ecosystem functions [6]. The fire in Uttarakhand is leading to significant losses of carbon stocks in forests, which is damaging the global climate [7]. A study [8] identified the reasons for the increase in the number of fires and suggested ways to mitigate them, including through better forest management. Portugal [9] focuses on the challenges of managing forest resources in the face of frequent forest fires. In the Central Himalayas, fires are caused by human impact and climate change, and proposed measures include the involvement of local communities [10]. In Nepal's alpine coniferous forests, fires change soil properties, which slows down ecological regeneration [11]. In northern Thailand [12] and Bangladesh [13], the lack of integrated approaches to fire prevention is highlighted. Intelligent models and

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satellite imagery have successfully predicted the risk of fires in the Iranian Gorkha forests [14]. Changes in fire regimes have led to homogeneity of forests in Jasper Park, which reduces their resilience [15]. It has been shown that soil thermal regimes affect the frequency of fires, which should be taken into account in forest management [16]. The effects of fire in a Sphagnosa ecosystem include changes in vegetation and hydrology [17]. In Scandinavia, historical fires in oak-dominated forests were of low intensity, did not destroy oaks with tree canopy, and yet provided a window of opportunity for the regeneration of this species [18]. In Southern Sweden and Australia, the impact of climate change on wildfire dynamics is being analyzed. Koala habitat recovery after fires depends on fire intensity [19]. In Brazil [20], the emphasis is on the role of fires in changing forest cover, and the recovery of plants afterwards depends on environmental conditions.

In the context of global climate change, forest fires are becoming more frequent, intense and uncontrolled, leading to significant biodiversity loss, ecosystem degradation, air quality degradation, social damage and accelerated climate change due to carbon emissions. Despite a growing body of research, there is no holistic interdisciplinary overview that systematically integrates the environmental, technical, governance and climate aspects of this phenomenon. This fragmentation of knowledge makes it difficult to develop effective response and adaptation strategies.

Thus, the problem is the need to systematize current scientific approaches to the study of forest fires in order to identify key challenges, scientific gaps and areas for integrated risk management in the context of climate change.

Forest fires are a serious environmental problem that significantly impacts natural ecosystems [21], causing significant damage to vegetation, fauna and soils. Their consequences include reduced biodiversity, land cover degradation, deterioration of air quality and climate change due to greenhouse gas emissions. Fire causes fall into two main categories: natural and anthropogenic.

Natural fire drivers include lightning, which is often the source of ignition in dry and arid regions. In such regions, high temperatures and low humidity create favorable conditions for the spread of fire. Lightning can ignite dry vegetation, which acts as fuel for fires. In addition, the natural process of spontaneous combustion of certain types of plant material, such as peat, can also cause fires, especially in conditions of prolonged drought.

Another natural factor is seasonal winds, which can contribute to the rapid spread of fire. For example, in many parts of the world, strong hot winds blow flames over long distances, making them difficult to control.

Human activity is the main source of forest fires. Despite the natural risks, a significant proportion of fires are caused by human negligence or intentional actions. The most common causes include:

– setting fire to dry vegetation, agricultural work, making fires or burning garbage often gets out of control and turns into large-scale fires. This is especially true in the spring and autumn, when dry grass is highly flammable;
– deliberate arson. In some cases, fires are caused by mercenary motives, such as clearing land for agricultural purposes, mining, or even creating conditions for building up the territory;
– power outages, explosions or leaks of combustible materials can also cause fires, especially in forested areas;
– unattended fires, cigarette butts or even improper use of equipment during outdoor recreation are an additional risk factor.

Forest fires cause enormous damage to vegetation. High temperatures destroy trees, shrubs and grasses, leaving behind scorched landscapes. Some plant species die completely, especially if they do not have adaptations to fire. At the same time, other species, such as eucalyptus or pine trees [22], can survive the fire or even use it as part of their natural cycle by promoting seed germination.

In addition to the physical destruction of plants, fires change the composition and structure of ecosystems. The burning of the organic layer of the soil reduces its fertility and causes erosion, which makes it difficult to regenerate vegetation. In the long term, this can lead to the transformation of forests into semi-deserts or other degraded landscapes.

The aim of research is an interdisciplinary analysis of scientific approaches to the study of forest fires, their impact on ecosystems, climate and human health in order to identify knowledge gaps and generalize effective management practices.

2. Materials and Methods

The object of research is forest fires as a complex natural and social phenomenon that encompasses ecological, climatic, technological and managerial aspects of their occurrence, spread and consequences for ecosystems and society. The article uses an interdisciplinary approach based on a systematic review of scientific sources on the problem of forest fires. The methodological basis is a bibliographic analysis of modern research using key terms such as "forest fire", "biodiversity", "modelling", "climate", "management", "health impact", etc. The VOSviewer software was used to structure and visualize the scientific discourse, which made it possible to identify key thematic clusters and determine the dominant research areas. Based on the analysis of the thematic clusters, the authors summarized knowledge about the impact of wildfires, risk management practices and opportunities for climate change adaptation. At the stage of analyzing bibliographic links and semantic classification of terms, the authors used auxiliary functions of artificial intelligence, in particular for clustering, pre-processing of literature sources and semantic analysis, in strict accordance with the requirements of academic integrity. All the data obtained was carefully checked and interpreted manually to ensure scientific accuracy and validation of the results. Thus, the use of AI technologies played the role of an analytical support tool, but did not replace expert opinion. The results presented in this article are based on verified sources, and the interpretations are those of the author.

3. Results and Discussion

Forest fires are a complex and multifactorial phenomenon caused by both natural processes and human activity [23, 24]. They pose significant risks to ecosystems, especially to vegetation, which is the basis of many natural processes. To minimize the damage, it is necessary to implement fire prevention measures, such as controlling human activity [25], monitoring fire-prone areas, and introducing modern technologies for rapid fire detection.

The keyword "fire" is located in the center and is the central element of the visualization, around which the other terms are grouped (Fig. 1).

The differently colored clusters represent different thematic areas of research related to forest fires:

– *red cluster*: terms related to the ecological impacts of fires (e. g., "disturbance", "biodiversity", "patterns");
– *blue cluster*: technical aspects, modelling and forecasting (e. g., "wildland fire", "model", "classification");
– *green cluster*: ecosystems and management (e. g., "restoration", "management", "habitat");
– *yellow cluster*: climate aspects and carbon impacts (e. g., "carbon", "climate", "deforestation");
– *purple cluster*: health impacts and chemical aspects (e. g., "emissions", "particulate matter", "smoke").

The relationships between the terms in the VOSviewer visualization (Fig. 1) demonstrate how different aspects of wildfire research interact with each other. "Fire" is the core of the entire network, as it has the highest number of connections to other terms. It is connected to terms in different clusters, which emphasizes the interdisciplinary nature of fire research. Red cluster have links to "disturbance", "biodiversity", "patterns", "habitat". Yellow cluster have links to "climate", "carbon", "deforestation", "emissions". Blue cluster have links to "model", "wildland fire", "classification", "risk". Purple cluster have links to "smoke", "emissions", "particulate matter", "health".

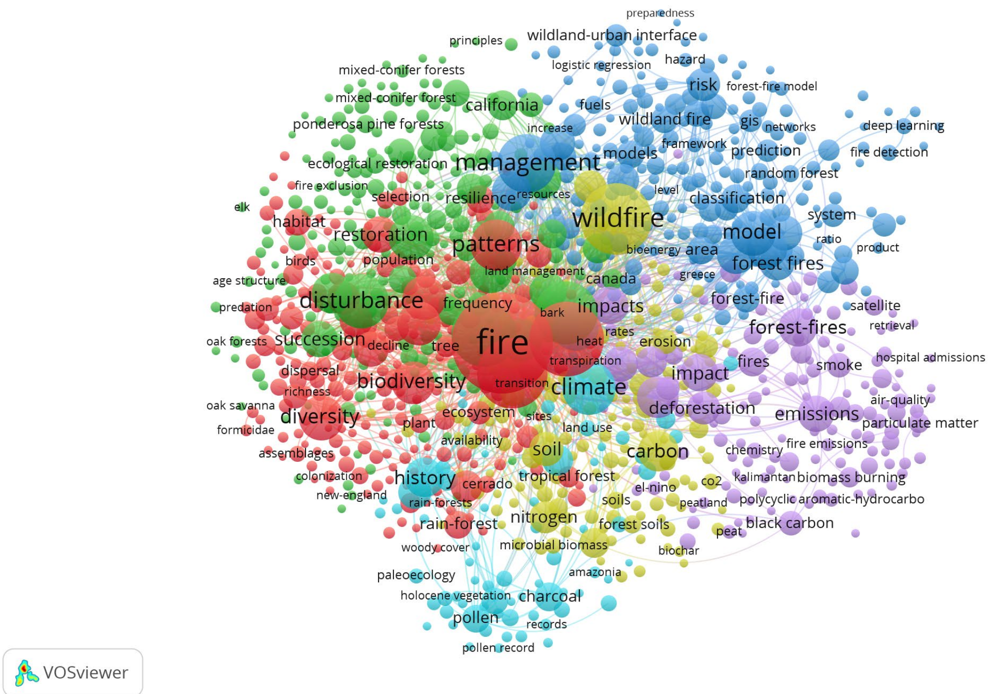

Fig. 1. Relationships between terms in a visualization in VOSviewer

There are also links within the clusters. Red cluster (ecosystems and restoration) "disturbance" has close links with "biodiversity", "succession", "diversity", because wildfires as ecological disturbances change biodiversity by initiating succession processes; "habitat" and "restoration" are interconnected with "resilience" and "population", which indicates how fires change habitats and how ecosystems recover from them. Blue cluster (technology and forecasting) "model" is related to "prediction", "classification", "GIS", "deep learning", as fire modelling depends on artificial intelligence, geographic information systems and data classification technologies; "risk" is related to "wildland fire", "hazard", "management", which indicates the fact that fire risk analysis helps to effectively manage landscapes. Yellow cluster (climate and emissions) "climate" and "carbon" have links to "deforestation", "emissions", "impact", as climate change increases fire intensity, and fires in turn increase greenhouse gas emissions; "soil" and "nitrogen" are linked to "land use" and "biomass burning", which indicates changes in soil properties by fire, the nitrogen cycle and land use. Purple cluster (impact on air quality and health) "emissions" and "smoke" have strong links with "particulate matter", "air quality", "black carbon", as smoke from fires significantly worsens air quality and contains toxic particles such as black carbon; "health impact" and "hospital admissions" are interconnected with "pollution", which confirms the impact on human health.

There are also links between clusters (Fig. 2):

– between the red and yellow clusters: the term "climate" from the yellow cluster is linked to "patterns", "disturbance" and "biodiversity" from the red cluster, indicating the impact of fires on climate and ecosystems simultaneously;

– between the blue and purple clusters: "model" from the blue cluster is linked to "smoke" and "emissions" from the purple cluster, highlighting the importance of modelling to predict the impact of fires on air quality;

– between the yellow and purple clusters: the link between "carbon", "emissions" and "health impact", as fires generate CO_2 emissions, which contribute to global warming, and also pollute the air, affecting human health;

– between the red and blue clusters: the term "management" from the green cluster is linked to "risk" and "model" from the blue cluster, emphasizing that forest management is based on risk assessment and fire forecasting.

Central themes: "fire", "climate", "emissions", "management" unite all the clusters, demonstrating the interconnectedness between environmental, climate, technical and management aspects.

Based on the analysis of visualization and key relationships (Fig. 3), promising areas of research in the field of forest fires can be identified in several main directions:

1. *Use of innovative technologies for fire monitoring and forecasting* (integration of satellite data and artificial intelligence, development of early warning systems).
2. *Research on the impact of forest fires on climate change* (analysis of greenhouse gas emissions, interaction between fires and the carbon cycle, analysis of long-term impact on climate processes).
3. *Study of the impact of fires on ecosystems and biodiversity* (study of ecosystem adaptation to fires, assessment of changes in biodiversity, impact on soils and hydrological systems).
4. *Development of sustainable forest fire management strategies* (risk modelling, planning of land use).
5. *Impact of fires on air quality and human health.*
6. *Adaptation to climate change* (development of climate-resilient ecosystems, monitoring and adaptation of natural ecosystems).
7. *Development of interdisciplinary approaches.*

Thus, promising areas of research include the use of technology (GIS, AI, satellites), climate change analysis, ecosystem adaptation, forest management, and human health impact assessment. Integration of environmental, social and technical aspects will help to improve the efficiency of wildfire management and reduce their impact on ecosystems and society.

The red cluster in the visualization created in VOSviewer represents terms related to the environmental impact of wildfires. This sector covers key concepts such as fire, disturbance, biodiversity, patterns, restoration, succession, diversity, habitat, ecology, and landscape. Fire is a major driver of many ecological changes. Studies consider it as a disturbance factor that can either sustain or destroy ecosystems depending on frequency and intensity [26], indicate a steady degradation of the fire-fuel feedback that is likely to continue with a warming and drying climate.

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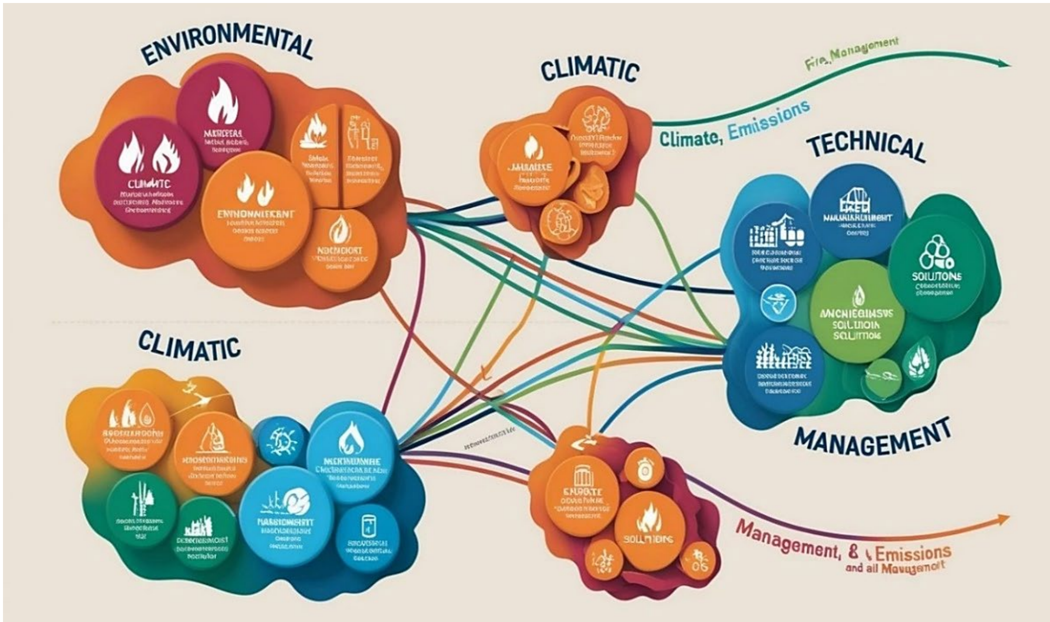

Fig. 2. A structural diagram of the relationships between clusters "Imagined with Al"

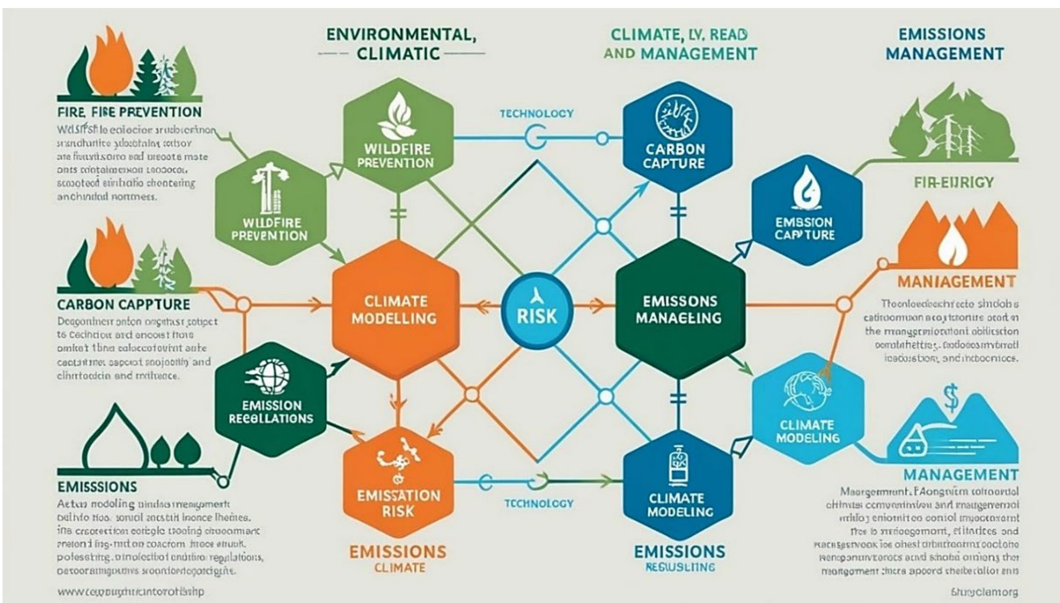

Fig. 3. Areas of research in the field of forest fires "Imagined with Al"

Wildfires are a natural disturbance factor that affects the structure and functioning of ecosystems. Studies [4, 27] indicate that fires are the dominant factor in disturbing the formation of plant and animal communities. Such disturbances can lead to changes in species composition, landscape structure, and vegetation regeneration. Studies show that fires can help restore certain species and maintain ecosystem dynamics. Forest fires affect the composition and diversity of species (biodiversity). The impact of fires on biodiversity is ambiguous. On the one hand, fires can destroy habitats and reduce species numbers. On the other hand, they can create new niches and promote the emergence of pioneer species, which increases overall biodiversity. For example, some plants are adapted to recover from fires and need fire to germinate their seeds. An important topic is the impact of fires on rare and endemic species. Studies [19] found that the most fire-resistant tree species in koala habitat was Eucalyptus eugenioides. [20] note that understanding long-term vegetation dynamics and patterns of plant regeneration is a potential next step to help shape fire management strategies in savanna forest mosaics.

Fires shape spatial and temporal patterns in ecosystems, affecting the mosaic nature of landscapes. Different intensities and frequencies of fires create diverse environments, which affects species distribution and ecological processes. Research in this area highlights the importance of understanding the role of fire in maintaining ecological balance and the need to integrate this knowledge into forest management strategies.

Attention is also paid to methods of restoring ecosystems after fires, how natural and artificial processes help to rehabilitate degraded areas, in particular by planting fire-resistant plants. Wildfires trigger succession processes that change the species inhabiting an area, from pioneer plants to more stable ecosystems. These processes are key to understanding the long-term impacts of fire. The process of ecological succession after fires is analyzed as an important component of natural recovery. Fires can increase biodiversity at a regional level by creating different ecological states within a landscape, but can also have negative effects if they are of high intensity. Research shows how fires alter habitats for plants and animals. Wildfires can both create new ecological niches and destroy vital habitats. For example, some species are adapted to frequent fires and rely on them for survival. Wildfires affect the ecological interactions between species. For example, fires change the cycling of nutrients in the soil, which affects plant growth and animal distribution. Fires are an important factor in shaping landscapes, creating mosaic structures. These changes can be either positive or negative depending on the frequency of fires. Such changes affect species dispersal processes and their viability.

The analysis of the links between the key terms of the red sector demonstrates how natural processes, environmental impacts and methods of ecosystem restoration after wildfires interact. Fire (the central term around which the entire sector is built) is one of the main natural disturbances that changes the structure of ecosystems, has a multifaceted impact on biodiversity, forms spatial and temporal patterns, and triggers the natural process of succession. Fire is a major factor in ecological disturbance, which in turn stimulates natural or managed ecosystem restoration, promotes changes in species communities, and changes the structure of landscapes. Biodiversity is closely related to fire dynamics, habitat, species interactions and ecosystem processes, and biodiversity restoration after fires is a priority for environmental programmes. Patterns of fire spread affect the landscape mosaic, determine how succession processes will occur after a fire, and shape the ecological structure of an area. Restoration is a response to the disturbance caused by fires, its key mechanism is natural succession, and ensures the return of populations and species and the restoration of habitats. Succession leads to changes in species composition and increased diversity, changing the structure of the landscape, creating conditions for long-term stability. Fires stimulate the formation of new ecological niches, increasing diversity, which is closely intertwined with biodiversity, focusing on changes in species composition, and disturbance increases diversity by creating conditions for pioneer species. Fires change habitats for plants and animals by destroying them with fire, and their restoration is a key aspect of environmental management. Wildfire is an important ecological factor that affects all aspects of ecosystems; landscape structure and ecological processes are altered by disturbance; ecology studies how species diversity adapts to frequent fire; and spatial and temporal patterns are an important object of ecological analysis. Landscape structure is affected by fire and influenced by patterns of fire spread, landscape ecology analyses the interactions between landscapes and ecosystem processes, and restoration of landscapes after fires is an important component of environmental management. Fire and ecosystem management ("management") is intertwined with all of the above terms, ensuring the integration of natural and anthropogenic processes. The impact of fires on ecosystem resources (water, soils, timber) ("resources") creates challenges for restoration and conservation.

Therefore, the red cluster demonstrates the interdisciplinary nature of research, encompassing both biological and ecological aspects. Fires are considered not only as a destructive factor but also as a natural process necessary for maintaining ecosystem balance. Research in this direction is important for developing forest management strategies and mitigating the consequences of fires. "Fire" is the central term that unites all other concepts, such as disturbance, recovery, succession, and diversity. The term "disturbance" defines the ecological impact of fires that changes the structure and functions of ecosystems. The relationships between terms reflect the complex dynamics of natural processes activated after fires, such as succession, changing patterns, and habitat restoration. Post-fire ecosystems become mosaic, which contributes to increased diversity and restoration of resilient landscapes. These are interconnected processes that emphasize the need for an integrated approach to forest management, adaptation to fires, and maintenance of ecological resilience.

Promising research directions that will help understand the impact of fires on ecosystems and develop effective strategies for their restoration and management in this sector, in our opinion, are:

1. Research on the ecological consequences of fires for biodiversity and habitats.
2. Study of the long-term consequences of fires for landscapes and climate.
3. Development of sustainable approaches to fire management and ecosystem restoration.
4. Integration of ecological, social, and technological approaches to create effective strategies for adaptation to climate change and increasing fire frequency.

The blue cluster in the visualization (Fig. 4) is related to technical aspects of forest fire research, particularly methods of modeling, forecasting, and risk analysis, and the key terms of this cluster include: "wildland fire", "model", "classification", "risk", "prediction", "remote sensing", "GIS", "fire detection", "deep learning", "hazard".

Fig. 4. The structure of the blue cluster on the visualization "Imagined with AI"

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Researchers focus on wildland fires – fires that occur in natural environments (forests, meadows, etc.). An important topic is the analysis of conditions that contribute to the occurrence of such fires and their spread. [8] demonstrated that the causes of fires differ significantly depending on location and season. [13] indicate that forest fires significantly contribute to forest destruction and biodiversity depletion.

Considerable attention is paid to the development of mathematical and simulation models ("model") that allow understanding the dynamics of fire spread, their impact on ecosystems, and evaluating the effectiveness of their control methods. [28] note that fire is a complex phenomenon, and accurate modeling contributes to emergency response management after ignition. The WRF-fire model, which was applied in China, is capable of accurately reproducing the real spread of fire. [29] developed a multifactor forest fire model using the Wang Zhengfei model to calculate the rate of fire spread.

Research [30] demonstrates that the Transformer model effectively uses spatial background information and periodicity of forest fire factors, significantly improving prediction accuracy. [14] used 3 ensemble machine learning classifiers for forest fire modeling: gradient boosting (GBC), random forest (RFC), and extremely randomized tree (ETC), which proved to be the most accurate classifier. Future fire predictions were made using the ETC model with data from the general circulation model CMIP6 EC-Earth3-SSP245 (GCM). It is predicted that the number of medium-class forest fires will decrease, while the number of high-class forest fires will increase, and that summer months, especially September, will be most affected by fires.

Classification of fires ("classification") by types (e. g., ground fires, crown fires) or by degree of danger for developing specific approaches to combat them. It is also used for automatic analysis of satellite data. [31] developed a classification of fire severity based on tree mortality, using 8 indicators of tree death and abundance.

Research on risks ("risk") focuses on assessing the probability of fires in different regions, taking into account climatic conditions, vegetation type, and anthropogenic impact. Development of fire prediction methods ("prediction") through analysis of data on temperature, humidity, wind speed, etc. Prediction includes short-term and long-term assessments.

The use of satellite data, remote sensing, and drones for monitoring forest fires allows detecting fires, tracking their progress, and assessing damage. [32] an unmanned aerial vehicle (UAV) based on the lightweight forest fire recognition model Fire-Net, capable of perceiving objects of different scales, in particular, small fires in wild forest conditions. Experimental results show that Fire-Net achieved 98.18% accuracy, outperforming state-of-the-art methods. [33] proposes an approach that combines UAV imaging with ground-based Internet of Things (IoT) sensors for early detection of forest fires, even if they are hidden under tree canopies. Inexpensive sensors measure temperature, humidity, and air quality, and to overcome communication limitations, UAVs are used as communication hubs to collect data from sensors and survey the area for smoke and fire. The proposed system, which is part of the FireFly project, aims to overcome the limitations of existing technologies and provide effective solutions for monitoring and preventing forest fires.

Geographic information systems ("GIS") are a tool for spatial analysis of fires. GIS allows integrating data on topography, vegetation types, and climatic conditions for modeling fire spread. [12] created "Forest Fire Susceptibility" maps using GIS-based Bayesian methodologies and Random Forest, incorporating twelve unique environmental and anthropogenic factors. RF outperformed the Bayesian model with AUC scores of 0.876 and 0.807, respectively. Key factors influencing fire occurrence are elevation, mean annual precipitation, distance to roads, and mean annual temperature. Conversely, variables such as slope direction, topographic wetness index, and slope percentage had less impact.

Development of automatic fire detection systems ("fire detection") using thermal cameras, satellite images, infrared sensors, etc. The main goal is rapid detection to reduce response time. In the study [34], an early forest fire detection system called Forest Defender Fusion is proposed. This system achieved high accuracy and long-term monitoring of the area through the use of the Intermediate Fusion VGG16 model and the Enhanced Consumed Energy-Leach (ECP-LEACH) protocol. The Intermediate Fusion VGG16 model receives RGB (red, green, blue) and IR (infrared) images from drones to detect forest fires. The Forest Defender Fusion system provides drone power consumption regulation and achieves high detection accuracy, allowing forest fires to be detected at early stages. The detection model was trained on the FLAME 2 dataset and achieved 99.86% accuracy.

The use of deep learning algorithms ("deep learning") to process large volumes of data, such as satellite images or drone videos, to automate fire detection and predict their spread. [13] emphasize that the application of machine and deep learning algorithms allows determining which areas are most prone to forest fires, with the Catboost model demonstrating the highest accuracy (AUC 0.83). Results also showed that NDVI and annual temperature have the greatest impact. Assessment of vulnerability to forest fires can be used in various locations around the world that include significant natural and anthropogenic characteristics.

There is always a risk associated with fires, particularly their impact on human settlements, infrastructure, and natural ecosystems. Attention is paid to identifying high hazard zones ("hazard").

It was analyzed the relationships between the terms. Wildland fires ("wildland fire") is the central term of the blue cluster, which covers all aspects of research: analysis and risk assessment ("risk") of natural fires depending on climatic, topographic, and human factors, creating models ("model") of fire spread and their impact on natural areas, detection of natural fires ("fire detection") in real time to prevent large-scale damage, use of satellite data ("remote sensing") for monitoring and analyzing their dynamics. Modeling is a central tool for predicting and evaluating fires, models ("model") are created to predict the probability of fire occurrence and their spread ("prediction"), the use of deep learning algorithms ("deep learning") increases their accuracy, and risk assessment models ("risk") are used to identify the most vulnerable regions, while geographic information systems ("GIS") support models through spatial data on landscape and climate. Classification ("classification") is used to analyze fires by type, intensity, and consequences, automatic classification of areas affected by fires is provided by data from satellites ("remote sensing"), deep learning algorithms ("deep learning") help automate the classification of large data sets, classification of fires by hazard level ("hazard") allows prioritizing resources to combat them. Risk assessment ("risk") is a key element of fire management, which is evaluated based on forecasts ("prediction") that take into account weather conditions, vegetation type, and human factors, and geographic information systems ("GIS") tools are used to create their maps. Moreover, risks are directly related to the hazard level ("hazard"), which is assessed using models. Fire prediction ("prediction") is based on big data analysis and the use of models, analysis of satellite data ("remote sensing") on temperature, humidity, and vegetation, algorithms ("deep learning") predict the occurrence and spread of fires based on historical data, helps detect fires ("fire detection") faster, minimizing their impact. The use of satellite technologies ("remote sensing") and drones provides real-time monitoring of fires, helps classify ("classification") fires by their impact and scale. Integration of satellite images into geographic information systems ("GIS") provides analysis of spatial data, satellite data is used for automatic detection ("fire detection") of ignition centers. GIS is the main tool for analyzing spatial data on fires, analyzing spatial-temporal patterns ("patterns") of fire spread is used to create risk maps ("risk") and hazard maps ("hazard"). GIS is integrated into modeling ("model"), providing data on landscape and climate. Real-time fire detection ("fire detection") is critical for operational response, satellite images ("remote sensing") are used for fire detection, and when combined with predictive models ("prediction"), they reduce response time, while detection of hazardous zones ("hazard") in real time allows focusing resources. Deep learning algorithms ("deep learning") are used to automate data analysis and prediction, effectively classify ("classification") fire data, are used to predict fire spread ("prediction"), help automatically identify ignition centers ("fire detection") based on images. Fire hazard analysis ("hazard") is conducted for people, ecosystems, and infrastructure, and its level depends on risks ("risk") assessed through models, and geographic information systems ("GIS") are used to visualize hazard zones.

Thus, the blue cluster focuses on engineering and technological approaches to studying and managing forest fires. The main emphasis is on developing tools for monitoring, predicting, and reducing risks. An important direction is the integration of satellite technologies, machine learning, and geographic information systems to improve fire response. This cluster shows how modern technologies and analytical approaches can be used to reduce the consequences of fires and support ecological safety.

"Wildland fire" is a central concept that is related to all aspects of fire management. Technologies such as "remote sensing", "GIS", and "deep learning" provide data for risk analysis, prediction, and classification of fires. Integration of "model" and "prediction" with risk and hazard assessment allows optimizing forest fire management. Modern technologies create the basis for accurate detection, prediction, and minimization of fire impact. These connections demonstrate how innovative tools can be used to improve fire response and risk management.

Key research prospects for the blue sector related to technologies, prediction, and management of forest fires cover several important directions that ensure the development of innovative solutions for monitoring and preventing fires:

1. Technological integration: use of AI, remote sensing, GIS, and prediction models for effective fire management.
2. Improvement of fire detection technologies and operational response to them.
3. Integration of ecological, social, economic, and technological research for comprehensive solution of forest fire problems.
4. Development of strategies that take into account the increased frequency of fires due to climate change.

These studies will help create more effective fire management systems, reduce their impact on nature and society, and ensure ecosystem resilience to growing climate challenges.

The green cluster in the visualization (Fig. 5) is related to ecological management, ecosystem restoration, population dynamics, and the impact of forest fires on habitats, and also contains the following 10 key terms: "management", "restoration", "resilience", "population", "ecological restoration", "resources", "fire exclusion", "selection", "frequency", "resources availability".

Forest and natural ecosystem management ("management") measures aimed at minimizing damage from fires, as well as preserving and restoring ecological balance. This includes controlling the accumulation of combustible materials, creating firebreaks, and using controlled burns. Attention is also paid to ecological and anthropogenic methods of restoration ("restoration") after fires. Research results [5] confirm the feasibility of using relatively early post-fire surveys to determine long-term forest recovery trajectories when planning forestry activities and can help improve tools for prioritizing forest restoration. Forest ecosystems are capable of recovering after fires. Studies assess which ecosystems are more resistant to fire impact and how to maintain this resilience ("resilience"). Research results [35] show that dry forest is relatively resistant to recurrent fires, has the ability to recover and adapt, and that climatic differences are the main factors determining the spatial variation in observed resilience. The impact of fires on plant and animal populations ("population") is studied, including changes in numbers, genetic variability, and migration processes. Ecological restoration ("ecological restoration") is a specific field of research focused on returning ecosystems to their natural state. In this context, methods of accelerating human-assisted recovery are considered. Research results [17] established that fire as a natural disturbance promotes the formation of gaps in stand canopies, creating favorable conditions for natural forest regeneration. Research also focuses on how fires affect ecological resources ("resources"), such as water, soils, vegetation, and animal populations, as well as ways of their rational use after fires. The practice of limiting natural fires ("fire exclusion") is applied in order to preserve certain ecosystems. However, the absence of fires in some cases can lead to the accumulation of combustible materials and increase the risk of catastrophic fires. Selection ("selection") reflects the process of natural selection or anthropogenic efforts aimed at growing plants and trees that are more resistant to fires. In regions with high fire frequency, selecting fire-resistant plant species can be a promising approach to ecosystem adaptation. This term is used to develop strategies for afforestation and adaptation of vegetation to climate change. Fire frequency ("frequency") is one of the key factors affecting ecosystem dynamics. Regular low-intensity fires can maintain ecological balance, while excessive frequency causes ecosystem degradation. Research results [6] indicate that greater fire frequency negatively affects both the density and diversity of tree layers.

Fig. 5. Structure of the green cluster study "Imagined with AI"

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According to results [3], fire recurrence is significantly influenced by post-fire vegetation, as well as topography and accessibility. Forests dominated by shrubs and sclerophyllous vegetation have a higher probability of reignition than forests with woody vegetation. Fire recurrence depends on time, with the year of the first fire being an important factor explaining the proportion of areas that burned twice. Identifying characteristics and types of post-fire vegetation in places with a high probability of fire recurrence can help prioritize territories and time windows for applying fire prevention and mitigation measures in already vulnerable forests.

Research on fire frequency helps develop prediction models and effective forest management plans. Fires affect the availability of natural resources ("resources availability"), such as water, soil nutrients, wood, and other ecosystem services. Fires can simultaneously destroy resources and create new conditions for their formation, such as fertile soils through ash accumulation. Studying the impact of fires on resource availability is the basis for forming sustainable ecosystem management policies.

Analysis of connections between terms in the green sector reveals the interaction between ecological management, ecosystem restoration, adaptation to fires, and rational use of natural resources. Management ("management") is a central term covering all aspects of planning, control, and restoration of ecosystems after fires; it defines strategies for ecosystem restoration ("restoration") after fires, including afforestation and habitat improvement; aims to increase ecosystem resilience ("resilience") to fires through species selection and controlled burns; an important part of it is controlling fire frequency ("frequency") to prevent ecosystem degradation; and includes monitoring the availability of resources ("resources availability") such as water, nutrients, and wood after fires. Ecosystem restoration ("restoration") is a key goal after fires, and the approach to it includes both natural processes and anthropogenic measures (e. g., tree planting, soil restoration) ("ecological restoration"); depends on ecosystem resilience ("resilience") to fires and their ability to recover naturally; selection of species for planting that are more resistant to fires ("selection") accelerates the recovery process; and the availability of resources ("resources availability") such as seeds and nutrients determines the success of restoration. Ecosystem resilience ("resilience") is their ability to adapt and recover after fires; can be affected by fire frequency ("frequency"); and fire exclusion ("fire exclusion") can temporarily increase resilience but in the long-term lead to accumulation of combustible materials and reduced adaptive capacity. Fires affect the number and dynamics of plant and animal populations ("population"); population recovery ("restoration") is critical for ecosystem restoration; selection of plants and animals ("selection") adapted to fires contributes to population stabilization; and resource availability ("resources availability") after fires, in turn, determines population survival and growth. Ecological restoration ("ecological restoration") is a comprehensive process aimed at returning ecosystems to their natural state; is an integral part of forest management ("management") after fires; aimed at increasing ecosystem resilience ("resilience") to future fires; and restoration of resources ("resources") (water, soils, vegetation) is part of this process. Resources ("resources") such as water, wood, and nutrients play a key role in ecosystem viability; fire exclusion ("fire exclusion") can contribute to their accumulation but also leads to the risk of large-scale fires; ecosystem restoration effectiveness ("restoration") depends on resource availability; and their availability and quality are affected by fire frequency ("frequency"). Fire exclusion policy ("fire exclusion") affects the accumulation of combustible materials and ecosystem dynamics; is one of the managements ("management") approaches used to preserve ecosystems; reducing fire frequency ("frequency") through exclusion affects long-term ecosystem stability; and exclusion can temporarily increase resilience ("resilience") but creates conditions for catastrophic fires. Selection of fire-resistant plant species ("selection") is an important management tool that accelerates recovery after fires ("restoration"); species adapted to fires contribute to population stability ("population"); and the use of resistant species increases the overall resilience of ecosystems ("resilience") to fires. Fire frequency ("frequency") is an important factor affecting all aspects of management and restoration; their recurrence can cause significant disturbances ("disturbance") in ecosystems; optimal frequency maintains ecosystem resilience ("resilience"); and management ("management") of fire frequency helps avoid their destructive consequences. Resource availability ("resources availability") after fires affects all aspects of restoration ("restoration"), determining their speed and success; and fire exclusion ("fire exclusion") can maintain resources in the short term but increases the risk of large-scale fires.

Thus, the green cluster reflects an interdisciplinary approach to studying forest fires, combining ecological, management, and restoration aspects. The main emphasis is on maintaining the natural balance through reasonable ecosystem management, restoring them after fires, and increasing resilience to future challenges. These studies form the basis for developing effective forest management strategies in the context of climate change.

"Management" is a central concept that unites all aspects of ecosystem restoration, adaptation, and management after fires. "Restoration" and "resilience" are interconnected through the need for natural and anthropogenic efforts to restore ecosystems. Fire frequency and fire exclusion policy determine the long-term stability and resilience of ecosystems. Selection of plants and animals adapted to fires is a promising tool for increasing resilience. Resource restoration after fires is the basis for ecosystem restoration and maintaining their long-term functioning. These connections demonstrate the need to integrate management, ecological, and technological approaches to adapt ecosystems to climate change and fire frequency.

The yellow cluster in the visualization (Fig. 6) concerns climatic, ecological, and carbon aspects related to forest fires. This cluster highlights the impact of fires on global processes such as climate change, carbon emissions, and ecosystem degradation, and contains the following keywords: "climate", "carbon", "deforestation", "emissions", "impact", "soil", "nitrogen", "deforestation rates", "biomass burning", "land use".

Climate is closely related to wildfires, as fires are both a consequence of climate change (e. g., drought, rising temperatures) and a catalyst for it through greenhouse gas emissions [36]. Research is focusing on how global warming is contributing to an increase in the frequency of fires. Forest fires are a powerful source of carbon emissions into the atmosphere. The loss of vegetation leads to a decrease in the ability of forests to absorb CO_2, which exacerbates climate change. The processes of carbon release and accumulation after fires are analyzed. Forest fires often cause forest degradation, which can lead to the complete loss of forests ("deforestation"). In this context, the relationship between anthropogenic factors, deforestation and fires is being studied. Fires release a significant amount of greenhouse gas emissions into the atmosphere, including CO_2, methane, and nitrogen oxides. Emissions reflect the global environmental impact of fires and the importance of monitoring them [37]. The impacts of fires cover a wide range of outcomes: climate change, ecosystem degradation, air quality degradation, and reduction of ecosystem services such as water purification and biodiversity conservation. Fires affect the chemical and physical composition of the soil, reducing its fertility, changing the content of organic matter, and contributing to erosion. The processes of soil degradation after intense fires are particularly studied. [11] found that average soil pH, electrical conductivity, and available potassium increased by 3%, 81%, and 53%, respectively, in the burned area, while available phosphorus decreased by 6%. Conversely, the average content of total nitrogen and organic matter decreased slightly by 20% and 12% in the burned area compared to the control area. Forest fires change the nitrogen cycle, as the burning of vegetation releases this element in the form of nitrogen gas, reducing its availability to plants. This can affect ecosystem recovery. Studies have highlighted how fires accelerate deforestation rates, especially in tropical regions. Deforestation and fires often work in synergy to degrade ecosystems. Fires are a form of biomass burning that involves natural processes and anthropogenic factors. It is a source of large volumes of greenhouse gases and aerosol particles that affect climate and health. Changes in land use (e. g., the conversion of forests to agricultural land) ("land use") often cause fires. In turn, fires affect future land use through land degradation.

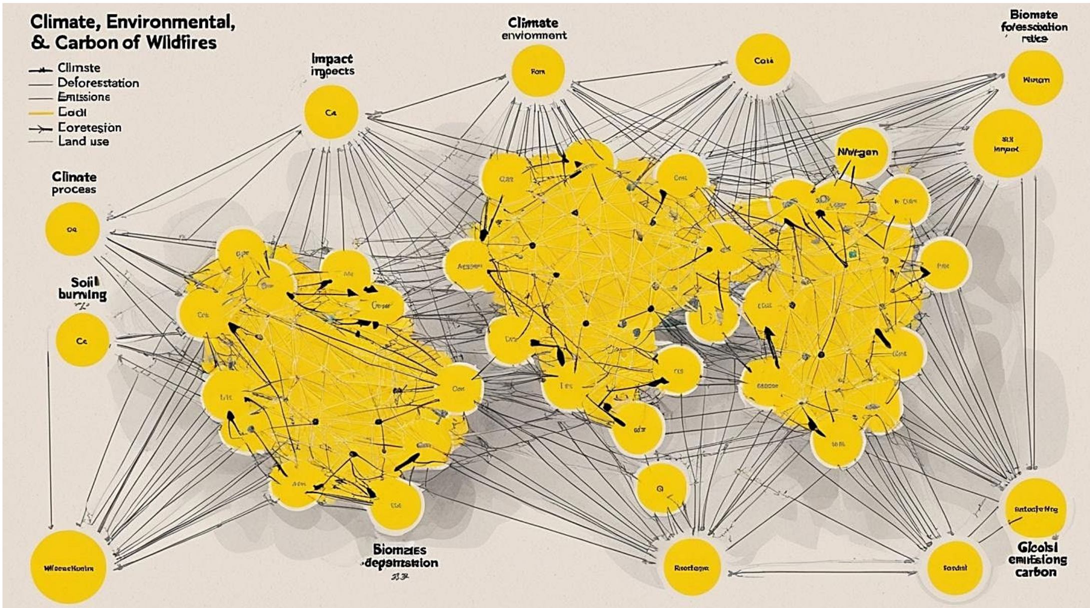

Fig. 6. Yellow cluster on the visualization of forest fires "Imagined with Al"

Analyzing the links between the yellow sector terms reveals how the climatic, environmental and social aspects of forest fires interact with each other. These terms form a holistic picture of the impacts of fires on climate, ecosystems and land use. Climate is a central term that combines climate change and the impact of fires, which cause emissions of greenhouse gases, carbon, and as a result, exacerbate global warming. Increasing deforestation rates due to fires exacerbate climate change by reducing the ability of forests to absorb carbon, and the climate change caused by fires has an impact on biodiversity, water cycles and land use. Carbon – a term that reflects the impact of fires on the carbon balance: biomass burning releases significant amounts of carbon into the atmosphere ("emissions"), fires change the carbon content of soils, reducing their fertility and carbon storage capacity, and deforestation due to fires reduces the ability of ecosystems to absorb carbon. Fires cause deforestation and accelerate deforestation rates, especially in tropical regions, while land use change, such as the conversion of forests to agricultural land, increases the risk of fire. In addition, deforestation due to fire has an impact on global ecosystems, including biodiversity loss and climate change. Greenhouse gas emissions are the main result of fires, and biomass burning is a key source of CO_2, methane and other greenhouse gases that contribute to climate change. Vegetation burning also releases nitrogen oxides, which contribute to the formation of tropospheric ozone. In general, emissions cause air pollution, which has an impact on human health and air quality. Fires have an impact on the climate, ecosystems and society: they deteriorate soil structure, reduce its fertility, increase the risk of erosion, change land use practices, and cause deforestation, ecosystem degradation and carbon imbalance. Soil is an important element of ecosystems that is significantly affected by fires; vegetation burning alters nitrogen cycling, reducing its availability in the soil; fires alter the level of organic carbon in the soil, reducing its fertility; and loss of soil structure due to fires leads to erosion and land degradation ("impact"). Nitrogen is a key element involved in soil and ecosystem restoration processes, fires reduce nitrogen in soils by releasing it as gases, nitrogen oxide emissions affect air quality and contribute to ozone formation, and biomass burning releases nitrogen in gaseous form, reducing its availability to plants. Deforestation rates – an indicator that reflects the extent of forest loss due to fires, is associated with changes in land use after fires, and its growth affects the climate due to the loss of carbon sinks and has a significant impact on global ecosystems. Biomass burning – a process that releases a significant amount of gases and aerosols, the main source of CO_2, methane and aerosols emissions, disrupts the carbon balance, increasing it in the atmosphere, and causes the loss of organic matter in the soil. Changes in land use have a significant impact on fire risk, cause deforestation, degrade ecosystems and reduce their resilience, and the frequency of fires depends on the type of land use (forests, pastures, agricultural land).

Thus, the yellow cluster reflects the global context of wildfires, focusing on their impacts on climate, greenhouse gas emissions, and land use change. This research is crucial to understanding the role of fires in climate change and to developing global strategies to reduce their impacts. Integrating emissions monitoring, land management, and climate change mitigation are key areas of focus in this cluster.

Climate change and fires mutually reinforce each other, creating a feedback loop that complicates global climate challenges. Fires are a key factor in soil degradation, biomass loss, and accelerated deforestation, which changes the carbon balance and global ecosystems. Emissions from fires affect not only the climate, but also air quality, human health and biodiversity. Integrating land use management, reforestation, and soil conservation is critical to mitigating the effects of fire. The interrelationships between carbon cycle changes, deforestation and land use should be taken into account in global climate models.

Key research perspectives in the yellow sector related to the climate, environmental and carbon impacts of wildfires cover important issues related to their impacts on climate change, elemental cycling and ecosystem management:

1. Study of greenhouse gas emissions and changes in the carbon balance.
2. Study of changes in the cycles of carbon, nitrogen and other elements.
3. Study of the processes of soil, vegetation and water resources recovery after fires.
4. Impact of fires in land and forest management strategies.
5. Integration of fire data into climate models to assess their long-term impact.

The research perspectives will help to better understand the role of wildfires in global ecosystems and develop effective strategies to mitigate and adapt to climate change.

The purple cluster (Fig. 7) in the visualization refers to the impact of wildfires on air quality, emissions of harmful substances, human health and chemical processes that occur during fires, and the main key concepts include: "emissions", "toxic gases", "smoke", "particulate matter", "air quality", "black carbon", "hospital admissions", "carbon emissions", "chemistry", "pollution", "health impact".

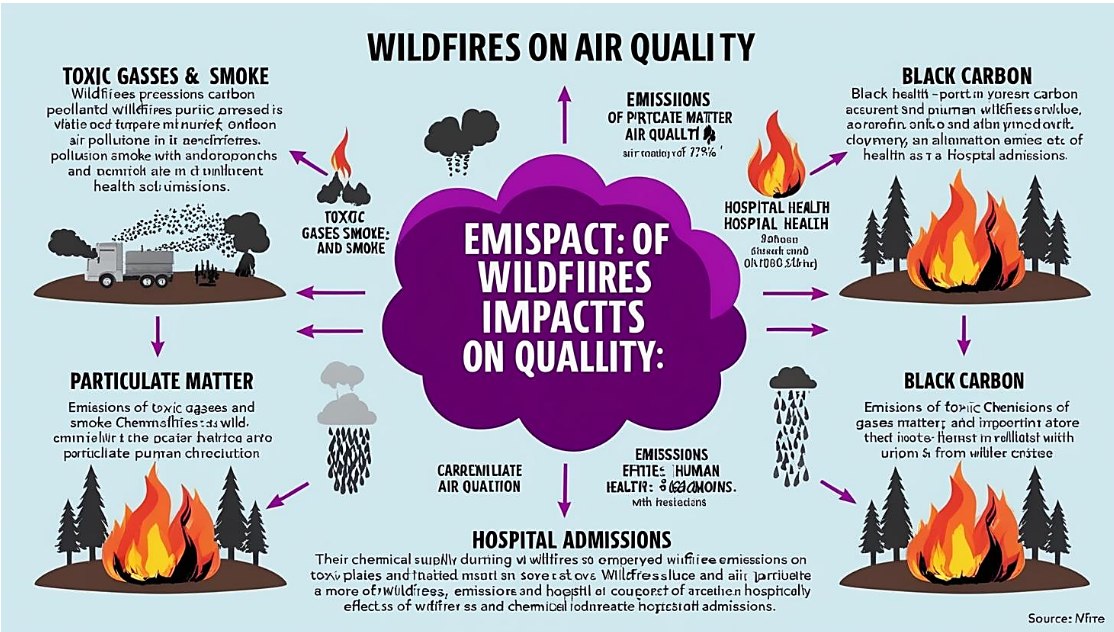

Fig. 7. Structure of the purple cluster of forest fires "Imagined with Al"

The purple cluster focuses on emissions from wildfires, such as greenhouse gases (CO_2, methane) and other harmful substances (nitrogen oxides, volatile organic compounds) ("toxic gases"). Emissions are a major contributor to air quality and global warming. A wide range of toxic gases have a serious impact on air quality, human health and climate processes. The study of their composition allows to better understand the long-term effects of fires, which highlights the need to develop monitoring technologies and measures to reduce their impact on the environment and society. Fire smoke contains fine particles, toxic gases, and carcinogenic substances. It spreads over long distances, affecting air quality even in regions that are not in the immediate vicinity of fires [38]. Forest fires are a source of fine particles (PM2.5 and PM10) ("particulate matter") that can penetrate the human respiratory system, causing health problems, including lung and cardiovascular diseases. Forest fires are a significant source of carbon emissions, contributing to the greenhouse effect. Particular attention is paid to the analysis of quantitative data on emissions from large fires. One of the main products of combustion during forest fires is black carbon, which is a powerful greenhouse agent that absorbs solar radiation and affects glacial melt, accelerating climate change. The long-term effects of such pollution are particularly dangerous. In areas affected by forest fires, the number of hospital admissions is increasing due to respiratory diseases, asthma, allergies and other diseases caused by air pollution. Forest fires initiate complex chemical processes in the atmosphere. For example, reactions that form ozone in the lower atmosphere, which also affects air quality and health. The impact of fires on air quality is significant. Polluted air worsens public health, as well as reduces visibility and creates problems for aviation and transportation. Forest fires have a negative impact on human health ("health impact"), causing chronic and acute respiratory diseases, as well as exacerbating cardiovascular diseases. An analysis of the relationships between the terms in the purple cluster reveals the complex interactions between wildfires, air quality, public health, and the chemical processes that occur during combustion.

The central term of the purple cluster is emissions, which describes the emission of gases and particles from forest fires, and has links to ("toxic gases") – namely (CO_2, methane, nitrogen oxides, CO), which affect air quality and health, ("particulate matter") – which are the main air pollutants (PM2.5, PM10).

"Carbon emissions" – emissions of CO_2 that affect the global climate balance and ("chemistry") – chemical reactions caused by emissions that form secondary pollutants such as tropospheric ozone. "Toxic gases" is related to "smoke" because toxic gases are a component of smoke that spreads over long distances, worsen air quality, affecting public health, cause respiratory diseases, asthma, cardiovascular disorders ("health impact"), and gaseous pollutants are the main components of air pollution during fires ("pollution"). The visible part of combustion products is ("smoke"), which contains gases, particles and aerosols. It also contains ("particulate matter") that easily penetrates the human respiratory system, includes ("black carbon"), which affects the climate and accelerates glacial melt, and exposure to smoke is the main cause of hospital admissions due to respiratory difficulties, and smoke significantly increases air pollution levels. The main air pollutant is ("particulate matter"), which affects public health, and an increase in their concentration in the air worsens its quality. PM2.5 and PM10 particles can cause chronic lung diseases and cardiovascular diseases ("health impact"), and particulate matter is an important component of atmospheric pollution ("pollution"). Air quality is significantly degraded by wildfires, resulting in increased levels of gas and particulate pollution ("pollution"), poor air quality affects public health by exacerbating chronic diseases ("health impact"), and increased illness due to poor air quality increases hospital admissions ("hospital admissions"). Black carbon is one of the main combustion products that affects climate and health. Much of it is released during forest fires. Black carbon is an important component of atmospheric pollution that contributes to climate warming by absorbing solar radiation and interacting with other atmospheric components to form secondary pollutants. Hospitalization is an indicator that reflects the impact of fires on public health. The main reason for hospitalization is exacerbation of respiratory and cardiovascular diseases due to air pollution ("health impact"). The number of hospitalizations is increasing in regions with poor air quality, and smoke exposure is one of the main factors of hospitalization. Carbon emissions are the result of burning vegetation during fires, CO_2 is the main component of emissions during fires, carbon emissions contribute to the greenhouse effect and global warming and are the main source of air pollution. Chemical processes play a key role in the formation of secondary pollutants. Chemical reactions produce ozone and other hazardous compounds ("toxic gases") that increase pollution. Chemical processes caused by fires affect the climate through the production of long-lived greenhouse gases. Air pollution is the result of wildfires, and the deterioration of air quality due to pollution affects regional health. Particulate matter is the main air pollutant, and black carbon is a significant component of air pollution.

The health impact reflects the effects of air pollution on public health, with poor health due to pollution leading to an increase in hospital admissions, gaseous pollutants causing respiratory diseases, and poor air quality being a major factor in health impacts.

Thus, the Purple Cluster focuses on issues related to air quality, public health impacts, and chemical aspects of wildfires. The main research topics include monitoring emissions, developing technologies to predict the spread of smoke, analyzing its composition and impact on the population. Of particular importance are measures to mitigate the impact of fires on air quality, as well as the development of strategies to protect the health of vulnerable populations.

For the restoration of fire-damaged areas, it is extremely important to take into account the biodiversity of tree species (increased fire resistance of broadleaf trees), especially in the context of climate change [39].

The authors of [40] found that both fire risk reduction and forest regeneration goals benefit from spatially coordinated planning at the landscape level among landowners. The authors of [41] note that a multidisciplinary approach to collecting and analyzing wildfire information can inform evidence-based policies and practices aimed at addressing the emerging environmental challenges caused by global wildfires. Proactive fire management, according to [15], is justified to restore fire as a vital ecological process and to promote forest resilience by overcoming the effects of centuries of fire suppression. The results obtained by [7] emphasize the sensitivity of aboveground biomass to fire frequency, with significant losses of carbon stocks observed in classes of high fire frequency. The authors of [16] note the possible influence of soil thermal regime on the occurrence of wildfires. A study [10] recommends risk reduction strategies, including dry pine leaf management, reforestation, construction of fire lines, and training of rural communities in fire management, which can effectively mitigate the growing threat of wildfires.

The critical analysis of the literature shows that researchers pay considerable attention to the problem of forest fires in the context of climate change. However, a number of unresolved issues have been identified: insufficient comprehensiveness of approaches to integrating natural and anthropogenic factors, limited accuracy of fire spread forecasting models, and poor integration of social aspects into risk management strategies. Existing research highlights the impacts of fires on biodiversity, soil quality and greenhouse gas emissions, but interdisciplinary approaches that take into account ecological, climatic and management factors at the same time need to be further developed. There is also a lack of models that provide accurate long-term forecasts of fire risks, taking into account climate change.

The results of the study have a number of distinctive features that ensure their practical relevance for solving the problem of forest fires. The integrated interdisciplinary approach of the study combines environmental, climatic and management aspects into a single system of analysis. This allows to consider forest fires in a comprehensive manner, taking into account both natural and anthropogenic factors. The multivariate analysis using clustering made it possible to identify and analyze five main clusters (red – environmental impacts, blue – technical aspects of modelling, green – ecosystem management, yellow – climate aspects, purple – air quality and health impacts), which allowed for the structuring of research on various aspects of forest fires. Analyzing the relationship between forest fires and climate change, which allows for the development of adaptation strategies to take into account future climate trends. Visualization of interrelationships, namely the use of VOSviewer software to create a visualization of key terms and their interrelationships, made it possible to identify central themes and promising research areas.

Despite the significant findings, the study has certain limitations that should be taken into account in practical application. Although the study mentions the anthropogenic causes of fires, a detailed analysis of the social and economic factors that influence the occurrence of fires and the development of fire prevention strategies requires further development.

Given the results and limitations identified, the following promising areas for further research can be identified. Integration of socio-economic factors, namely the inclusion of social, economic and behavioral aspects in fire risk models to better understand anthropogenic factors. Deepening research on ecosystem restoration, namely the study of effective methods for restoring different types of ecosystems after fires, including research on the impact of fire on species diversity and soil structure.

4. Conclusions

The results of the cluster analysis of thematic areas of research related to forest fires demonstrate the interdisciplinary nature of this problem. The identified multi-colored clusters allow to present the main research areas in a structured way and emphasize their importance in the context of global environmental challenges. The analysis of the color-coded clusters representing the main areas of research in the field of wildfire provides a holistic view of the current state of knowledge and priorities in this area. Each cluster highlights important aspects related to fires, their impact on nature, society and climate, as well as management and prevention measures.

The five color clusters identified reflect the main research areas and their interconnections. The red cluster highlights the ecological impacts of fires on ecosystems, showing that fire is not only a destructive factor, but also a natural process necessary to maintain ecological balance. Research confirms that fires affect biodiversity, landscape structure and create a mosaic of ecosystems that facilitates natural succession and regeneration. The blue cluster focuses on the technological aspects, demonstrating significant progress in the development of models for predicting fire spread. The green cluster highlights aspects of ecosystem management, revealing that the dry forest ecosystem shows relative resilience to repeated fires. The research confirms that fire as a natural disturbance contributes to the formation of gaps in stands, creating favorable conditions for natural forest regeneration. At the same time, the results indicate a negative impact of increased fire frequency on the density and diversity of tree cover. The yellow cluster focuses on climate and the carbon cycle, demonstrating the relationship between wildfires and global climate processes. Studies clearly show that an increase in the frequency of fires has a negative impact on above-ground biomass, causing significant losses of carbon stocks. The results of the analysis confirm that fires and deforestation work in synergy to exacerbate ecosystem degradation. The purple cluster analyses the impact of fires on air quality and public health. Air quality deteriorates significantly due to forest fires, leading to increased levels of gas and particulate pollution. Poor air quality affects public health by exacerbating chronic diseases, leading to an increase in hospitalizations.

The interdisciplinary nature of the research presented through the thematic clusters confirms the complexity and multifaceted nature of the wildfire problem. Each cluster reflects a key aspect of this phenomenon, ranging from its impact on ecosystems to technical solutions for prevention and control. This approach allows not only to better understand the causes and consequences of fires, but also to develop effective strategies to minimize their impact on nature, climate and society.

The environmental impact analysis showed that forest fires have a significant impact on biodiversity, soil quality and greenhouse gas emissions. It was determined that the integration of data on land use, climate indicators, and anthropogenic impacts increases the objectivity of fire risk assessment.

The integration of the results of all clusters allowed to form a holistic picture of the forest fire problem, identifying key interrelationships

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between different aspects. The results confirm the need for coordinated planning at the landscape level among landowners to reduce fire risk and achieve forest restoration goals. A multidisciplinary approach to collecting and analyzing fire information enables evidence-based policies and practices to address the environmental challenges posed by global fires.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other, that could affect the research and its results presented in this article.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors have used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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