ORGANIZATION AND IMPROVEMENT OF THE FIRE PROTECTION SYSTEM FOR FOREST ECOSYSTEMS: THE CASE OF THE STATE ENTERPRISE «KRASNOPILSKY AGROLISGOSP»

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Introduction

Forest ecosystems are one of the most important components of the natural environment, ensuring the maintenance of ecological balance and playing a key role in supporting the sustainable development of society. They perform a wide range of functions, including climate regulation, soil protection, water conservation, recreational, and resource–related functions. Forests contribute to biodiversity conservation, accumulate carbon, reduce the negative impact of climate change, and constitute an important element of the economic development of regions.

Under current conditions, the importance of forest resources is growing significantly; however, at the same time, the influence of negative factors on their condition is also increasing. One of the most serious threats to forest ecosystems is forest fires, which lead to significant ecological, economic, and social losses. As a result of fires, forest plantations are destroyed, soils degrade, natural ecosystems are disrupted, and biodiversity decreases. In addition, fires negatively affect air quality and pose a threat to human life and health.

The relevance of the forest fire problem is determined by modern global processes, in particular climate change, which is manifested in rising air temperatures, reduced precipitation, and an increase in the duration of dry periods. Such conditions contribute to a higher level of fire hazard and complicate fire suppression processes. A significant influence is also exerted by the anthropogenic factor, which is manifested in non–compliance with fire safety regulations, economic activity, and recreational pressure on forests.

For Ukraine, the problem of forest fires is especially relevant due to the combination of natural and anthropogenic factors, as well as the impact of current socio–economic and military conditions. The consequences of hostilities, the presence of explosive hazards, limited access to certain territories, and damage to infrastructure significantly complicate the organization of effective forest fire protection.

Under these conditions, the need to improve the forest fire protection system becomes particularly important. This system should be based on an integrated approach and combine preventive, organizational, and technical measures. An effective protection system involves the timely detection of fire outbreaks, forecasting their development, prompt response, and minimization of negative consequences.

The object of the study is the processes of occurrence, development, and spread of forest fires within forest ecosystems.

The subject of the study is the organization of the forest fire protection system in the activities of the State Enterprise “Krasnopilskyi Agrolisgosp”.

The aim of the study is the scientific substantiation and development of effective organizational and technical measures to improve the level of fire protection of forest areas within a specific forestry enterprise.

To achieve this aim, the following research objectives were defined:

– to investigate the peculiarities of the occurrence and development of forest fires;
– to analyze the natural and economic conditions of forest stand functioning;
– to assess the effectiveness of the existing fire monitoring and detection system;
– to analyze fire protection measures;
– to develop practical recommendations for improving the forest protection system.

The methodological basis of the study is the application of a set of general scientific methods, including analysis, synthesis, generalization, comparison, a systems approach, as well as elements of statistical analysis and observation. The use of these methods ensured a comprehensive study of the problem and made it possible to obtain well–grounded results.

The scientific novelty of the study lies in improving approaches to the organization of forest fire protection, taking into account modern challenges, including climate change and restrictions related to martial law.

The practical significance of the obtained results lies in the possibility of their application in the activities of forestry enterprises, public administration bodies, and emergency rescue services in order to increase the effectiveness of measures aimed at the prevention and elimination of forest fires.

The structure of the study is determined by its aim and objectives and includes an introduction, the main part, conclusions, and a list of references. The study consistently examines the theoretical foundations of the problem, analyzes the practical state of forest fire protection, and proposes directions for its improvement.

Peculiarities of the occurrence of forest fires and firefighting technologies. A large part of the territory of Ukraine is covered with forests, which are a true national treasure and a source of pride for our people. Forests require careful protection, since their negligent use may lead to destructive consequences. Forest fires are especially dangerous, as they represent one of the most serious environmental threats capable of disrupting the natural balance and causing damage to entire forest areas. Climate change and the growing anthropogenic impact contribute to the increasing frequency with which such fires affect large territories.

In Ukraine, the situation is further complicated by the consequences of hostilities, which increase the likelihood of such disasters. During forest fires, not only are enormous numbers of trees destroyed, but many animals and birds also perish, buildings are damaged, and tremendous material losses occur.

The main hazardous factors of such fires are high temperature, which causes ignition of everything within the combustion zone; thermal radiation, due to which combustible materials may ignite even beyond the fire center; and heavy smoke, which irritates the respiratory tract, negatively affects the psychological state of people, and in severe cases may cause carbon monoxide poisoning.In addition, smoke reduces visibility and complicates the movement of vehicles as well as the work of rescue services.

Despite preventive forest protection measures, the summer months still create favorable conditions for the occurrence and spread of fires. Statistics indicate that every year in Ukraine from 10 to 15 thousand forest fires are recorded over an area exceeding 500 hectares. The main causes of forest fire occurrence include the human factor, which accounts for 60% of cases, negligence of organizations and expeditions (19.7%), logging activities (3.5%), agricultural burning (6.7%), natural factors such as lightning (8.1%), and other causes (2%). Thus, in nearly 90% of cases, the occurrence of forest fires is associated with careless human handling of fire.Thus, in 90% of cases, responsibility for forest fires lies with humans and their careless handling of fire.

An important aspect of forest fire research is also the analysis of the conditions of their spread and the dynamics of their development. A fire in a forest environment is a complex physicochemical process that depends on many variables, among which weather conditions, the structure of vegetation cover, and terrain play a key role.

One of the determining factors is wind, which not only contributes to the spread of flames but also determines the direction of fire movement. In strong winds, the rate of fire spread may increase several times, which significantly complicates the process of localization. At the same time, a change in wind direction may create unpredictable situations that pose a threat to rescuers.

The composition and structure of forest stands are also of great importance. Young coniferous forests, especially pine forests, are characterized by high fire hazard due to the presence of resinous substances that ignite easily. Deciduous forests, by contrast, have lower combustibility; however, when a significant amount of dry vegetation accumulates, they may also become a source of intense burning.

Special attention should be paid to forest litter, which consists of dry leaves, needles, branches, and organic residues. It is often the primary source of ignition and contributes to the transition of a ground fire into a crown fire. The accumulation of a large amount of combustible material increases the risk of rapid fire development even in the presence of minor ignition sources.

Terrain also significantly affects the nature of fire spread. On slopes, fire spreads uphill more quickly, which is explained by the rise of hot air and the preheating of vegetation. In lowlands, by contrast, fires may develop more slowly but are often accompanied by heavy smoke.

Thus, taking into account the complex of natural and anthropogenic factors makes it possible to assess fire hazard more accurately and to develop effective measures aimed at reducing it.

Additionally, it should be taken into account that the intensity and rate of spread of forest fires largely depend on the moisture content of combustible materials. When the moisture content of forest litter and vegetation is low, even a minor ignition source may lead to a large–scale fire. During periods of prolonged

drought, the risk of fire occurrence increases several times, which requires strengthened monitoring of the condition of forest areas.

An important factor is also the seasonality of fire occurrence. The largest number of ignitions is observed in the spring and summer periods, when dry vegetation accumulates and weather conditions are characterized by high temperatures and low humidity. At this time, enhanced fire safety measures and restrictions on access to forest territories should be introduced.

The level of economic development of the territory also has a significant influence on the occurrence of fires. In particular, the presence of forest roads, recreation areas, leisure sites, and forestry operations increases the probability of fire outbreaks due to the human factor. In this regard, the organization of control over compliance with fire safety rules and the implementation of preventive work among the population become especially important. Equally important is consideration of the spatial distribution of fire hazard. Different forest areas have different levels of fire risk depending on the type of vegetation, the age of plantations, stand density, and the presence of combustible materials. This determines the need for zoning the territory according to the level of fire hazard and for a differentiated approach to the organization of protection measures.

Modern scientific studies indicate the expediency of using fire hazard indices that take into account a complex of meteorological and ecological indicators. Such indices make it possible to predict the probability of fire occurrence and to take preventive measures in a timely manner.

In addition, it is important to consider the possibility of the secondary consequences of forest fires, which are manifested in the form of soil erosion, disruption of the water regime of territories, a decrease in forest productivity, and changes in species composition. In the long term, this may lead to ecosystem degradation and the loss of their ecological functions.Thus, the problem of forest fires requires an integrated approach that includes not only the analysis of their causes, but also the assessment of spread conditions, forecasting of fire development, and the development of effective preventive measures. The combination of scientific approaches with practical measures will make it possible to significantly improve the level of protection of forest ecosystems and minimize the negative consequences of fires.

The following types of fires are distinguished:

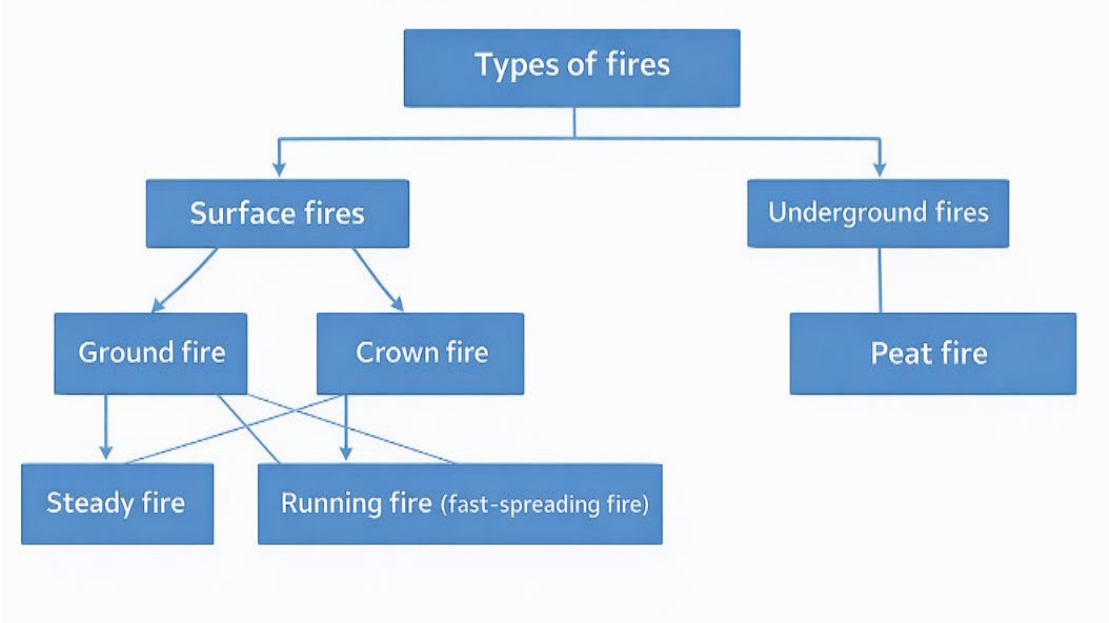

Figure 1. Types of fires

Table 1. Characteristics of forest fire types

No.	Type of forest fire	Characteristics
1	**Surface fire**	A fire that spreads through the forest floor fuel layer, including lichens, mosses, forest litter, grasses, shrubs, woody debris, windthrown material, and logging residues. It may also affect the lower vegetation layer, including young growth and underbrush (see Fig. 1.2).
2	**Fast–spreading surface fire**	A surface fire with a frontal edge moving at a speed of more than 0.5 m/min and characterized by intensive flaming combustion. Such fires cause significant burning of the forest floor cover.
3	**Crown fire**	A fire that spreads through the crowns of forest stands. In this case, a surface fire often acts as a component of the crown fire (see Fig. 1.3).
4	**Sustained crown fire**	A crown fire with an intensity of up to 4 km/h that affects tree crowns and is accompanied by stable surface burning. As a result, almost the entire area is burned out, and only charred tree trunks remain.
5	**Underground fire**	A fire associated with the smoldering of the peat soil layer without open flame (see Fig. 1.4).
6	**Slow–spreading surface fire**	A surface fire with a frontal edge moving at a speed of less than 0.5 m/min, in which combustion occurs mainly in a flameless form, that is, through the smoldering of surface combustible materials.
7	**Running crown fire**	A crown fire spreading at a speed of up to 4 km/h, affecting both tree crowns and the front of a sustained surface fire. As a result, the area may burn out almost completely, leaving only charred remains of tree trunks.

It should be noted that almost any forest fire at the initial stage of its development takes the form of a surface fire and, under appropriate conditions, may develop into a crown fire or an underground fire.

Figure 2. Surface fire

The appearance of surface and crown fires is schematically illustrated in Fig. 2 and Fig. 3, respectively.

Figure 3. Crown fires

The appearance of an underground (peat) fire is schematically illustrated in Fig. 4.

Figure 4. Peatland burning

The occurrence and development of forest fires depend significantly on weather conditions. According to weather conditions, the following fire danger classes are distinguished: no fire danger, moderate fire danger, high fire danger, and extreme fire danger.

The detection of forest fires is critically important for preventing their further spread and reducing their consequences. A rapid response to ignition makes it possible to minimize potential damage and human casualties, as well as to preserve natural resources. However, modern methods of forest fire detection and forecasting are still not sufficiently effective.

Forest fires are a complex process that may break out in any part of a forest. Therefore, it is necessary to have a variety of effective monitoring and detection tools in order to ensure a prompt response. At present, the main methods of forest fire detection are ground–based observation, observation from fire towers, aerial patrols, and satellite observation.

Forest monitoring is a systematic observation of forest conditions aimed at ensuring the effective management and protection of natural resources. This process contributes to the assessment of changes in forest ecosystems, the identification of problems, and the development of strategies to overcome them. Traditional forest monitoring methods are an important means of determining the extent of forest areas, their structure, and species composition. Table 2.

The collection and analysis of meteorological data constitute an important component of traditional monitoring methods that influence the condition and dynamics of forest ecosystem development. Such data include temperature indicators, precipitation levels, air humidity, and other climatic parameters, which make it possible to trace the relationship between climatic conditions and forest health. However, traditional approaches have their own limitations, such as significant time and resource expenditures, limited territorial coverage, and insufficient accuracy and detail of the information obtained. In this regard, it is advisable to combine traditional methods with modern technologies, in particular by applying geographic information systems and remote sensing tools for more effective monitoring and management of forest resources.

Traditional forest monitoring methods demonstrate effectiveness in local studies; however, they also have certain disadvantages. Ground–based observations usually cover only individual sites, which makes it impossible to form a comprehensive picture of the state of the forest ecosystem. In addition, such approaches require considerable human and financial resources. At the same time, modern technologies such as geoinformation analysis, remote sensing, and machine learning algorithms are becoming increasingly popular among researchers and forestry specialists due to their efficiency and innovative approach.

Modern technological development makes it possible to significantly improve the effectiveness of forest ecosystem monitoring through the integration of various data sources. The combination of satellite observation, geographic information systems, and unmanned aerial vehicles provides оперативе and highly accurate information on forest conditions.

Table 2. Main methods for assessing the condition of forest ecosystems

No.	Method name	Method characteristics
1	**Forest area inventory**	This method is based on detailed inventory and forest management processes. Forest inventory involves the establishment of sample plots in designated forest stands and plantations, while forest management planning ensures land delineation, land classification, and the calculation of timber stock according to age categories.
2	**Forest mensuration**	This method is aimed at determining critical stand characteristics such as species composition, age, density, structure, and tree diameters. It enables forest management organizations to understand changes in forest structure under the influence of anthropogenic and natural factors, which is of key importance for maintaining biodiversity and ecological diversity.
3	**Assessment of indicators**	The evaluation of certain indicators of forest stand condition, such as density, tree height, timber volume, as well as the presence of pests and pathogens, helps determine the overall health status of forest areas.
4	**Sample–based regional survey**	This method consists in analyzing tree parameters and forest cover characteristics in selected areas, which contributes to the collection of detailed data on the structure and functioning of forest ecosystems. This creates an in–depth database for further analysis and forecasting of forest dynamics.
5	**Tree condition monitoring**	This method is focused on identifying signs of diseases and pests in trees and assessing their spread, thus allowing prompt control of negative changes and prevention of potential large–scale damage.
6	**Satellite imagery**	This is an effective method for obtaining spectral information on vegetation cover. It makes it possible to assess the condition of forest areas, sanitary condition, logging areas, and other important parameters, as well as to track the dynamics of changes in forest cover over large territories.

Under the conditions of modern information technology development, the use of automated data analysis systems for fire danger forecasting is becoming especially relevant. Such systems are based on mathematical models that take into account meteorological indicators, vegetation condition, historical fire data, and other parameters.

One of the promising areas is the application of machine learning methods, which make it possible to identify hidden patterns in large datasets. This allows the accuracy of fire occurrence forecasting to be improved and preventive measures to be taken in a timely manner.

An important component of modern monitoring is the integration of various sources of information into a single system. For example, the combination of satellite observation data, ground–based sensors, and weather stations makes it possible to obtain a more complete picture of the state of forest ecosystems.

Early warning systems are also being actively introduced, automatically signaling an increase in the level of fire danger. Such systems may be used for the оперативе notification of the relevant services and the population.

The use of modern digital technologies in forest monitoring significantly increases the efficiency of natural resource management and contributes to reducing the risk of large–scale fires.

A special role is played by the use of vegetation indices, in particular NDVI, which makes it possible to assess the condition of vegetation cover and identify areas of stress or damage. This allows potentially dangerous sites, where the risk of fire occurrence is elevated, to be identified in advance.

Thus, the introduction of digital technologies into the monitoring system is a key direction for increasing the efficiency of forest resource management.

One of the most advanced and at the same time effective methods of monitoring forest areas in the 21st century is satellite mapping combined with continuous remote monitoring. The use of satellite imagery makes it possible to obtain an objective and informative assessment of forest condition, track changes in ecosystems, and plan appropriate measures for their conservation. Satellite mapping technologies provide a large volume of relevant data that may be useful for various purposes. For example, by analyzing image tones, the typical green color of forest areas can be identified, since chlorophyll, which is the main pigment of plants, absorbs light predominantly in the green spectrum. This makes it possible to distinguish forested areas and create accurate maps of their location.

Satellite imagery also makes it possible to analyze forest stand density, providing an opportunity to assess forest condition in different regions. Areas with higher tree density are usually represented in darker

shades in images, since tree crowns and branches block sunlight. This makes it possible to identify areas with high forest density, which indicates good forest condition and ecological stability within the relevant territories. This effect is clearly illustrated in Fig. 5 [15].

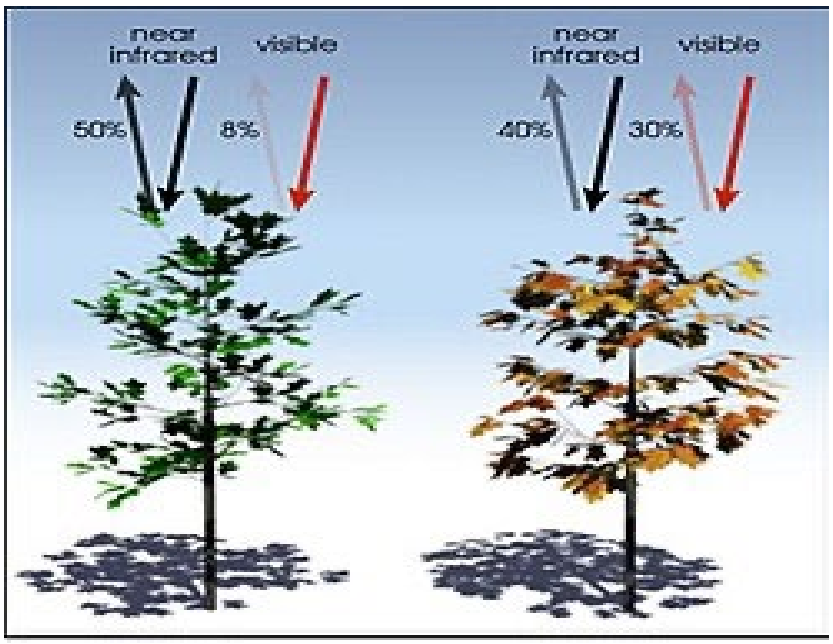

Figure 5. Application of NDVI for the identification of healthy and affected plants

Satellite imagery makes it possible to carry out a detailed analysis of the structure of forest areas. The use of modern data processing algorithms facilitates the identification of different tree species, the determination of crown parameters, and the detection of trees, roads, and other structural elements. This approach ensures the assessment of forest ecosystem biodiversity, the identification of areas in poor condition, and the development of priority measures for their restoration and conservation. See Fig. 6.

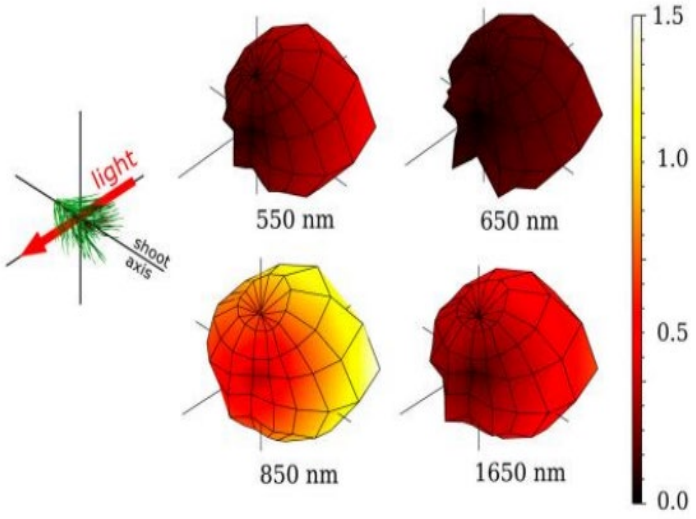

Figure 6. Scattering phase functions of a Scots pine shoot sample measured at four different wavelengths; the illumination geometry is shown in the upper left corner [16].

The analysis of changes in forest cover is one of the key areas of satellite imagery application. Comparing images taken at different time periods makes it possible to assess the dynamics of degradation

processes caused by deforestation, the spread of diseases and pests, as well as spatial changes in the distribution of forest areas. Such information is of crucial importance for the development of strategies aimed at the conservation and restoration of forest resources.

In addition, satellite imagery plays an important role in the detection of forest fires and the assessment of their extent. The analysis of anomalies in the color and structural characteristics of images helps identify the presence of fire and trace its spread. These data contribute to a rapid response, including the organization of fire suppression measures and the minimization of damage caused by natural disasters. Figure 7 presents the spectral reflectance characteristics of certain woody components, such as tree trunks and individual pieces of bark [44].

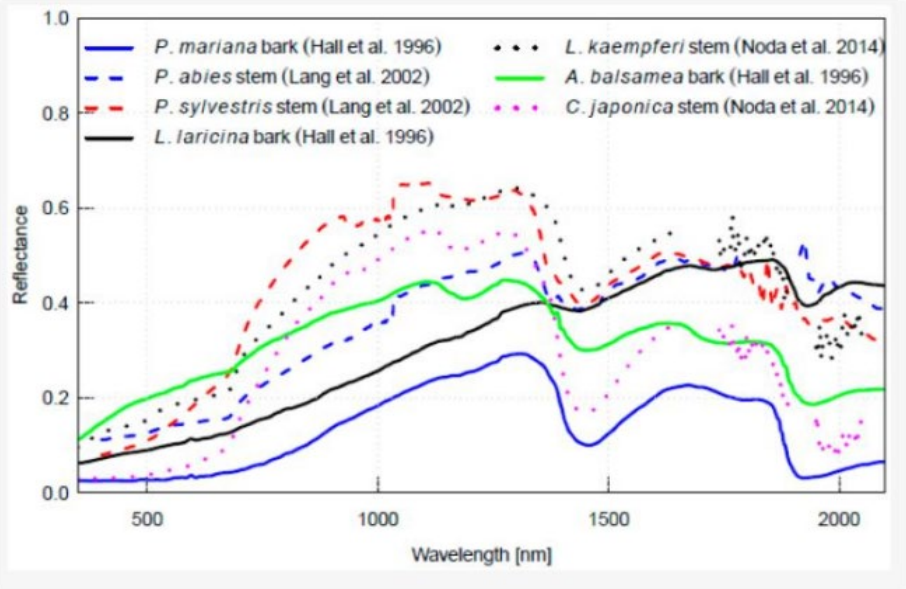

Figure 7. Reflectance spectra of woody components (tree trunks or pieces of bark) [41].

Firefighting technologies. The following methods are used to combat forest fires:

Various methods are used to combat forest fires depending on the type of fire, its scale, weather conditions, terrain, and available resources. In particular, the edge of a surface fire may be beaten with green branches or burlap in order to move burning particles toward the center of the fire and reduce combustion intensity. In addition, the fire edge may be covered with soil using shovels or special devices, which helps mechanically suppress the flames, cool combustible materials, and restrict air access. To limit the spread of fire, mineralized strips and trenches are created with the help of cutters, trench-digging machines, bulldozers, or hand tools, clearing the surface down to the mineral soil layer. One of the effective methods is also backburning, when the area in front of the advancing fire front is intentionally burned to create a protective strip free of combustible material. In certain cases, explosives may be used to create trenches and barriers or to suppress flames by means of ejected soil and shock waves. In order to prevent the uncontrolled spread of prescribed burning, it is carried out from existing control lines, such as forest roads, clearings, ditches, wide watercourses, or specially created mineralized strips. Fire suppression may also be performed with motor pumps, as well as by delivering water from airplanes and helicopters, which cools burning materials and contributes to the cessation of combustion. In addition, chemical agents are used to slow the spread of fire, reduce oxidation processes, cool combustible materials, and limit oxygen access. Under certain conditions, artificial precipitation may also be induced by acting on cloud fronts with special substances delivered by artillery or aircraft. [31].

The application of various firefighting methods requires clear planning and coordination of actions among units. In this context, it is important to determine the optimal fire suppression strategy, which depends on the scale of the fire, its type, and the available resources.

Particular importance is attached to the fire localization strategy, which involves limiting fire spread by creating barriers and carrying out controlled burning. This approach makes it possible to minimize the affected area and reduce risks to the environment.

Modern approaches to fire suppression also involve the use of specialized software tools for modeling fire development. This makes it possible to predict fire behavior and make more informed decisions regarding resource deployment.

An important factor is the safety of personnel involved in firefighting. This requires an adequate level of training, the use of personal protective equipment, and compliance with established safety protocols.

Thus, effective forest fire suppression requires a comprehensive approach that combines various methods and technologies.

The effectiveness of applying different forest fire suppression methods largely depends on the type of fire, weather conditions, terrain, and available resources. For example, mechanical methods (such as the creation of mineralized strips) are most effective for containing surface fires, whereas aerial firefighting is advisable in the case of large crown fires.

Chemical agents help slow the spread of fire; however, their use requires consideration of environmental consequences. In turn, the combined application of different methods (mechanical, water–based, and chemical) ensures the best results in firefighting.

An important component is also the speed of response, since extinguishing a fire at its early stages significantly reduces resource expenditures and the scale of damage.

In addition to traditional forest fire suppression methods, innovative technologies and approaches are becoming increasingly important under modern conditions. In particular, unmanned aerial vehicles equipped with thermal imaging cameras are being actively introduced, making it possible to rapidly detect fire outbreaks even in hard–to–reach areas and under conditions of limited visibility.

An important direction of development is the use of geographic information systems (GIS), which ensure the integration of various types of data–meteorological, topographic, and satellite data–for the creation of detailed fire danger maps. This makes it possible not only to respond promptly to fires but also to plan preventive measures.

Modern methods also include the use of automated fire detection systems based on smoke, temperature, and infrared radiation sensors. Such systems provide continuous monitoring of territories and significantly reduce response time to ignition.

Of particular importance is the application of mathematical models for predicting fire spread. These models take into account wind speed, vegetation type, terrain, and other factors, making it possible to determine the probable direction of fire movement and optimally allocate forces and resources for its suppression.

An important aspect is the environmental safety of the methods applied. Certain firefighting agents, particularly chemical substances, may have a negative impact on the environment; therefore, their use must be justified and controlled. In this regard, environmentally safe technologies, such as the use of water vapor, bio–based foams, and the minimization of interference with natural processes, are gaining increasing popularity.

The issue of logistics and firefighting support is no less important. The effectiveness of fire suppression largely depends on the speed of equipment delivery, the availability of water resources, the condition of roads, and the organization of interaction between units. Under difficult conditions, mobile command posts are used to ensure real–time coordination of actions.

Special attention should be paid to personnel training, since the success of fire suppression depends not only on technical support but also on the professional skills of rescuers. Regular drills, training, and emergency response exercises are a necessary condition for improving the effectiveness of fire units.

Thus, the modern forest fire suppression system should be based on a combination of traditional methods and the latest technologies, ensuring a comprehensive approach to solving this problem. The integration of innovative solutions, improvement of organizational capacity, and efficient use of resources make it possible to significantly reduce the scale of fires and minimize their negative consequences for the environment and society.

Particular attention should also be paid to the issues of strategic fire risk management, which involves the systematic analysis of potential threats and the development of long–term fire prevention measures. Such an approach is based on assessing the probability of fire occurrence, identifying the most vulnerable forest areas, and developing appropriate response scenarios. This makes it possible not only to reduce the number of fires but also to minimize their consequences if they occur.

An important element of the modern fire protection system is the implementation of the principles of risk–oriented management. These principles provide for the priority allocation of resources to the most dangerous areas characterized by high fire load, a significant amount of dry vegetation, or difficult access

conditions. Such an approach increases the efficiency of resource use and ensures a more rational organization of fire protection measures.

In addition, the integration of fire protection systems with other areas of forestry plays a significant role. In particular, sanitary cuttings, tending of forest plantations, clearing of logging residues, and the creation of firebreaks contribute to reducing the amount of combustible material and lowering the risk of fire occurrence. Thus, preventive measures are an integral component of an effective protection system.

Consideration of the social factor is equally important. A high level of fire danger is largely associated with human activity; therefore, information and awareness–raising work among the population is one of the key directions of prevention. The organization of educational campaigns, installation of warning signs, restriction of access to forests during fire–hazard periods, and strengthening control over compliance with fire safety regulations make it possible to significantly reduce the number of ignition cases.

Under modern conditions, the development of automated decision support systems is also an important direction. Such systems use large volumes of data and make it possible to quickly assess the situation, predict fire development, and determine the optimal ways of suppressing it. The use of artificial intelligence and data analysis algorithms opens up new opportunities for improving the effectiveness of fire safety management.

The issue of adapting the fire protection system to climate change is of particular importance. Rising air temperatures, reduced precipitation, and longer dry periods require a revision of existing approaches to the organization of fire safety. This involves improving forecasting systems, increasing the readiness of fire units, and introducing new firefighting technologies.

Thus, effective forest fire suppression should be based on a combination of preventive, organizational, technical, and innovative measures. Only a comprehensive approach that takes into account natural, technogenic, and social factors can ensure an adequate level of protection of forest ecosystems and minimize the negative consequences of fires.

Research Conditions. The State Enterprise “Krasnopilskyi Agrolisgosp” is located in the south–eastern part of Sumy Oblast and covers an area of 11,522 hectares. The forests in this area develop under conditions of a temperate continental climate with a sufficient amount of precipitation. However, certain natural factors, including high air temperature, low soil moisture, and the presence of young coniferous plantations, may contribute to the risk of fire occurrence and spread. Water bodies and rivers in the region can significantly assist in fire suppression; however, their effectiveness decreases when precipitation is insufficient.

The total area of the forest fund assigned to the enterprise is 11,522 hectares, of which 9,548.1 hectares are covered with forest vegetation. These territories are used for various purposes, including environmental protection, historical and cultural purposes, scientific research, recreation and health improvement, and protective functions.

According to forest site zoning, the territory of the agrolisgosp belongs to the North–Eastern Sumy Forest–Steppe. Oak forests, maple–linden–oak forests, and floodplain meadows typical of the Central Russian Forest–Steppe District predominate here. This zoning was developed by the specialist S. A. Hensiruk.

The climate in the area of the enterprise is temperate continental. It is characterized by a long warm summer with a moderate amount of precipitation and a relatively mild winter.

The natural conditions of this region may contribute to the occurrence of forest fires. For example, high temperatures combined with low soil moisture increase the risk of ignition and complicate fire suppression. The presence of a significant proportion of deciduous tree species increases the amount of combustible material, facilitating the spread of flames. At the same time, rivers and ponds provide the necessary access to water for fire suppression; however, in periods of precipitation deficit, the water level in these bodies may decrease, which makes firefighting more difficult.

The organization of forest fire protection involves the implementation of a systematic set of measures aimed at preventing the occurrence and spread of fires, as well as ensuring the prompt and effective elimination of ignition sources. This process includes several key stages:

Introduction of modern technologies. The use of innovative methods for fire detection and monitoring, in particular drones with thermal imaging cameras and satellite observation systems. However, under the current conditions of martial law, such methods are limited, since the use of drones is prohibited in border regions.

Monitoring of the forest environment. Continuous observation of forest areas to ensure the timely detection of threatening factors and the application of preventive measures.

Development of fire protection plans. The creation of detailed response strategies in the event of fire occurrence, including cooperation with other emergency rescue services and ensuring the availability of the necessary resources and equipment.

Organization of training activities. Regular improvement of personnel qualifications in the field of fire safety, the conduct of training sessions, and the provision of proper theoretical and practical training in specialized institutions.

Interaction with local communities. Active involvement of the local population in the fire prevention process through awareness campaigns, training activities, and close cooperation with the media to disseminate information on fire danger.

Formation of a specialized fire protection service. Establishment of an organization responsible for the detection, localization, and suppression of fires, equipped with appropriate resources and qualified personnel.

Establishment of fire safety standards. The development and implementation of clear regulations prohibiting activities that may potentially cause ignition, such as open burning, smoking, or the use of firearms near forests.

The effective organization of the forest fire protection system also requires a clear distribution of functions and responsibilities among different stakeholders. These include state authorities, forestry enterprises, rescue services, and local communities.

The coordination of their activities is carried out through the creation of unified management centers that ensure prompt decision–making and control over the implementation of measures.

The issue of financing is equally important, since ensuring an effective fire protection system requires substantial material resources. Investment in modern technologies, equipment, and personnel training is a necessary condition for improving the effectiveness of this system.

International cooperation also plays an important role, as it makes it possible to adopt advanced experience and implement best practices in the field of forest fire management.

In conclusion, only a comprehensive approach to the organization of fire protection can ensure an adequate level of safety for forest ecosystems.

The organization of forest fire protection should be based on the principles of systematicity, continuity, and adaptability. This means that all measures should be interconnected and aimed not only at fire suppression, but also at fire prevention.

An important element is the creation of an integrated management system that includes monitoring, forecasting, planning, and operational response. Such a system makes it possible to ensure effective coordination among different services and the optimal use of resources.

In addition, it is necessary to take into account international experience in the field of forest fire management, which involves the active use of digital platforms, automated alert systems, and analytical forecasting models.

All the above–mentioned measures are basic elements of the forest fire protection system aimed at preserving natural ecosystems.

Assessing the effectiveness of the monitoring and observation system for forest fires is a key stage in determining the success of measures aimed at protecting forests from fire. This process includes the analysis of various types of data, such as the results of monitoring potential fire risks, the prompt detection of ignitions at early stages, the timeliness of response to incidents, and the effectiveness of fire suppression measures.

During the assessment, actual results are considered in comparison with the planned goals and indicators. Important aspects include the accuracy and speed of fire detection, the effective use of available resources and equipment, the scale of fire spread, as well as the assessment of damage caused to the natural environment and people. Such actions make it possible to identify the strengths and weaknesses of the existing system, highlight problematic areas, and propose measures to improve fire management strategies. The obtained results serve as a basis for making rational decisions and developing updated fire protection strategies.

The key factors affecting the effectiveness of forest protection measures are presented below:

The effectiveness of forest protection measures depends on several key factors. One of the most important among them is the speed of fire detection, since the timely identification of an ignition source makes it possible to respond rapidly and prevent the fire from spreading over large areas. Equally important is the accuracy of determining the fire location, because effective resource management and proper organization of response actions depend on correct localization. A significant role is also played by alert and communication systems, as well-established coordination between stakeholders and the rapid transmission of information minimize response time and support efficient decision-making. In addition, the promptness of fire response

and suppression is essential, as the ability to mobilize the necessary personnel, machinery, and equipment in time significantly reduces the scale of damage and contributes to successful fire localization at the early stages.

The implementation of regular assessment and improvement of monitoring and response systems is an integral component of the long–term strategy for combating forest fires [36].

Research Results. The use of measures aimed at protecting forest plantations from forest fires is an important component of forestry activities [38]. Several methods and measures applied at the specified enterprise to protect forests from fires are presented below:

Monitoring and surveillance: this measure includes fire warning systems that may be installed in forests, continuous patrolling and observation for the presence of fires, awareness–raising activities among the population, and the installation of special mechanical barriers along the potential path of fire spread. Owing to this measure, incidents can be detected at the initial stages of their development (Table 3).

Table 3. Preventive and precautionary forest fire protection measures Implemented at the enterprise

Measure	Result
Barriers manufactured and installed	3
Warning signs installed	4
Maintenance of mineralized strips and firebreaks	Not carried out due to the evacuation of the population from the Krasnopillia and Myropillia territorial communities and the destruction of infrastructure in the villages and settlements of the district
Preventive talks at schools on compliance with forest fire safety rules	Not carried out
Presentations in the mass media	Not carried out

The organization of patrolling and fire suppression is an important component of the strategy for protecting forest areas. Regular inspection of forests contributes to the detection of potential fires at an early stage and enables an immediate response. Foresters use fire extinguishers, fire tankers, and other specialized equipment, which is listed in detail in Table 3.

Table 4. Forest firefighting equipment available at the enterprise

Total firefighting equipment, units	ZIL	Others	Availability of motor pumps	Availability of RLO
0	0	0	1	10

Firebreak corridors are clearings created by removing vegetation along the boundaries of forest areas or between individual forest sections. They are intended to reduce the intensity and rate of forest fire spread by serving as buffer zones.

Informing the public and forest users is one of the key aspects of ensuring fire safety. Priorities include educational activities regarding fire safety rules, explanation of bans on the use of open fire in hazardous areas, as well as reminders about the need to promptly notify the relevant services in the event of fire occurrence. The timely dissemination of such knowledge can significantly reduce the number of fire incidents.

Technical means and equipment also play a special role in fire protection. They are used for the prompt detection of ignition sources, the direct suppression of fires, and their further localization. Such means include fire engines, aviation resources, in particular helicopters, water supply systems, hand tools for firefighting, and other specialized equipment. An important aspect of the effective functioning of this equipment is regular technical maintenance, as well as systematic personnel training through drills. Thus, all available resources at the disposal of the relevant services require a comprehensive and coordinated approach in order to ensure maximum effectiveness in combating forest fires. The available resources of the agrolisgosp are listed in Table 5.

Table 5. Availability of fire suppression resources and firefighting equipment [14]

No.	Name of firefighting equipment and fire suppression resources	Availability as of 01.01.2025
1	Fire engines AC–40 and ARS–14	0
2	Forest fire modules	1
3	Patrol vehicle	2
4	Motor pumps	1
5	Fire beaters	7
6	Fire hoses	80
7	Fire nozzles	2
8	Wheeled tractors	2
9	Forest ploughs, soil throwers	1
10	Backpack forest fire extinguishers	10
11	Chainsaws	1
12	Shovels	25
13	Axes	5
14	Rakes	10
15	Wetting agents	0
16	Canisters	10
17	Radios, total	1
18	Duty clothing and special footwear	10
19	First aid kits	1
20	Cups for drinking water	15
21	Containers for drinking water	3

The implementation of the fire protection action plan at the enterprise involves the following stages:

The implementation of the fire protection action plan at the enterprise involves several interrelated stages. First of all, it is necessary to develop a list of measures aimed at ensuring fire safety, taking into account existing risks and current legislative requirements. After that, responsible persons or teams should be appointed to organize the implementation of the plan and supervise its execution. An equally important stage is the provision of the necessary resources, including materials, equipment, and funding, required for carrying out the planned activities. The next stage involves the practical implementation of preventive and operational measures intended to prevent fires and ensure safety. At the same time, continuous monitoring of the implementation process should be carried out in order to promptly identify shortcomings and improve the effectiveness of the fire protection system. In addition, fire safety plans and procedures must be regularly updated with regard to technological development, new regulatory requirements, and conclusions drawn from previous experience.

The analysis of forest protection measures at the enterprise demonstrated the effectiveness of certain methods. The monitoring system confirmed its efficiency by enabling the detection of fires at their initial stages. Patrolling and prompt fire suppression are key components of fire management. Educational and informational campaigns among the public contributed to raising awareness and fostering a responsible attitude toward forest resources. For the effective protection of forest plantations, it is necessary to apply various methods and means, taking into account the specific features of local conditions and landscape characteristics.

The conducted analysis indicates the positive impact of the implemented measures on reducing the level of fire danger. In particular, there is a tendency toward a decrease in the number of ignition cases and the area of damaged territories.

At the same time, the obtained results indicate the need for further improvement of the fire risk management system, in particular through the expansion of the material and technical base, an increase in the level of automation of monitoring processes, and improved coordination between services.

Thus, the effectiveness of fire protection measures directly depends on the comprehensiveness of the approach and the level of implementation of modern technologies.

The assessment of the effectiveness of the forest fire monitoring and control system is one of the key stages in determining the success of measures aimed at protecting forests from fire. This process includes the analysis of a large volume of data, including the results of monitoring fire danger levels, the timeliness of fire detection, the promptness of response to fire incidents, and the effectiveness of fire suppression [1].

As part of the assessment, actual achievements are compared with planned goals and performance indicators. This includes the analysis of such parameters as the accuracy and speed of fire detection, the optimal use of resources and equipment, as well as the assessment of the scale of fire spread, its destructive impact on the environment, and the risks to human life [49].

The results of such an assessment help identify the strengths and weaknesses of the monitoring system, determine critical problem areas, and make it possible to formulate proposals for improving forest protection measures and strategies. On the basis of these data, appropriate measures are developed to enhance the effectiveness of fire protection.

The main factors influencing the effectiveness of fire protection measures are described below:

Fire detection. An important characteristic is the speed of ignition detection. The use of modern technologies–satellite systems, drones, and automatic fire indicators–makes it possible to significantly improve this parameter [4].

Geolocation accuracy. Providing precise coordinates of the fire location is crucial for effective resource management and response. Such tools as modern geographic positioning systems ensure a high level of accuracy [20].

Alert and communication systems. The level of effectiveness of interaction between the services involved in fire suppression is analyzed. Automated alert systems and clear coordination of unit activities have a positive impact on response effectiveness [31].

Promptness of response and fire suppression. The capabilities of resource provision (firefighting equipment and machinery) and staff qualifications are evaluated. Clearly organized and rapid response facilitates fire localization at the initial stages, minimizing its impact [22].

Special attention is also paid to the assessment of fire protection lines, that is, their contribution to restraining the spread of fire. The key aspects of such an assessment include:

Width and length. The lines must be wide enough to stop the fire while at the same time covering the entire area of potential risk.

Condition and maintenance. Regular clearing of vegetation and ensuring accessibility for rescuers and equipment significantly increase the effectiveness of the lines [21].

Location. The placement of fire lines should cover the most hazardous areas and take into account natural barriers.

Analysis and adaptation. Continuous monitoring and updating in accordance with environmental or climatic changes increase their effectiveness [29, 37].

The analysis of data from the Forest Fire Record Book, in which all fire incidents within the enterprise territory are registered, made it possible to establish that the number of fires per year after the implementation of preventive measures in 2023 decreased compared with the period prior to the introduction of these measures. At the same time, this decrease may be partially explained by the reduced number of forest visitors during 2023, which accordingly lowered the probability of fire occurrence. This aspect may be characterized as a human factor, which is difficult to influence significantly due to the limited number of available tools, in particular preventive talks and lectures, which often demonstrate insufficient effectiveness. Despite this, the problem of fire occurrence remains relevant. However, it should be noted that in the period from 2022 to 2023, not a single fire was recorded within the enterprise territory, whereas in 2021 and previous years, two to three fire incidents were usually registered annually (see Table 6).

It is advisable to evaluate the effectiveness of fire protection efforts on the basis of the efficiency of preventive measures. In this context, attention should also be paid to the positive trend in the reduction of the area affected by fires. In particular, the average area of forest land damaged by fire in 2021 amounted to 0.5 km², whereas in previous years it reached 2.8 km² (see Table 6). Thus, the results of the implemented measures demonstrate a favorable trend. This provides grounds for asserting that the preventive actions introduced within the enterprise territory are effective in preventing the occurrence and spread of forest fires.

Table 6. Forest fires on the territory of the enterprise

Date	Area at the time of fire occurrence	Forest area affected by the fire
06.06.2015	0.4	0.7
30.06.2015	1.2	3.2
25.07.2015	0.6	0.6
27.08.2016	0.3	0.5
08.09.2016	0.3	0.3
18.07.2017	0.8	1.0
20.08.2017	0.7	1.2
22.08.2019	0.4	4.2
17.09.2021	0.5	0.7
31.07.2022	1.0	1.5
28.08.2023	1.3	2.0
02.08.2024	2.0	2.1

The analysis of the data presented in Table 6 and visualized in Figure 8 in the form of a graph allows for a well-grounded conclusion that the positive results achieved are not accidental. They are the result of a systematic approach to organizing fire safety and the effective implementation of a комплекс of preventive measures at the enterprise. In particular, the graph clearly shows a steady downward trend in the number of fire incidents over the studied period, which indicates an increased level of control and timely response to potential threats.

Particular attention should be paid to the effectiveness of fire response teams. Due to their оперативність and coordinated actions, in most cases fires are successfully localized at early stages. This is confirmed by the data for 2021, where the fire area at the time of detection is almost equal to the final burned area. Such a result indicates a high level of preparedness of the services and the effectiveness of early fire detection systems.

The evaluation of the implemented measures also confirms their significant contribution to reducing the risk of fire occurrence. In particular, firebreaks (mineralized strips) and specially equipped fire lines play an important role. They not only limit the spread of fire but also create conditions for rapid access of firefighting equipment to ignition sites. The availability of appropriate infrastructure – including roads, water sources, and observation points – significantly increases the efficiency of fire suppression.

In addition, territory monitoring is an important component of the system. The use of modern surveillance tools, including video monitoring, satellite observation, and unmanned aerial vehicles (drones), makes it possible to quickly detect fire outbreaks even in hard-to-reach areas. Patrolling and regular inspections have also proven their effectiveness, as they contribute not only to fire detection but also to prevention by ensuring compliance with fire safety regulations.

At the same time, despite the achieved results, there is still potential for further improvement of the system. In particular, it is advisable to strengthen coordination between different fire service units, implement unified digital platforms for real-time information exchange, and expand the use of innovative technologies such as automated risk analysis and fire prediction systems.

Additionally, attention should be given to improving staff qualifications, conducting regular training and drills, and enhancing the regulatory framework. The comprehensive implementation of these measures will not only maintain the achieved level of safety but also ensure further reduction of fire risks.

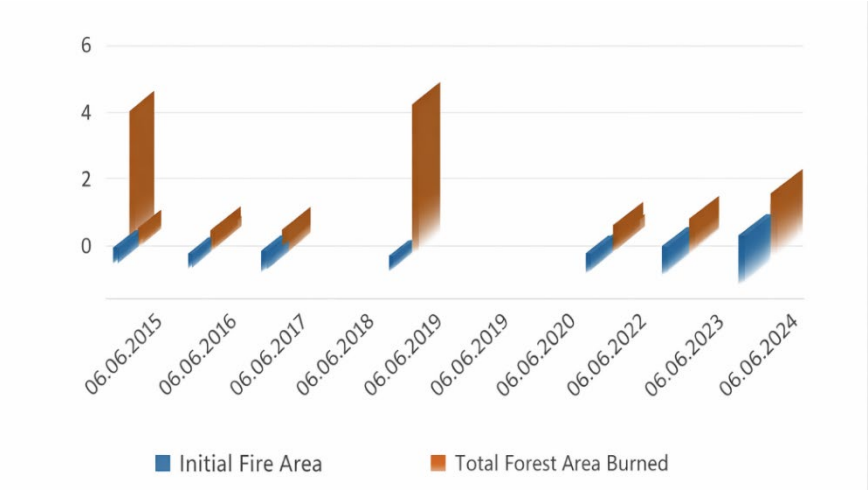

Figure 8. Dynamics of fire occurrence within the agrolisgosp territory

Thus, the results of the study clearly demonstrate that a systematic approach to fire protection – including infrastructure solutions, monitoring, patrolling, and rapid response – is an effective tool in combating fires and ensuring the safety of the enterprise.

After the end of military operations in the forest areas under the ownership of the agrolisgosp, it would be advisable to improve the system of interaction between fire services and introduce innovative technologies for monitoring potential threats. The application of such solutions would significantly increase the level of safety and provide even better fire protection for the enterprise.

Knowledge of the specific features of forest fire spread, as well as the rate of its propagation along the front, flanks, and rear, is essential for analyzing its further behavior. This makes it possible to accurately assess the area of ignition within a certain territory over a specific period of time and to optimally plan measures for fire localization and suppression. Such an approach contributes to the effective calculation of the resources and technical means required for emergency response, as well as for the protection of residential areas and other strategically important facilities located within the risk zone.

The introduction of adjusted coefficients and the refinement of the geometric shape of forest fire spread would improve the quality of managerial decision–making regarding the localization and elimination of ignitions. This would also have a positive effect on the efficiency of allocating human resources and equipment involved both in firefighting and in preventing threats to settlements, material assets, and infrastructure.

One of the main reasons for the insufficient effectiveness of measures aimed at the prevention and suppression of forest fires in the modern context is a whole range of factors:

One of the main reasons for the insufficient effectiveness of measures aimed at preventing and suppressing forest fires under modern conditions is a combination of interrelated problems. These include the unsatisfactory level of preventive work with the population regarding fire safety both in forest areas and in settlements, the insufficient provision of local self-government bodies with the resources necessary for fire prevention and suppression, the lack of a trained network of volunteer fire brigades or instructors in many forest regions, the absence of an effective system for informing citizens about emergencies and alerting them during such events, the shortage of firefighting resources including specialized equipment and water supply sources, as well as the accumulation of flammable waste and weeds around settlements.

To eliminate these problems and reduce the catastrophic consequences of natural forest fires, it is necessary to improve a set of preventive and operational measures, which may be divided into two groups:

Organizational and legal measures should include the improvement of the legislative framework regulating the protection of forest ecosystems and the sustainable development of forestry, the development of modern methods for monitoring and forecasting forest fire spread, including improved algorithms for calculating fire danger indicators, and the intensification of information and awareness-raising work among the population through media platforms. They should also involve strengthening control over compliance with fire safety regulations in areas adjacent to forest stands, economic facilities, and recreation sites, creating specially equipped recreational zones arranged in accordance with fire safety requirements, expanding opportunities for the rapid collection, analysis, and transmission of information on forest fires to the relevant

services, and improving methods for carrying out urgent emergency rescue operations during the elimination of large-scale fires.

Engineering and technical measures should include the creation of firebreaks, mineralized strips, and protective forest edges intended to limit the spread of forest fires, as well as the preparation of the resources and means necessary for preventing their occurrence and ensuring effective suppression. Such measures should also provide control over the level of preparedness of forces and equipment for counteracting fire danger, including the deployment of operational groups to regions with an increased risk of forest fires. In addition, they should involve regulating the condition of forest ecosystems through the optimization of stand composition, the clearing of logging sites, the removal of clutter from non-logging areas, and the carrying out of sanitary cuttings and similar operations. Considerable importance should also be attached to improving methods, technologies, and means of forest fire detection, including continuous duty at fire observation posts and towers, the integration of satellite and aerial monitoring systems, and ground patrolling. Another important task is the creation and training of non-staff fire-rescue units in settlements and at economically important facilities located in or near forest areas.

This set of measures is aimed at increasing the effectiveness of the system for preventing large–scale forest fires, reducing their negative consequences, and ensuring coordinated interaction among the management structures of the Unified State System for Emergency Prevention and Response, local self–government bodies, executive authorities at various levels, and specialized units for suppressing natural fires.

Conclusions

As a result of the conducted research, the problem of the occurrence and spread of forest fires within the State Enterprise “Krasnopilskyi Agrolisgosp” was comprehensively analyzed, and a set of organizational, technical, and preventive measures aimed at improving the efficiency of fire protection of forest ecosystems was substantiated.

It was established that forest fires are a complex multifactorial phenomenon, the occurrence of which is caused by the interaction of natural and anthropogenic factors. At the same time, the human factor plays a decisive role and in most cases is the main cause of ignitions. Climatic conditions, in particular elevated temperatures, prolonged dry periods, and low humidity, also create a favorable environment for the rapid development of fires.

During the study, the characteristics of forest plantations within the enterprise territory that affect the level of fire danger were analyzed. In particular, the presence of coniferous species, a significant amount of forest litter, and dry vegetation increase the probability of fire occurrence and spread. At the same time, natural water bodies may act as a restraining factor, although their effectiveness depends on hydrological conditions.

The assessment of the existing monitoring and observation system showed that it is generally effective, especially in terms of early fire detection. At the same time, it was found that traditional monitoring methods have certain limitations related to insufficient territorial coverage and significant resource expenditures. In this regard, the expediency of introducing modern technologies, in particular remote sensing of the Earth, geographic information systems, and automated data analysis systems, was substantiated.

The conducted analysis of measures aimed at protecting forest plantations from fires confirmed the effectiveness of applying a set of preventive and operational actions, such as patrolling, the creation of mineralized strips, the use of specialized equipment, and informational and awareness–raising work among the population. It was established that timely detection and prompt response are the key factors in the successful localization of fires and the minimization of their consequences.

The analysis of statistical data indicates a positive trend toward a reduction in the number of fires after the implementation of appropriate measures, which confirms their practical effectiveness. At the same time, a number of problems were identified, in particular insufficient material and technical support, limited financial resources, as well as imperfections in the system of informing and interaction between services.

Based on the conducted research, improvements to the fire protection system were proposed, including the introduction of innovative monitoring technologies, an increase in the level of process automation, the development of an early warning system, as well as strengthened coordination among all stakeholders.

Particular attention should be paid to increasing the level of environmental awareness of the population, which would make it possible to reduce the number of fires caused by the human factor. The development of the system of staff training and professional preparation is also important, as it will ensure a more effective response to emergency situations.

Promising directions for further research include the development and implementation of intelligent fire safety management systems based on artificial intelligence technologies, big data analysis, and mathematical modeling. This would make it possible to increase the accuracy of fire danger forecasting and improve the effectiveness of managerial decision–making.

Thus, the results of the study confirm the need for a comprehensive approach to the organization of forest fire protection, combining traditional methods and modern technologies, ensuring the efficient use of resources, and contributing to the preservation of forest ecosystems.

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