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Original Research

Evaluation of Natural Fire Hazard Factors of the Forest Area in the Kostanay Region

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Abstract

This study is conducted to determine the degree of natural fire hazard in the territory of the Kostanay region using remote sensing data. The Kostanay region belongs to the group of heightened danger with favorable climatic conditions for the occurrence of fires. The combination of insufficient moisture with a shift towards a more arid continental climate creates a natural environment for the occurrence of forest fires. This work aims to improve the methodology for the integrated assessment of natural factors and conditions influencing the occurrence of forest fires using remote sensing data, allowing to determination of the degree of natural fire hazard in the territory of the Kostanay region. For the integrated assessment of natural fire hazards using remote sensing data, we identified and mapped the main natural factors (fuel, geomorphological, and meteorological) influencing the occurrence of forest fires. The verification of the developed zoning models for the territory based on the degree of risk of occurrence and the intensity of the spread of forest fires, grounded on the study of ignition points, confirmed the accuracy of the identified zones. The majority of fires occur in high and extreme-risk zones.

Keywords: forest, natural fire hazard, remote sensing data, Geographic Information System (GIS), Kostanay Region

Introduction

The provided text discusses the current consequences of climate warming in the Northern Hemisphere, specifically the increase in extreme climate events [1]. In modern climate conditions, the repercussions of anthropogenic impact on the natural environment are exacerbated, and the dynamics of its recovery require a considerable amount of time.

According to N.P. Kurbatsky, wildfires are a powerful factor in the destruction, regeneration, and formation of forests [2]. With changes in climatic conditions and the spread of flourishing flora in forested areas, wildfires have become one of the leading natural factors [3]. Forest fires are a natural factor that, in some cases, determines the type of landscape and its spatial-temporal dynamics. The occurrence and spatial spread of forest fires are influenced by natural factors and conditions, such as climatic and phytocenotic factors, which determine the conditions of the fire and its consequences. Human activity further increases the spatial impact of forest fires [4, 5].

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The spread of fire in a forest area, uncontrolled by humans, occurs when three factors are present: combustible materials, a source of ignition, and weather conditions conducive to the ignition of these materials. Fires typically start with the burning of dry leaves of trees and forest litter, then engulf the entire forested area. The risk of fires in forests from various sources of ignition is associated with weather conditions that determine the dryness of combustible materials. Forest fires most commonly occur during the fire-prone season. Climatic conditions (such as drought) and features of regional vegetation influence the frequency of fires, with the spring and fall periods characterized by a higher number of fires compared to the summer period.

The frequency of forest fires is increasing due to the constant expansion of industrial development in the natural environment, population growth, and the growing importance of forests for recreation [4, 6]. The trend of an increasing number of forest fires is also expected in connection with the forecast of climate warming [7].

A forest fire leads to a transformation in the entire landscape structure, and it also reduces forest properties such as stability, water conservation, environmental protection, and other characteristics. Additionally, the pyrogenic factor poses a danger to the population [8, 9]. The recovery of forest landscapes is determined by landscape self-organization under modern climate conditions, and the direction of the recovery process may develop towards changing the invariant. Post-fire succession depends on various factors, such as geographical location, climate, vertical and horizontal structure of natural systems, relief characteristics, topographical conditions, tree species, successional phase, and the presence of seed sources [10, 11].

After the impact of the pyrogenic factor, components of the natural environment change in various kinds. In the case of ground fires, the main impact is on the lower vegetation layers, primarily the forest floor, and the duration of their recovery depends on the forest type. In spruce forests of the green moss type, the death of lichens and mosses is caused not only by the fire but also by the heat impact [12], and the recovery of the forest floor may take 2-3 years or more [13].

The resilience of forests to the pyrogenic factor is determined by the morphological and physiological characteristics of tree species. According to P.A. Tsvetkov [14], the pyrogenic index of forest species is a combination of properties resistant to forest fires developed through phylogenesis. Therefore, the pyrogenic properties of wood can be classified as biological-geographical.

The research object is the territory of the Kostanay region, located in the northern part of the Republic of Kazakhstan. The forest vegetation in the region includes birch, aspen-birch forests, and pine forests. White poplar, wood willow, black alder, buckthorn, pine, and even cedar (in the relic cedar-birch grove in the Taranovsky district) are found to grow, while saxauls are encountered in the southern part.

According to the map of fire-prone areas in the Republic of Kazakhstan, the territory of the Kostanay region falls into the category of increased danger with favorable climatic conditions for the occurrence of fires [15]. The combination of insufficient moisture with a shift towards a more arid continental climate creates a natural environment for the occurrence of forest fires.

Modern RS (Remote Sensing) systems provide the capability to obtain both overview and detailed information about natural fires of various scales. In the Kostanay region, with its vast territory, the use of satellite fire monitoring methods is particularly relevant, as controlling fires scattered over a giant area (more than 196 thousand square kilometers) using traditional ground methods is costly and complex.

The goal of this work is to improve the methodology of integrated assessment of natural factors and conditions influencing the occurrence of forest fires, using remote sensing data, enabling the determination of the degree of natural fire hazard in the territory of the Kostanay region.

To determine the probability of fire occurrence risk, we have studied the natural conditions and their influence on the potential spread of fire and evaluated 12 types of initial data in the territory of the Kostanay region.

The novelty of this work lies in the development of a methodology for assessing natural factors and conditions affecting the occurrence of forest fires based on the study of complex natural causes of their emergence, using RS (Remote Sensing) and GIS technologies. The innovative contribution of the authors lies in the selection of all-natural factors influencing the occurrence of forest fires, using RS and GIS technologies.

For the first time in the Kostanay region, a fire hazard forecast map has been created using RS (Remote Sensing) and GIS technologies to monitor the condition of potentially hazardous areas and control the dynamics of their development to develop recommendations for their prevention.

Material and Methods

The main stages of the integrated assessment of natural fire hazards are presented in Fig. 1.

At the first stage, factors of natural fire hazard are determined, i.e., factors that influence or may influence the occurrence and spread of natural fires.

At the second stage, based on the local features of the research region and using the selected fire hazard factors, we developed an assessment scale. The weighting coefficients of the factors were established using an expert method based on ranking the factors according to the degree of natural fire hazard (Table 1).

All factors are divided into three main groups: fuel, geomorphological, and meteorological, most of which have a cumulative effect, meaning fires occur due to the cumulative impact of these factors on the environment.

The fuel factor is a significant factor and is formed based on three vegetation spectral indices: NDVI (Normalized Difference Vegetation Index), NDMI (Normalized Difference Moisture Index), and EVI (Enhanced Vegetation

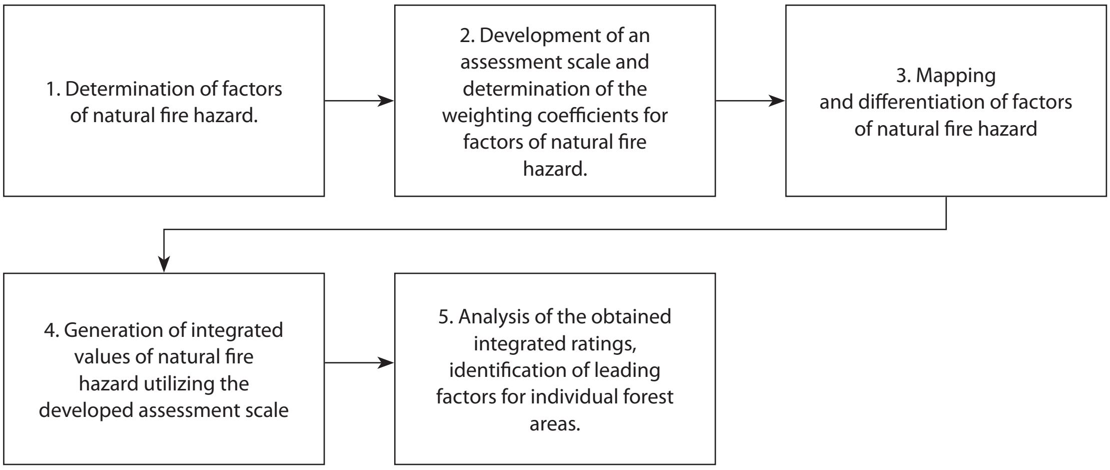

Fig. 1. Block diagram of integrated assessment of natural fire hazard.

Index). These indices were obtained using data from the Landsat 8 satellite before the occurrence of the fire.

NDVI (Normalized Difference Vegetation Index) is an index that reflects the productivity and biomass of vegetation cover [16]. A positive correlation between NDVI and the number of fires is observed due to an increase in biomass volume with the age of forest stands. Thus, the risk of fires is elevated in mature forest stands.

NDMI (Normalized Difference Moisture Index) is an indicator of vegetation and soil moisture, playing a crucial role in assessing the potential and severity of forest fires [17]. Moisture present in the soil and vegetation reduces the risk of natural fires and diminishes their energy in case of ignition. Soil moisture-holding capacity, evaporation rate, and precipitation depth play an important role for each soil type.

EVI (Enhanced Vegetation Index) is an index of vegetation productivity that reflects structural changes in vegetation cover (e.g., leaf area index, plant type, and architecture) and is particularly suitable for forested areas [18]. Changes in the amount and distribution of fuel over time, caused by vegetation growth under drought conditions, influence these indices.

The influence of the relief on the development of a fire is manifested both directly and indirectly. Relief indicators are represented by the following variables: digital elevation model, slope, and aspect. Slope, aspect, and ruggedness were calculated based on the DEM (resolution = 30 m) using the tools of the Spatial Analyst module of ArcGIS 10.8 GIS.

The first indicator characterizing the relief is the absolute height. In the studied area, the number of fires decreases with increasing elevation. When analyzing this indicator, it is important to consider that with increasing elevation, the air temperature decreases, and the amount of combustible biomass decreases. In mountainous areas, fires can spread quickly over short time intervals, while in flat areas, they move significantly slower. This is explained by numerous obstacles in mountainous terrain and the slowed movement of fire down the slopes.

The results of the analysis of the frequency of fires based on elevation above sea level show that vegetation communities are more frequently damaged by fires at altitudes ranging from 200 to 1000 meters above sea level. The highest frequency of fires is observed at elevations between 200 m and 500 m above sea level. At elevations below 200 m and above 1000 m above sea level, the number of fires is significantly lower.

The Earth's surface is rarely perfectly flat. As the slope of an area increases, the number of fires decreases because on steep slopes, conditions for plant growth are unfavorable, and biomass accumulates weakly. Additionally, under the influence of gravity, dead plant residues move downhill. A completely different situation is observed in flat areas, which promotes the rapid spread of forest fires. The slope gradient influences soil temperature, the thickness of the ground layer of air, the depth of the snow cover, the amplitude of daily temperatures, the thickness of the soil profile, and erosion intensity.

The relief also indirectly influences local weather conditions and microclimates on slopes. The slope aspect determines the type and quantity of vegetation. Different solar heating intensities on slopes with different aspects have a strong impact on the moisture content of combustible material in the forest and on the local wind regime, which, in turn, affects fire behavior. Southern and western slopes receive more sunlight and warmth than northern and eastern slopes. As a result, plants thrive better on southern and western slopes, and biomass increases. Additionally, combustible materials dry faster under the influence of sunlight. In such conditions, a fire can quickly ignite and spread.

We classified the slope aspect into five danger classes based on data on forest fires from 2018 to 2022. The majority of fires were recorded on slopes with southern and western aspects, followed by southwest and southeast slopes. Eastern, northwest, northeast, and northern slopes were categorized into danger classes 2 and 3. Northern slopes showed the lowest proportion of forest fires; therefore, the danger class was determined to be low. Terrain ruggedness highlights areas

Table 1. Assessment Scale of Factors of Natural Fire Hazard

Factors	The weighting coefficient of the factor	The degree of natural fire danger				
		Extreme	Tall	Moderately high	Moderately low	Low
The fuel factor						
NDVI	10	0.6–0.5	0.5–0.4	0.4–0.3	0.3–0.2	0.2–0.1
EVI	10	0.6–0.5	0.5–0.4	0.4–0.3	0.3–0.2	0.2–0.1
NDMI	10	-0.3–0.2	-0.2–0.0	0.0–0.2	0.2–0.4	0.4–0.6
Forest-growing formations	10	Light – coniferous	Deciduous	Deciduous woodlands	Shrubby	Shrubby woodlands
Geomorphological factors						
DEM, m	8	200–500	500–700	700–1000	< 200	> 1000
Dissection, m	8	0.6–0.4	0.4–0.2	0.6–1	0–0.2	–
Exposure, rumba	7	South. Western	South–east. south–west	Eastern	Northeast. Northwest	North
Slope, degree	8	0–4	4–6	6–9	9–13	13–40
Meteorological factors						
The average value of direct solar radiation in the fire-hazardous period (April–September), kW/m^2 per day	8	> 3.4	3.4–3.2	3.2–3.0	3.0–2.8	< 2.8
Coefficient of evaporation from the soil surface during the fire-hazardous period (April–September), mm	7	> 150	150–140	140–130	130–120	< 120
Average temperature during the fire-hazardous period (April–September), °C	8	> 21	21–19	19–17	17–15	< 15
Average precipitation in the fire-hazardous period (April–September), mm	6	> 15	15–20	20–25	25–30	> 30
Total	100					

with varying degrees of linear segmentation due to ancient and modern erosion processes, and lake and ridge-valley segmentation. The spread of fire across the plateau of the hill is somewhat faster than across the bottom of the ravine, which is related to changes in wind speed in the forest slope due to the effects of airflow. At the exit from the ravine, the spread of fire accelerates, which is associated with the high angle of inclination of the flame torch [19].

Meteorological factors are an important determinant of fire intensity [20–22]. The initial data for mapping the meteorological factors of the research region are the statistical series for the fire-dangerous period (April–September) based on the data from the Republican State Enterprise "Kazhydromet" [23]. Precipitation, temperature, and relative humidity indicators were taken for each observation period of the month for each weather station in the research region. Subsequently, data averaging and processing were carried out in the ArcGIS 10.8 program, and interpolation was performed in the Spatial Analyst module.

Air temperature significantly influences the occurrence of fires. As the temperature increases, the number of ignition cases also rises. Additionally, there is a close relationship between the average air temperature and the duration of the growing season. In turn, the growing season and the fire-dangerous season are characterized by approximately the same duration and nearly coinciding calendar dates in all latitudinal zones. This allows for estimating the duration of the fire-dangerous season based on the expected temperature of the growing periods. Such an estimate relies on the clearly expressed correlation of these indicators with the geographical latitude of the area [22, 24].

Solar radiation plays a crucial role in the process of evaporation of moisture from the forest floor. Solar radiation can indirectly impact fire intensity by influencing the fuel's productivity and moisture content. The intensity of evaporation is proportional to the amount of absorbed solar radiation and depends on the presence of moisture in the forest floor. There is a close relationship between absorbed solar radiation and the average daily humidity deficit in the air [25, 26].

When solar radiation increases, the number of fires also increases. It is possible that with the growth of solar radiation,

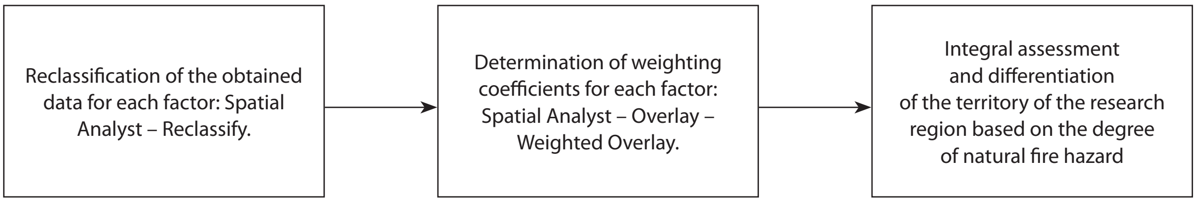

Fig. 2. Algorithm for the integral assessment of natural fire hazard using ArcGIS software

conditions become more favorable for ignition. Combustible materials, drying faster, may spontaneously ignite.

An increase in precipitation reduces the risk of fires, indicating the presence of a moderate negative correlation between these factors. In conditions of constant air temperature rise, reduced summer precipitation poses serious problems for providing forests with moisture and increases the risk of fire occurrence.

A humidity deficit in the air proportionally increases the evaporation of the vegetation and soil, thereby enhancing the combustible materials' susceptibility to ignition. The evaporation of the soil-vegetative cover affects the moisture content in the soil and combustible materials. It has been established that the course of relative air humidity has a primary minimum (45–50%) in May and a less pronounced minimum in September, almost throughout the forested zone, contributing to the occurrence of fires in spring and autumn.

To assess evaporation from the soil surface during the fire-prone period, considering the physiogeographic conditions, the most suitable method is the calculation of the total evaporation in the zone of insufficient moisture, as proposed by N. N. Ivanov.

$$E_0 = 0.0018 \times (100 - f) \times (25 + t)^2 \times 0.8 \quad (1)$$

where E_0 – evaporation for the month, mm;
f – average monthly (fire-prone period) relative humidity of the air, %;
t – average monthly (fire-prone period) air temperature, °C.

At the third stage of the work, all factors of natural fire hazard were mapped and differentiated in the territory of the Kostanay region.

The subsequent fourth stage of the work involves calculating the integrated values of natural fire hazard using the developed assessment scale (Table 1). Weight coefficients are determined by an expert method based on ranking indicators by the degree of natural fire hazard. For the integral assessment of the natural fire hazard level of the territories of the Kostanay Region, the algorithm shown in Fig. 2 was applied.

The final fifth stage of the work is characterized by the analysis of the obtained integrated ratings and the determination of leading factors for individual forest areas.

Results and Discussion

The main forest-forming species is Scots pine, with birch and aspen, shrubby willow, wild rose, and tamarisk forming both pure and mixed stands among other tree species. Forests are located only on ancient alluvial sands, along the ridges of ancient dunes, and the upper parts of their slopes. Birch and aspen forests are concentrated in the lower parts of sandy ridges, often adjacent to the shores of saline lakes. Shrubby willow and honeysuckle are associated with riverbanks and lakeshores. Wild rose and tamarisk grow on ridges and slopes. Sandy-cotton grass steppes form in clearings and glades. Narrow strips of meadow-saltwort vegetation are characteristic along the borders of pine forests.

The steppe vegetation includes feather grass (Stipa pennata), Becker's fescue (Festuca beckeri), blue lyme grass (Koeleria glauca), Siberian wheatgrass (Agropyron sibiricum (Willd.) P. Beav.), and mugwort (Artemisia). The southern part of the area is predominantly covered by wormwood-saltwort and grassy-wormwood vegetation.

The climate of the forestry research region, situated away from large water bodies, is distinctly continental, characterized by hot dry summers and cold winters with little snow. Low winter temperatures and high summer temperatures, combined with dry winds, dust storms, and late spring, and early autumn frosts, negatively impact the growth and development of woody and shrubby vegetation. An advantageous climatic factor is the abundance of solar radiation and a relatively long frost-free period [27].

The region is affected by unfavorable climate factors such as droughts, dry winds, strong winds, dust storms, late spring and early autumn frosts, severe winter frosts, snowstorms, and a low amount of atmospheric precipitation. Drought increases towards the south, accompanied by high evaporation rates. The combination of high temperatures, low humidity, and high wind speeds contributes to atmospheric droughts, leading to a decrease in soil moisture levels beyond the reach of plants. The cumulative effect of drought primarily manifests in the reduction of growth processes in woody and shrubby vegetation as well as forest crops, which, during prolonged dry periods, can lead to plant mortality. The existing distribution of pine, birch, aspen, and various shrubby plantations is logically derived from the specific climatic factors of the forested area.

The relief of the territory where the key areas are located is quite complex, and its origin is associated with alluvial and subsequent aeolian processes. Aeolian relief forms alternate with gentle sandy ridges and lower, rolling elevations with small depressions between them. Among the elevated dune-like sands, a winding network of channels forms on the plains of meadow-steppe areas. In some places, especially in the lower parts along ridges and embankments, they have the character of flood meadows, inundated by spring thaw waters and sometimes marshy.

Based on satellite imagery using ArcGIS, we obtained maps of natural fire hazard factors for the Kostanay Region (Fig. 3).

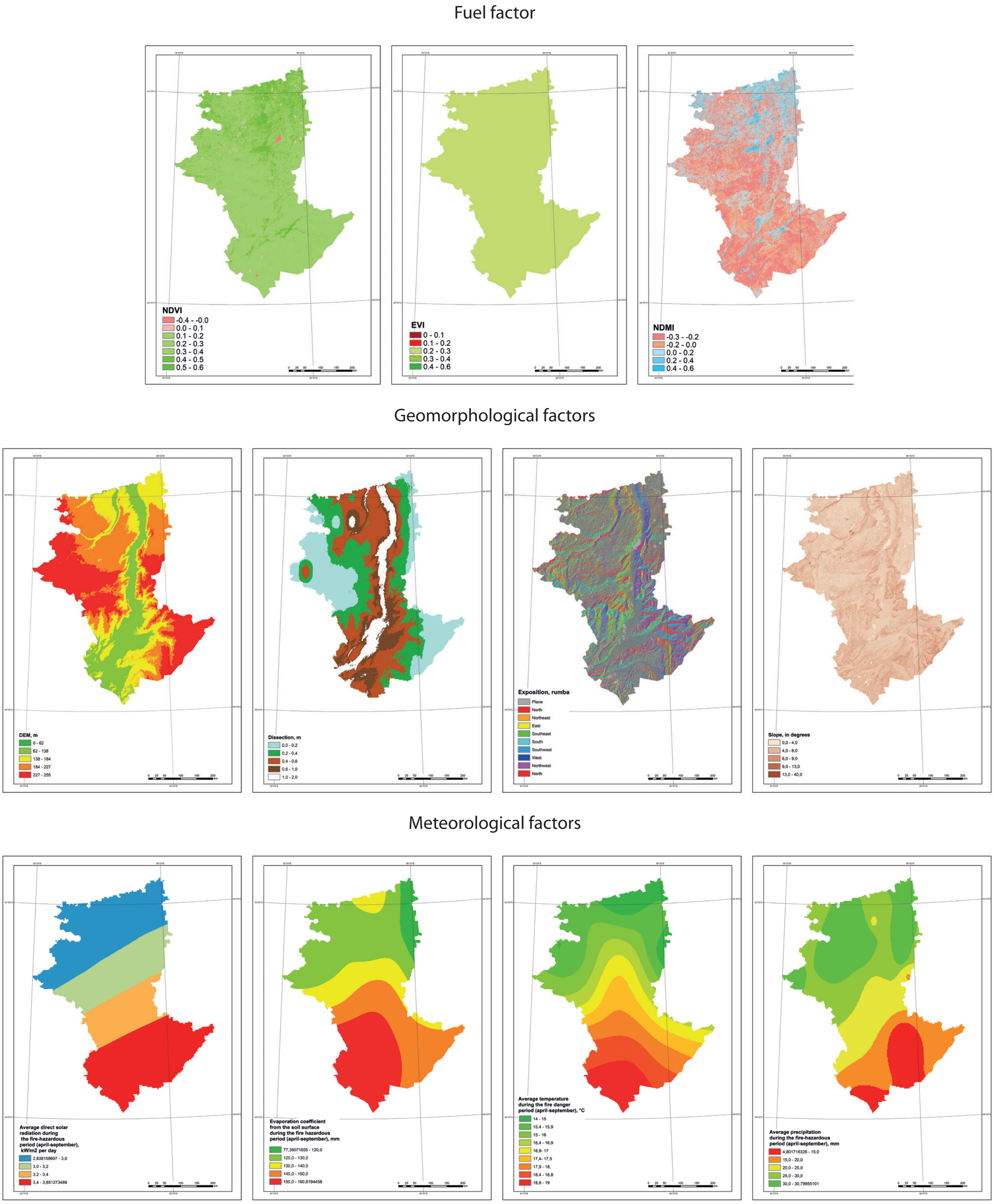

Fig. 3. Natural Fire Hazard Factors of the Kostanay Region

The results of assessing natural factors of fire occurrence and frequency (Fig. 4) indicate that the overwhelming majority of the territory of the Kostanay Region falls into the moderately high-risk zone.

Based on the analysis of ignition points in the Kostanay Region and information from literary sources, it has been determined that the light coniferous and deciduous forest formations are most susceptible to the risks of natural fires. The shrubby sparse forest formations exhibit a low class of fire hazard.

A high risk of forest fires is observed in the forests of river alluvial plains (low river terraces), terraces, and slope-valley locations represented by pine island forests on sandy hills and inter-ridge depressions on sandy soils; pine forests with birch patches on the outskirts on poorly formed sod-podzolic soils of hilly-ridge sandy elevations. These areas are characterized by a flat relief (Turgai Hollow) with slopes ranging from 0.5 to 5 degrees. The average direct solar radiation during the fire-prone period ranges from 3.23 to 3.65 kW/m² per day, and the evaporation coefficient from the soil surface during the fire-prone period ranges from 118.8 to 160.6 mm. Typical features of this territory include a relatively grassy cover and the absence of sandy deserts. Additionally, the predominant flat relief, without mountains or river systems, can serve as a natural barrier against fires.

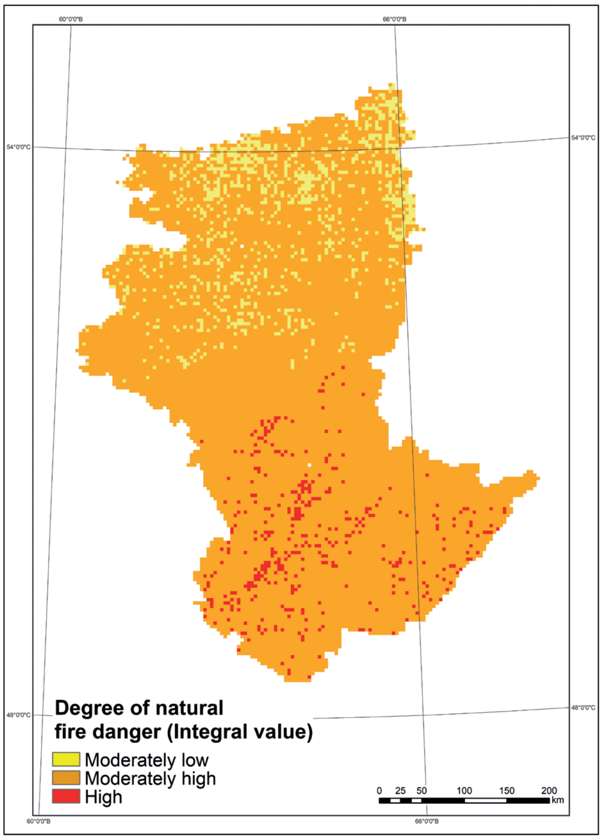

Fig. 4. Zoning of the territory of the Kostanay Region based on the degree of natural fire hazard

Uphill fires are observed in the light coniferous forest formations, and their intensity is determined by the moisture content and the quantity (density) of plants per unit area. In this zone, fires occur when the ground cover (mosses, lichens), litter, and fallen branches dry out, creating optimal conditions for the formation of a continuous fire edge and its transition between plant community groups. The occurrence of forest fires in this zone is most often observed on the southern slopes of the terrain during prolonged dry periods.

In the region, the frequency and scale of forest fires are increasing; only in the years 2018–2022, significant areas (2,020,429.5 hectares) were registered [28]. However, the occurrence of forest fires over time and their distribution across the territory is highly uneven. Fig. 5 illustrates the distribution of fires across the territory from 2018 to 2022 [29].

During the verification of data on the zoning of fire occurrence risks in areas with high and moderately high risks, more than 87% of ignition points were identified. Areas with moderately low fire occurrence risks account for 13%. The verification results confirm the necessity of considering the factors that influence these hazardous phenomena in forests. The spread and intensity of forest fires depend significantly on the characteristics of vegetation and terrain, as well as wind speed and the moisture content of forest combustible materials.

The largest fire was recorded on September 2, 2022, covering an area of more than 43,000 hectares out of the 106,000-hectare forest fund of forestry, causing damage to over 90 residential houses. During the summer period of 2022, the air temperature in the region occasionally rose to 32°C, which is 1.3 times higher than the average for 2021 (25.1°C), while the precipitation was twice as low. On this site, trees were massively felled and broken at heights of 2.5 to 3.5 meters and scattered in two opposite directions, as a result of the so-called "explosion" caused by the meeting tongues of flames (see Fig. 6).

The prolonged drought, which facilitated the rapid spread of the fire in 2022, has also hindered the natural regeneration of the forest in recent years. The summer of 2023 proved to be dry as well, with prolonged rains only starting towards the end of the summer, promoting the germination of Scots pine seedlings. Unsprouted seed material from the spring began to germinate massively in the fall, primarily in low-lying areas where moisture persists for a longer time. During on-site inspections after the fire, spring seedlings were also found in areas where winter logging had taken place, involving the skidding of fallen trees, which, in turn, damaged the topsoil layer, facilitating the penetration of seeds into soil conditions relatively prepared for germination. For the pine forests of this region, moisture, or more precisely, its high level, plays a crucial role.

As a result of abundant rainfall from August 30 to September 20, 2023, the process of natural regeneration is observed, namely the appearance of Scots pine seedlings

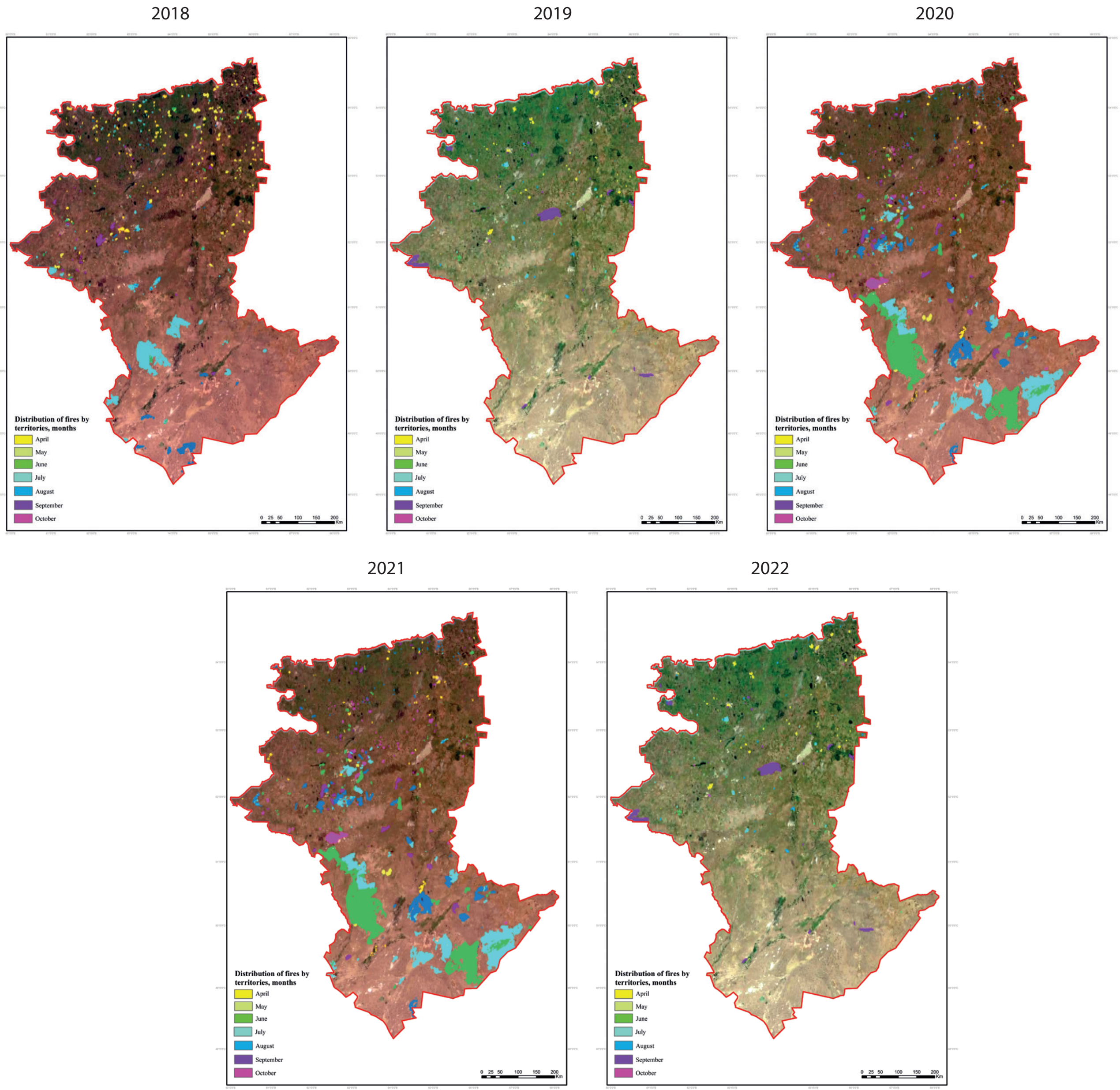

Fig. 5. Distribution of fires across the territory of the Kostanay Region, 2018–2022.

(self-sown) aged 20–30 days. The emergence of seedlings is due to the presence of undamaged fruit-bearing pine stands, known as seed trees. On average, there are about 1–2 seedlings per square meter, and there are also individual areas where seed accumulation is observed, mainly in low-lying areas with moisture accumulation and places where soil disturbance facilitates natural regeneration (see Fig. 7).

The characteristic fungus for burnt soils, fireplaces, and ash heaps is the wavy hair fungus (Rhizina undulata). The wavy hair fungus (Rhizina undulata) can affect the roots of coniferous trees aged 20–50 years, which is an unfavorable factor for seedlings. Conifers are predominantly affected by the wavy hair fungus (Rhizina undulata), while the roots of deciduous trees are not affected by this fungus (see Fig. 8).

Fig. 6. Massive tree fall after the 2022 fire

Fig. 7. Natural regeneration of Scots pine

Fig. 8. Wavy hair fungus (Rhizina undulata).

During the analysis of fire occurrence risks, it was assumed that in areas with a moderately high and high degree of risk, the rapid spread of fire occurs during drought. This assumption is indirectly supported by the results of studying fire traces over the past five years.

Conclusions

1. The methodology for assessing natural fire danger using remote sensing data for forested areas is a key element in developing prospective wildfire management plans in the context of climate change. Research enables the utilization of the obtained data to determine the risks of fire occurrence in similar territories depending on natural factors.
2. Twelve factors of natural fire danger have been identified and mapped. Based on the local characteristics of the studied area, a rating scale was developed, and the weight coefficients for each factor were determined using an expert method.
3. The integral assessment allowed for zoning the territory of the Kostanay region based on the degree of natural fire danger. A high degree of risk for forest fires is observed in the forests of river alluvial plains (low river terraces), terraces, and slope-valley locations, represented by pine island forests on sandy hills and inter-ridge depressions with sandy soils; pine forests with birch patches on the outskirts on poorly formed sod-podzolic soils of hilly-ridge sandy elevations.
4. The results exhibit a high correlation with the map of fire frequency in the Kostanay region for the period from 2018 to 2022. Verification of the developed zoning models for the degree of fire occurrence risk and the intensity of forest fire spread, based on the analysis of ignition points, confirmed the accuracy of the identified

zones. The majority of fires occur in zones of moderately high and high risk, accounting for 87%.

5. Factors hindering the natural regeneration of pine forests include the deep burning of the forest litter and soil cover, mechanical impact on the soil and seedlings by equipment used for clearing firebreaks, and the fungus undulating rubber (Rhizina undulata), which affects the roots of coniferous trees.
6. All the results obtained by the authors in this study are scientifically justified. According to the data obtained, it should be noted that the territory of the Kostanay Region is characterized by increased fire hazards. Significant fluctuations in the number and area of fires were also recorded depending on the seasonal vegetation conditions and climatic regime of this area.

The study involved the examination and systematization of a significant number of factors causing natural fires. As a result of such research, the authors concluded about the possibility of creating features with higher predictive ability. Therefore, the development of approaches to forming indicators of anthropogenic fire hazard can be considered as a subsequent direction of research.

In general, the results of this study can be applied to predict the risk of fire occurrence and control their development, to develop recommendations for their prevention.

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Conflict of Interest

The authors declare no conflict of interest.

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