Risk analysis in the management of forest fire in Russia

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Abstract. In the Russians forests, from 10 to 15 thousand forest fires are annually registered, and according to forecasts, the tendency of increasing damage from fires in the country's forests will grow. The final annual damage from forest fires in 2010 amounted to 550.4 thousand hectares of forest covered by fire. The article discusses the risks of forest fires determined by a combination of natural, economic and social factors. Based on an expert survey, an assessment was made of the probability of occurrence of risk events taking into account the categories of forests in Russia. The expert assessment used two criteria - the probability of a forest fire and the extent of expected losses from the occurrence of risk. It is shown that the most vulnerable to forest fires are forests located near homes, social and industrial facilities, as well as recreational forests. Three categories of forests have been proposed for the purpose of continuous monitoring of fire danger, firstly, forests located near dwellings, social and industrial facilities, secondly, forests with a developed network of roads and having a high level of timber value.

1. Introduction
Unprecedented climate change and the increase of anthropogenic load, leading to an increase in the number of forest fires and their negative consequences, determine the need to predict and assess the risk of fire danger [1]. Forest fires are a global disaster and they have catastrophic consequences not only for Russia, but also for other countries of the world where they threaten the population, fauna, residential and industrial facilities.

It is difficult to estimate the probability of occurrence of forest fires and the scale of their consequences, for a number of reasons. Historical information about forest fires are discrete and limited in time. There are specific factors in different regions and countries that affect the number of forest fires and the damage caused by them.

The legislation on forest fires in countries varies significantly, as well as methods for assessing the risks of their occurrence. A number of authors argue that legislation on forest fires concerns only their consequences, and less attention is given to forest fire management and risk assessment in forestry [2].

It is known that meteorological conditions affect the probability of a fire by determining the amount of energy required for an ignition (temperature), or by affecting the humidity of the fuel (relative humidity, wind speed) [3]. Professor V.G. Nesterov invented the Nesterov empirical drought Index in 1949 [4]. The Nesterov index is an empirical drought index widely used in Russia (GOST R 22.1.09-99, 2000, Standartinform, Moscow). G.N. Korovin and A.S. Isaev believe that up to 98% of fires in settled flat regions of Russia are caused by human faults, and in remote northern regions thunderstorms are responsible for 50% of cases [5]. If Russia uses the Nesterov index to assess the likelihood of a fire,
the European Dryness Index KBDI (Keetch — Byram Drought Index) is used for the same purpose in Europe [6].

The models of all the above mentioned indices are based on common meteorological variables usually available by nearby meteorological stations. The Nesterov and KBDI indices differently reflect the combination of meteorological conditions favorable for fires. In both cases it was proved applicable and a useful tool for early warning. They are a useful tool for early warning of fires.

The Canadian Forest Fire Danger Rating System includes three moisture indices (the fine fuel moisture, the duff moisture and drought code) and is used in the estimation of the Fire Weather Index (FWI), and the fire risk in Canada [7], Baumgartner Index is used in Germany [8]. The calculation of the index is based on the amount of precipitation and the potential evapotranspiration.

Precipitation is another factor that affects fire risk. One of the simplest drought index used in the fire risk assessment is the Swedish Angstrom Index [9]. The Angstrom Index uses only air temperature and relative humidity in its calculation and provides an indication of the likely number of fires on any given day. The index is based on the statistical relationships between the reported number of fire events and several antecedent-weather-related data. The Angstrom index is a daily index that does not take into consideration the rainfall; this seems to be a weakness for the index use.

Alexander M. E.(2008) proposed a rating methodology for fire hazard in forests and rural areas, to be used in fire management [10]. The fire hazard class is derived from the Fire Weather Index (FWI) System as low; moderate; high; very high and extreme.

Most of the indices are cumulative and follow a similar pattern in their evolution over time, i.e. they increase steadily with no rain and fall down or are reduced when rain occurs.

Fire risk rating indices, based on empirical relationships between pre-event meteorological conditions and the number of observed fire outbreaks, can be a useful tool towards understanding forest fire hazards. These are perceived as tools that can assist forest managers to take preventive measures.

Presently, to predict wildfires risks, imitation models and fire sensitivity indices (FSI) are used [11]. They allow counting on the probability of forest fires risks at the regional level. The calculation of the index requires remote sensing data [12]. In the Weibin You (2017) notes the importance of risk assessment and mapping of forest fire risk areas for forest land planning and protection purposes. It is noted that the accumulation of information about forest fires and data on the risks realized can significantly reduce losses in the future [13]. Researchers analyzed the causes of risk. The Dumollard (2018) associates the risks of forest fires with the state and structure of the stand [14]. Research results show that the risk of summer fire spreading is largely dependent on soil moisture; the spread of winter fires is associated with a mass of volatile debris and atmospheric dryness [15]. At the same time, in a number of articles noted the importance of risk analysis and modeling in the prevention of forest fires [16, 17].

Wildfires is the main cause of forest losses in the Russian Federation and 2,902.2 thousand ha of forests have died from forest fires over the past 10 years, with half of the forest fires occurring due to anthropogenic factors.

The trends of these years, such as an increase in air temperature, changes in the duration of the warm period, are also causes of an increase number of wildfires. Researchers note that in the coming decades the climate will become drier, and the consequences of increasing the frequency of fires in combination with logging may pose a risk to the sustainability of forests in the future [18]. The potential danger of forest fire arising under meteorological conditions does not always become a real fire. Moreover, under Russian conditions, forest fires near cities and towns pose the greatest threat.

To assess the economic damage caused by forest fires, indicators of the level of territories fire danger Parente (2016) and the cartographic method are used [19]. The National Fire Danger Rating System (NFDRS) fire danger rating system is used in a number of countries and the USA. In addition to the characteristics associated with fuel models, the NFDRS calculates the index of forest fires due to human fault and the index of forest fires from lightning.

In Russia, there is also an estimated scale of the level of fire danger in the regions, which is based on taking into account the number of forest fires arising depending on forest vegetation conditions [20].
However, at the present time it is necessary to take into account primarily anthropogenic factors when assessing the risks of forest fires. Existing indices are applicable for assessing the environmental consequences of forest fires. Forest fires cause great economic and social damage. It is important to assess the economic and social damage from forest fires. The aim of the study was to identify possible economic losses during the implementation of a risk event in the form of a forest fire, taking into account its territorial localization.

2. Methods
Economic and mathematical methods were used to assess the likelihood of forest fires bearing significant economic and social damage. Information on the economic damage from forest fires is presented on the official website of the Russian Federal Forestry Agency. To determine the likelihood of forest fires and economic losses, the expert assessment method was used [21].

Assessing the level of significance of a risk event and its occurrence is offered by the following formula:

\[
P_n = \frac{\sum_{j=1}^{N} P_{nij}}{N}
\]

where \(P_n\) is the consequences of the implementation of the \(i\) risk event; \(P_{nij}\) is consequences from the implementation of \(i\) risk event according to the \(j\) expert; \(N\) is the number of the expert (from 1 to \(N\)).

Each section of the forest fund was evaluated by experts from the standpoint of the occurrence of a risk event in the form of a forest fire and the possibility of its localization in the short term or in the long term (table 1).

\[
P_{p ij} = f(P_n \times W_i) = \frac{\sum_{j=1}^{N} P_{nij} \times W_{ij}}{N}
\]

where \(P_{p ij}\) is the assessment of the probability of the \(i\) implementation of the risk event by the \(j\) expert, \(W_{ij}\) is the probability of resolving (implementing) the \(i\) risk event, according to the \(j\) expert.

To assess the level of the risk event significance and the chance of a forest fire in forestry, a scale Harrington should be used, supplemented by a verbal description of each interval of the scale and two criteria (table 1) [22].

| Change interval criteria | Loss level | Description of the risk event |
|--------------------------|------------|------------------------------|
| 1.0 – \(P_n\) – 0.70    | high       | Extremely high level of significance of a risk event. Complex affects all indicators of the territory. Catastrophic level of losses |
| 0.69 – \(P_n\) – 0.40   | permissible| The permissible significance level of the risk event. Refers to the number of important for the territory. Critical level of loss |
| 0.39 – \(P_n\) – 0.00   | low        | The low level of significance of the risk event for the territories. Allowable loss level |

The first assessment criterion is the level of losses in the implementation of a risk event (the scale of assessment is from «the consequences are minimal» to «the consequences are very high»). The second assessment criterion is the probability of occurrence of a risk event in the form of a forest fire (table 2).
Table 2. The quantitative scale of the risk of forest fires ($W_{ij}$).

| Change interval | Probability  | Description of the risk event                                      |
|-----------------|--------------|---------------------------------------------------------------------|
| $1.0 - W_{ij} - 0.80$ | very high    | the probability of forest fire throughout the year                  |
| $0.79 - W_{ij} - 0.60$ | high         | the probability of forest fires during the fire-danger season       |
| $0.59 - W_{ij} - 0.40$ | permissible  | the probability of a forest fire during the fire-danger period, with deteriorating weather conditions |
| $0.39 - W_{ij} - 0.20$ | low          | the probability of a forest fire during the fire-danger season, with a significant worsening of weather conditions or lightning |
| $0.19 - W_{ij} - 0.00$ | very low     | the probability of a forest fire in an extremely dry period or when hit by lightning |

3. Results

We have analyzed the damage caused to the forests of Russia by forest fires. Table 3 presents the dynamics of the forests, losses owing to forest fires from 2007 to 2017, which reflects the accumulated damage to the forests of Russia in the amount of 2,902.2 ha or 180 million €.

Table 3. Losses owing to forest fires, thousand ha.

| Total for Russian Forestry | 2007 | 2010 | 2012 | 2014 | 2016 | 2017 | Amount from 2007 to 2017 |
|---------------------------|------|------|------|------|------|------|-------------------------|
| Central Federal District  | 5.5  | 142.0| 22.4 | 4.9  | 1.5  | 1.1  | 228.4                   |
| Northwest Federal District| 5.7  | 8.3  | 18.6 | 10.3 | 0.7  | 0.4  | 103.0                   |
| Volga Federal District    | 0.5  | 195.3| 9.5  | 3.9  | 1.6  | 0.9  | 270.6                   |
| Southern Federal District | 3.0  | 2.9  | 0.9  | 0.9  | 0.5  | 3.2  | 17.6                    |
| North Caucasus Federal District | 0.1  | 0.06 | 0.001| 0.02 | 0.2  | 0.02 | 288.2                   |
| Ural federal district     | 5.2  | 20.4 | 27.1 | 20.7 | 16.1 | 9.1  | 192.3                   |
| Siberian Federal District | 135.1| 79.6 | 137.6| 98.8 | 0.1  | 64.5 | 1 121.7                 |
| Far Eastern Federal District | 42.1 | 101.7| 14.3 | 271.8| 3.9  | 16.8 | 1 314.0                 |
| Amount                    | 197.4| 550.4| 230.7| 411.6| 138.3| 96.4 | 2 902.2                 |

The most vulnerable regions are the North-West Federal District, the Siberian Federal District and the Far Eastern Federal District, where over 1 million ha of forest fires have died from forest fires over a decade. The maximum damage to the forests of Russia was caused in 2010 and was amounted to 550.4 thousand ha. From 10 to 15 thousand forest fires are registered annually in the forests of Russia, therefore the tendency of increasing damage to forest resources will be exacerbated. In this regard, it is necessary to consider the fire danger, as the probability of the occurrence of risk events associated with the occurrence of forest fires in forests and to establish the factors that determine them for the purposes
of preventive management. The risks of forest fires are determined by a combination of natural, economic and social factors.

Natural factors are forest growing and climatic conditions, as well as conditions associated with the soil, terrain and hydrography of the area. Economic factors are associated with the activities of people in the forests [23]. Social factors are understood to be factors related to anthropogenic stress due to the presence of people in forests and recreation, which leads to violation of fire safety rules, as well as deliberate arson. The risks of forest fires associated with natural factors are well understood and are based on fire hazard indices. The risks of forest fires associated with economic and social factors need to be assessed.

Therefore, the assessment and forecasting of forest fire risks associated with the activities of people require their methodological development. According to the results of an expert survey, it was established that the most hazardous areas are forest plots located near residential houses and social facilities (table 4).

Table 4. Forest fire risk profile from the perspective of economic and social damage.

| Objects of monitoring | Estimation of risk consequences | Estimation of risk probability | Final risk assessment |
|-----------------------|--------------------------------|-------------------------------|----------------------|
| Forest plots near settlements, urban and rural forests | 0.98 | 0.92 | 0.90 |
| Forest areas near industrial facilities | 0.90 | 0.81 | 0.72 |
| Forest areas in the zone of recreation of the population (parks of cities) | 0.88 | 0.68 | 0.60 |
| Forest plots with a developed system of roads, operational forests | 0.56 | 0.85 | 0.47 |
| Forest areas with a developed system of roads, especially valuable forest tracts, minimal logging | 0.62 | 0.79 | 0.48 |
| Forests in the desert, steppe, and low forest areas | 0.42 | 0.66 | 0.27 |
| Forest reserves, national and natural parks | 0.76 | 0.38 | 0.28 |
| Protective, water protection forests and minimal exploitation | 0.62 | 0.37 | 0.23 |
| On average by monitoring sites | --- | --- | 0.50 |

These forest areas are subject to double load - natural and anthropogenic, so the risk of forest fires persists throughout the year. These sites require continuous monitoring of fire danger. The level of anthropogenic fire danger in a forest area primarily depends on the number of settlements located within the limits of accessibility, the number of inhabitants in them, the distance to these settlements, the availability of transport routes and their type.

Taking into account expert assessments, for monitoring fire danger in the forests of the regions of the Russian Federation three groups of territories were identified, depending on the expected losses upon the occurrence of risk events and the probability of the risk occurring.

The first group of monitoring sites united forests located near homes, social and industrial facilities ($F_1$). These sites are also subject to threats of forest fires, due to the high anthropogenic load. Estimation of the probability of the $i$ risk event in the range from 1.0 to 0.6. The consequences of the occurrence of risks in these forests are estimated by experts as catastrophic, while the probability of risks occurring throughout the year is high.
The second group of monitoring sites included areas of the forest fund ($F_K$) located in transport accessibility and having a high level of commercial attractiveness of valuable forests (the second category of monitoring objects). Estimation of the probability of the $i$ event in the range from 0.59 to 0.30. The consequences of the occurrence of risks in these forests are estimated by experts as critical, while the probability of risks occurring throughout the year is high.

The third group of monitoring objects includes a lot of forest areas with different degrees of natural fire danger, according to which the risks of forest fires ($F_F$) should be expected. Estimation of the probability of the $i$ risk event in the range from 0.29 to 0.1. The consequences of the occurrence of risks in these forests are estimated by experts as critical, while the probability of occurrence of risks throughout the year is low.

Denote the forest area of a separate region of the Russian Federation as ($F_R$).

The above categorization of objects is very conditional and, if necessary, can be easily extended to the characteristics of regional forestry systems [24].

Sale | . | - the operator of the determination of the value of the protected forest area, necessary to establish the extent of the probable damage in case of its destruction in the event of a fire; here in the space of risk analysis appear variables $\text{sale}[F_R]$, $\text{sale}[F_K]$, $\text{sale}[F_A]$, $\text{sale}[F_F]$.

There are three sets of fire danger levels:
- high fire risk (forest areas near settlements, urban and rural forests, near industrial facilities, in the recreation area of the population):

$$F_k \cap F_j \cap F_f$$  \hspace{1cm} (3)

- medium fire risk (forest areas with a developed network of roads, operational forests, especially valuable forests, with a developed system of roads, but with minimal logging):

$$\left( F_j \cup F_k \cup F_f \right)/\left( F_k \cap F_j \cap F_f \right)$$  \hspace{1cm} (4)

- reduced fire risk (forests in desert, steppe, and low forest areas, nature reserves, national and natural parks, protective, water protection forests and forests with minimal exploitation):

$$F_R /\left( F_k \cup F_j \cup F_f \right)$$  \hspace{1cm} (5)

From here you can determine the probable damages from risk events:

$$\text{sale}\left[ F_k \cap F_j \cap F_f \right]$$  \hspace{1cm} (6)

$$\text{sale}\left[ \left( F_j \cup F_k \cup F_f \right)/\left( F_k \cap F_j \cap F_f \right) \right]$$  \hspace{1cm} (7)

$$\text{sale}\left[ F_R /\left( F_k \cup F_j \cup F_f \right) \right]$$  \hspace{1cm} (8)

It is more convenient to present them in normalized form through the loss of territory from the realization of the risk of a forest fire. These forest losses will be expressed in terms of the proportion of forest area covered by fires in the area of forests classified into the relevant monitoring category:

$$V_H = \frac{\text{sale}\left[ F_k \cap F_j \cap F_f \right]}{\text{sale}\left[ F_R \right]}$$ \hspace{1cm} (9)

$$V_H = \frac{\text{sale}\left[ \left( F_j \cup F_k \cup F_f \right)/\left( F_k \cap F_j \cap F_f \right) \right]}{\text{sale}\left[ F_R \right]}$$ \hspace{1cm} (10)

$$V_L = \frac{\text{sale}\left[ F_R /\left( F_k \cup F_j \cup F_f \right) \right]}{\text{sale}\left[ F_R \right]}$$ \hspace{1cm} (11)
Long-term annual observations of the fire situation in the regions of Russia make it possible to determine the losses caused by forest fires for selected categories of territories and, taking into account expert assessments, to determine the probability values for the occurrence of risk events.

Here the systemic risk can be expressed by the following amount

$$R(t) = V_{M}(t) 	imes P_{M}(t) + V_{M}(t) 	imes P_{L}(t) + V_{L}(t) 	imes P_{L}(t)$$  \hspace{1em} (12)

In formula (12), all variables are represented as functions of time $t$. This makes it possible to estimate the losses and the probability of risks occurrence of forest fires, taking into account temporary changes.

4. Conclusion

The risks of forest fires are among the most dangerous. Forest fires suffer significant economic and social losses that must be considered when forecasting risks. These risks require continuous monitoring. To determine the likelihood of risk events from the perspective of economic and social damage, you can use the method of expert assessments. This method allows you to create a risk profile of forest fires. The risk profile allows you to establish the most dangerous of them, bearing maximum social and economic losses with a high probability. To predict the risk of losses from forest fires, it is necessary to involve long-term statistical observations.

Three categories of forest land have been proposed for fire hazard monitoring purposes. The first group of monitoring sites includes forests exposed to threats of forest fires, due to the high anthropogenic load, which are located near homes, social and industrial facilities. Assessing the probability of the risk of forest fires in the forests of Russia in three categories allows you to project this information on current and future risks.

The proposed expression for determining the level of risk from the standpoint of economic and social damage can serve as useful information and analytical support in assessing and managing the risks of forest fires at the regional level. Using the proposed approach, it is possible to establish the probability of occurrence of risk in the monitoring dynamics and reduce the costs of managing forest fires in the future.

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