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Development of an Algorithm for Calculating the Moisture Content and Time of Forest Fire Maturation of Forest Combustible Materials for Determining Forest Fire Hazards

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Abstract: Nowadays, forests play an important role in stabilizing the ecological balance, being one of the most important components of the biosphere. Due to the vital activity of forests, the gas composition of the atmosphere is normalized. Mass forest fires have the opposite effect. They cause irreparable damage to flora and fauna, contribute to the melting of Arctic ice, an increase in the Earth's temperature, and destabilization of the carbon balance. The purpose of this study is to develop an algorithm for calculating the moisture content and time of forest fire maturation of forest combustible materials. To achieve this goal, the main factors determining a forest fire hazard have been studied, as well as a review of existing methods for assessing forest fire danger and scientific papers on forest pyrology. As a result of the analysis of the research aimed at studying the rate of drying of forest combustible materials (FCM), depending on the physical properties and environmental parameters, a dependency of changes in moisture content over time was obtained. With its help, knowing the initial moisture content of FCM, it is possible to calculate the periods of fire maturation for each component of the forest plantation. Cooperative use of the resulting algorithm with a digital twin of a forest stand makes it possible to identify the most fire-hazard forest areas and estimate the period of their fire-prone maturation.

Keywords: wildfires; forest combustible materials; fire hazard; modeling and simulation; digital twin; digital technologies; strategic planning

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1. Introduction

Forest fires are a powerful natural and anthropogenic factor that has a significant impact on the functioning and condition of forest ecosystems. Year after year, the problem of forest fires does not lose its relevance; global forest fires occur more than 200,000 times a year, which characterizes them as a powerful source of environmental and economic damage [1]. The environmental damage caused by forest fires manifests itself in the form of losses of natural, labor, material, and financial resources in the national economy, as well as in the form of a deterioration in the social and hygienic living conditions of the population [2]. In Russia, forest fires happen to be a significant part of all-natural disasters that occur annually. A substantial share falls on the Far East region, where 70–90% of the entire forest area is covered by fires. According to the Information System for Remote Monitoring of Forest Fires of the Federal Forestry Agency of the Russian Federation, the area of forest land covered by fires in 2022 exceeded 9 million hectares [3,4]. The problem of forest fires is also intrinsic to the Mediterranean climate region, affecting countries such as Greece, Spain, Italy, Portugal, Turkey, and France [5]. Mediterranean pine forest and maquis ecosystems are particularly susceptible to fire, and fires are common in these regions and countries. An analysis of fire data from 2009 to 2018 shows that, on average, 26,839 hectares were burned annually in Greece; 67,639 hectares in Italy; 99,083 hectares in Spain; 138,841 hectares in Portugal; and 11,831 hectares in France [6]. In terms of the number of fires per year, there were 986 forest fires in Greece; 5527 in Italy; 12,182 in Spain; 18,345 in Portugal; and 3810 in France. Over the past decade, approximately 2631 forest fires have occurred in Turkey annually, burning an average of 9096 hectares of forest area. Wildfires have caused significant loss of lives and environmental damage worldwide. According to [7], in the period 1998–2017, 6.2 million people were affected by forest fires and volcanic activity, which led to 2400 deaths worldwide from suffocation, injuries, and burns. In addition to loss of life, forest fires also cause enormous economic damage. For example, the 2020 wildfires in California caused USD 10 billion in damage [8]. According to the head of the Russian Ministry of Natural Resources and Ecology, the damage from forest fires in 2022 is currently RUB 9.3 billion. Of this amount, RUB 5.5 billion is included in the cost of extinguishing these fires. The damage caused to forestry is estimated at RUB 3.8 billion, and the total area affected by fires across the country is 3.3 million hectares [9]. In addition, forest fires have a far-reaching impact on the environment. In [10] it is stated that the expansion of areas prone to severe fires can affect the regeneration of trees, soil erosion, and water quality; this could lead to deforestation, further exacerbating the effects of climate change. The release of carbon dioxide during fires also contributes to greenhouse gas emissions, enhancing the effects of global warming. The destruction of ecosystems can also lead to the loss of biodiversity and the destruction of entire ecosystems, further damaging the environment. Climate change is projected to lengthen the fire season and increase drought levels, leading to more destructive fires in the future [11]. Giannakopoulos et al. [12] predict that the forest fire season in the Mediterranean region will lengthen by 2–6 weeks by 2030–2060, with Turkey likely to be one of the most heavily affected countries. New approaches to fire management include developing strategies to assess potential fire risk areas and using early warning systems such as infrared detection cameras, thermal imagers, video analytics, artificial intelligence, and sensor applications to detect fires quickly and effectively [13]. Accordingly, forest fire organizations are paying more and more attention to research related to this topic.

Forest fires have a significant impact on the destabilization of the carbon balance and exacerbate the process of global warming, which, in turn, contributes to the occurrence of fire-prone weather conditions. Where geographic conditions make it difficult to monitor forest fires, different techniques can be used to detect fires. The analysis of existing methods—such as the Australian NFDRS [14], Spanish DER [15], French Numerical Risk [15], Italian IMPI and IREPI INDEX [15], Portuguese PORT [15,16], Finnish FFMI [17], Canadian CFFDRS [18–20], and the American NFDRS [21] forest fire hazard assessment systems—showed that the vast majority of methods are based on empirical coefficients. These coefficients are based on the experimental data of the particular areas that have been collected over a few decades. It means that the existing national systems of an estimation of fire danger were developed considering specific natural conditions and the flammability of the certain territory and cannot be transferred to other terrains without infringement of structural integrity and radical change in the formulas contained in them. The abundance of empirical coefficients makes it impossible to modernize and widely use these methods. The lack of universal and flexible systems for monitoring and assessing the fire hazard of forest plantations leads to the complication of localization and elimination of the source of the fire. All this testifies to the necessity of introducing new systems of forest fire danger monitoring, including the use of digital technologies. An alternative to empirical coefficients can be the physical properties of FCM. A forest fire hazard assessment model based on the physical properties of FCM would make it more flexible, accessible, and versatile, and would also minimize the number of empirical coefficients. They will appear as additional parameters to account for environmental effects. This will allow the model to be applied in different areas with minimal changes in its structure and to be used for strategic forest management planning of particular regions.

2. Materials and Methods

The ability of a certain type of FCM to ignite when exposed to an ignition source is largely determined by its moisture content. In this regard, it is logical to assume that the method of assessing the fire hazard of forest plantations based on the moisture content in each type of FCM is quite promising. This is especially true for hygroscopic FCM, the moisture content of which directly depends on external conditions; they are prone to drying out and belong to the category of FCM that supports combustion. Under the moisture content of combustible material, it is usually considered to be the ratio of the mass contained in the water sample to the dry mass of the sample [22]. From the point of view of FCM fire hazard, the most informative indicator is the critical moisture content. This parameter is characterized by such (limiting) amount of moisture at which the spread of combustion on the combustible material is possible [23]. Thus, the presence of a dependence describing the moisture content of FCM on time would make it possible to obtain a model describing the process of FCM drying to critical values and, consequently, reaching fire maturity.

The influence of the physical properties of a substance on its drying rate was studied by a group of Tomsk scientists headed by A.M. Grishin. During A.M. Grishin's research, they managed to derive a dimensionless coefficient γ characterizing the drying rate of a particular type of FCM [24]:

$$\gamma = \frac{\rho_{dry} \cdot \varphi_{dry} \cdot C \cdot R \cdot T^2}{\rho_2 \cdot q_2 \cdot E} \quad (1)$$

where ρ_{dry} is the density of dry organic matter; φ_{dry} is the volume fraction of dry organic matter; C is the heat capacity of dry organic matter; R is the universal gas constant; T is the initial temperature; ρ_2 is the density of water; q_2 is the specific heat of vaporization of water; and E is the activation energy. This coefficient can act as a parameter, considering the physical properties (such as density of dry organic matter, volume fraction of dry organic matter, heat capacity of dry organic matter, etc.) of a particular type of FCM in assessing the fire hazard of the material by moisture content.

The processes of FCM drying in natural conditions were also studied by other researchers. Of particular interest is the work of G.N. Korovin [25], which states that the drying of FCM is characterized by periods with a constant and decreasing rate, it comes at a time when the moisture content of FCM is asymptotically approaching the equilibrium. Further, the scientist assumed that the drying rate of FCM on the part of the curve corresponding to the decreasing rate period is proportional to the difference between the current and equilibrium moisture content.

As a result, the following dependence was obtained:

$$\frac{dW}{dt} = -k \cdot \left(W - W_p\right) \quad (2)$$

where k is the coefficient taking into account peculiarities of FCM; W is the current moisture content of FCM; W_p is the equilibrium moisture content of FCM.

After integration, we obtain the following equation:

$$\frac{W(t) - W_p}{W_0 - W_p} = e^{-k \cdot t} \quad (3)$$

where $W(t)$ is the moisture content of FCM at time t; W_p is the equilibrium moisture content of FCM; W_0 is the equilibrium moisture content of FCM at time $t = 0$; k is the coefficient, taking into account the peculiarities of FCM.

Expression (3) was taken as the basis for further corrections to obtain a dependency for forest fire hazard estimation based on critical moisture content values and determination of forest-fire-maturation time. As the first correction, instead of the coefficient k, taken in [25] as an empirical value determined experimentally, we introduce the previously considered coefficient γ (1). It should be noted that Expression (3) does not take into account such environmental parameters as relative humidity φ and air temperature T. To eliminate this shortcoming and to introduce the second correction, we turn to the work of Van Wagner (Van Wagner S.E.), in which the influence of weather on the drying rate of FCM, mainly forest floor of Scots pine, was investigated [26]. As a result of the research, the Canadian scientist obtained the following conclusion: under constant external conditions, i.e., when $\varphi, T, W_p = \text{const}$, the logarithmic drying rate of FCM is directly proportional to the difference $(1 - \varphi)$, and the logarithm of the rate is inversely proportional to T. Based on the analysis of scientific research, an algorithm for calculating the moisture content and time of the forest fire maturation of forest fire materials was developed, the following assumptions were made: the ambient temperature is constant, and the relative humidity of the air in the considered time period is constant ($\varphi, T, W_p = \text{const}$). The features of the chosen area are not taken into account. The input parameters for the calculation are presented in Table 1.

Table 1. Set of input data.

Parameter	Designation	Measurement Unit
Dry organic matter density	ρ_{dry}	$\frac{kg}{m^3}$
The dry organic matter volume fraction	φ_{dry}	
Heat capacity of dry organic matter	C	$\frac{J}{kg \cdot K}$
Activation energy	E	$\frac{J}{mol}$
Initial moisture content	W_0	%
Critical moisture content	$W_к$	%
Equilibrium moisture content	W_p	%

In the first stage, a coefficient that characterizes the rate of drying of forest fuel γ is calculated (1).

Next, the moisture content of LGM is determined:

$$W(t) = W_p + \left(W_0 - W_p\right) \cdot e^{-(1-\varphi) \cdot \gamma \cdot t \cdot e^{\frac{-1000}{T}}} \tag{4}$$

where $W(t)$ is the moisture content of FCM at time t; W_p is the equilibrium moisture content of FCM; W_0 is the moisture content of FCM at time $t = 0$; φ is the relative air humidity; γ is the coefficient characterizing the drying rate of FCM depending on physical properties; and T is air temperature.

Using transformations of Expression (4) describing the dependence of water content of FCM on time, we can calculate the time of forest fire maturation for a particular type of FCM (Δt)—the time interval required to dry the considered type of FCM to the critical moisture content ($W_к$):

$$\Delta t = \frac{\ln\left(\frac{W_к - W_p}{W_0 - W_p}\right)}{-(1 - \varphi) \cdot \gamma \cdot e^{\frac{-1000}{T}}} \tag{5}$$

where Δt is the time of forest fire maturity of FCM; $W_к$ is the critical moisture content of FCM.

Dependencies (4) and (5) derived based on Formula (3) contain corrections that take into account the influence of physical properties on the drying rate of FCM, as well as the ambient temperature T and relative air humidity φ. Thus, Expressions (4) and (5) serve as the basis for the proposed model of the methodology for assessing the fire hazard in forest stands depending on the prevailing types of hygroscopic FCM based on values of the critical moisture content.

To reveal the dependence of water content of FCM on time, $W(t)$ (4), and to calculate the time after which the considered type of FCM will reach fire maturity, Δt (5), the following set of initial data is necessary.

Taking into account data from the literature sources [27–31]—which contain the results of studies of physical properties of FCM and data obtained in the course of observations of changes in the equilibrium moisture content depending on fluctuations in relative air humidity—we obtain the following Table 2:

Table 2. Physical properties and moisture content values for some types of FCM.

	Parameters (at φ = 60%, T = 15 °C)						
Type of FCM	ρ_{dry}	φ_{dry}	C	E	W_{κ}	W_p	W_{max}
Fallen Pine needles	520	0.06	1397	32,000	30	7.7	140
Pine snag	495	0.25	1894	86,670	50	11	75
Coarse woody debris	340	0.17	1739	68,900	50	13	123
Forest floor	1000	0.005	1670	44,455	230	10	420

It is worth mentioning that Formulas (4) and (5) obtained in the course of this work contain the assumption of invariability of the ambient temperature and relative air humidity within the period under consideration ($\varphi, T, W_p = \text{const}$). It should be noted that the proposed model needs to be refined and correction coefficients introduced based on experimental data, which will take into account the peculiarities of the considered terrain, daily variations in ambient temperature, relative air humidity, and, consequently, the equilibrium moisture content of FCM.

Based on the data in Table 2, we can calculate the coefficient of FCM drying rate γ (see Table 3):

Table 3. Values of drying rate coefficient γ for some types of FCM.

Type of FCM	Fallen Pine Needles	Pine Snag	Coarse Woody Debris	Forest Floor
Γ	0.289	0.828	0.447	0.058

The data in Tables 2 and 3 allow using Expressions (4) and (5) to reveal the dependence of moisture content of the type of FCM under consideration on time and to calculate the time of its fire hazard maturation.

3. Results

Verification of data consistency and assessment of the significance of differences between experimental data and the results obtained from the derived model will be conducted using Pearson's fit criterion χ^2 (chi-square) with the following raw data (see Table 4):

Table 4. Input data.

Type of FCM	ρ_{dry}	φ_{dry}	C	E	W_{κ}	W_p	W_{max}	φ	T
Fallen Pine needles	520	0.06	1397	32,000	30	7.7	140	46	20

Based on the results of the studies conducted in [32], the following graph of the dependence of moisture content of FCM on time was plotted (see Figure 1):

Comparative analysis of the plots obtained by the experiment and using the obtained dependence (4) shows discrepancies in some places. The error of calculations ranges from 0% to 33.3%, and the arithmetic mean of the error is 9.8%. However, it can be seen that the functional dependence is chosen correctly. To assess the significance of the discrepancy between the empirical (observed) and theoretical (expected) values, let us apply Pearson's fit criterion χ^2. Considering the data in Appendix A we obtain the critical value of $\chi^2_{\text{кр}} = 37.7$ with the significance level of $\alpha = 0.05$ and the number of degrees of freedom k = 25. It is easy to see that the required condition of hypothesis acceptance is fulfilled as the obtained value of χ^2 = 10.24 is less than the critical value (see Appendix A, Figure 2):

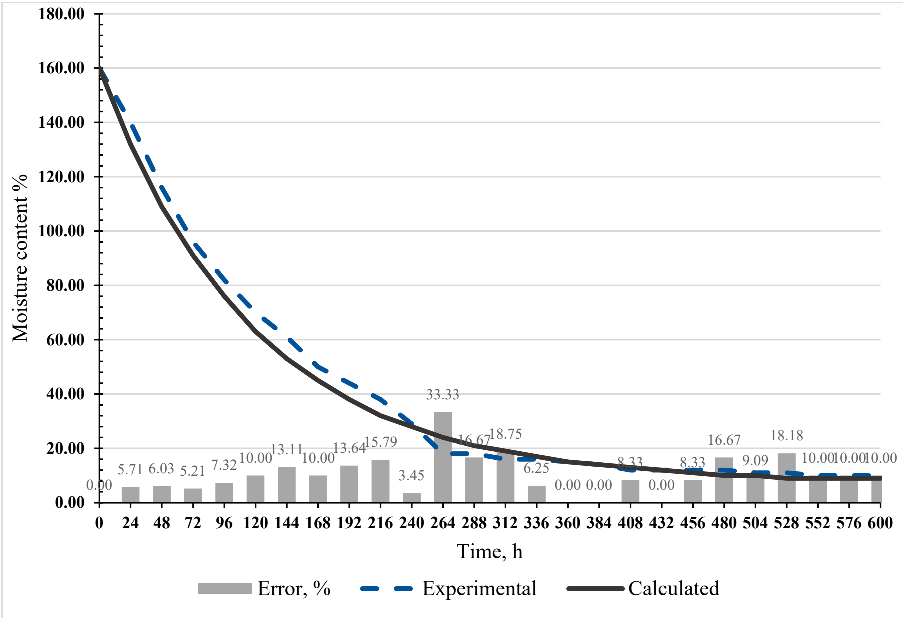


Figure 1. Pine needle moisture content plots.

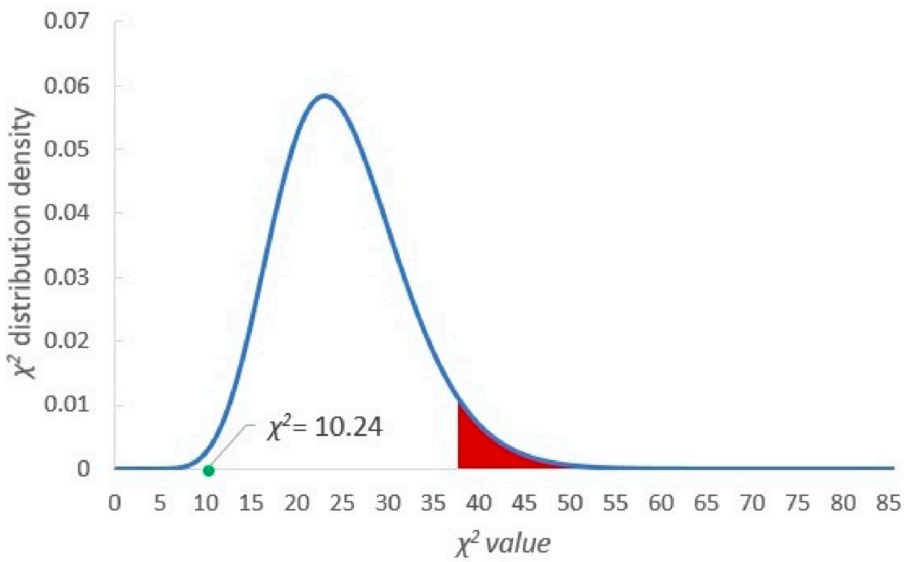


Figure 2. Pearson's fit criterion χ^2 distribution.

To interpret the results obtained by Formulas (4) and (5) and to pass directly to classes of fire hazard, taking into account information in the studies [23,27–31], we propose to introduce the following scale (see Table 5):

Table 5. Fire hazard scale.

		Moisture Content of FCM, %			
Paint Color	Fire Hazard Class	Pine Snag	Coarse Woody Debris	Fallen Pine Needles	Forest Floor
Dark green	1	100–70	200–100	330	650–350
Green	2	70–50	100–50	330–150	350–230
Yellow	3	50–25	50–30	150–30	230–25
Orange	4	25–10	30–10	30–13	25–14
Red	5	10–8	10–8	13–6	14–6

The first class of fire hazard corresponds to the condition of increased and maximum moisture content of FCM, observed in the case of prolonged stay of FCM in conditions of heavy rains, melting snow, and flooded terrain. There is no danger of ignition. The second class corresponds to low fire hazard and characterizes the state of natural moisture content of FCM, in which smoldering processes are impossible. The third fire hazard class corresponds to the state of forest fire maturity, in which FCM are capable of smoldering and combustion from household fires. The fourth class is an indicator of the readiness of FCM to be ignited by campfires. The last class corresponds to the state of full fire maturity, in which the FCM is capable of ignition from burning matches and sparks.

However, it is necessary to make several reservations relating to the assessment of forest fire hazard in general: the most favorable conditions for the spread of fire are an air temperature of 17 °C and above; relative humidity of 53% and below; the amount of rainfall, which excludes the possibility of ignition in the forest at 5 mm or more. A smaller amount leaves some danger of fire occurrence [23].

4. Discussion

The peculiarity of the proposed approach of forest fire hazard estimation is that it allows us to take into account the properties of each type of HCM and to distinguish the most fire-prone areas of the considered forest plantation. The compatibility of this method of forest fire hazard assessment with digital technologies, in particular, with digital twins, should be noted.

As an example, we can cite the results of a study of a test plot of a pine forest. On 20 April 2022, with the help of an unmanned aerial vehicle, a flight was made through the territory of the village of Kamshilovka (Russia, Shchelkovsky district; 55.948165, 38.127995), due to which it was possible to obtain a high-resolution orthophoto map (Figure 3):

Figure 3. Orthophoto map of the experimental area.

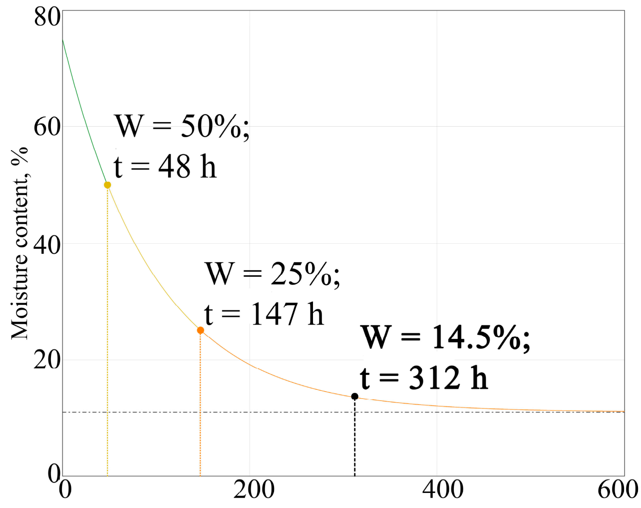
On the day of the survey, the ambient temperature was 17 degrees Celsius, the relative humidity of the air was 60%, and the moisture content of hygroscopic FCMs in the forest was close to the maximum possible, due to the presence of flooded areas. In this regard, to demonstrate the methodological approach and visualize the difference in the degree of fire maturity for different types of FCM, it is proposed to consider the moisture content of the prevailing types of hygroscopic FCM after Δt = 312 h (13 days) in the absence of precipitation and the following conditions (see Table 6):

Table 6. FCM and environmental condition parameters.

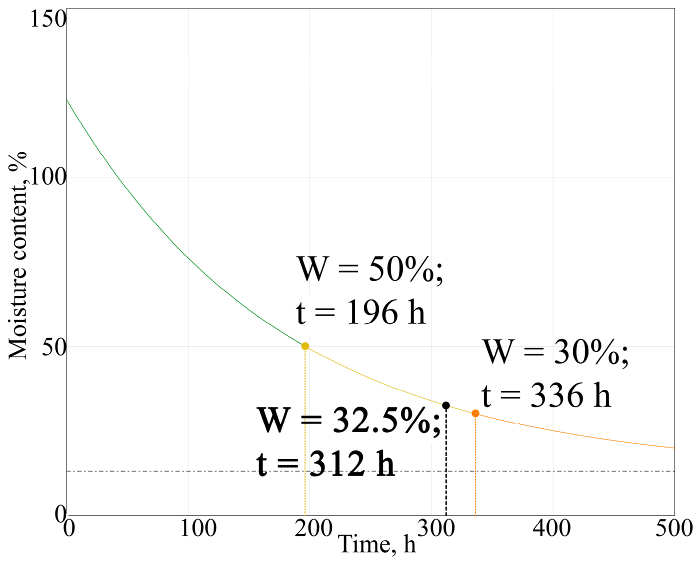
	FCM Parameters			Environmental Parameters		
Type of FCM	γ	W_0	W_K	Δt	T	φ
Snag	0.828	75	11	312	17	0.6
Coarse woody debris	0.447	123	13			
Forest floor	0.058	420	10			

It should be noted that during the day the state of the environment varies, there are fluctuations in temperature, humidity, and possibly wind and/or precipitation. As a result, moisture content values may fluctuate. Currently, the work on ways to take into account daily fluctuations in atmospheric temperature and air humidity for subsequent integration with this methodological approach is underway.

Plots of changes in the moisture content of the prevailing types of hygroscopic FCM under the above conditions, plotted using Expression (4), and the periods of fire maturation for each hazard class, calculated by Formula (5), are shown in Figure 4:

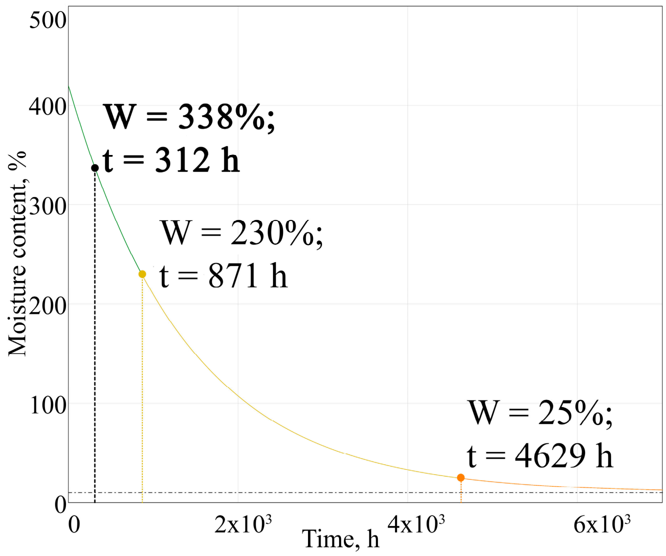


(**a**)



(**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. (**a**) Dynamics of change in moisture content of pine snag; (**b**) dynamics of change in moisture content of coarse woody debris; (**c**) dynamics of change in moisture content of forest floor.

Having analyzed the models of changes in the moisture content of the dominant types of hygroscopic FCM in the considered terrain, taking into account the data in Table 5, we obtain the following map of the fire hazard of the experimental site by types of FCM based on their moisture content in the absence of precipitation during the period in question (Δt = 312 h) and under the conditions given in Table 6 (Figure 5):

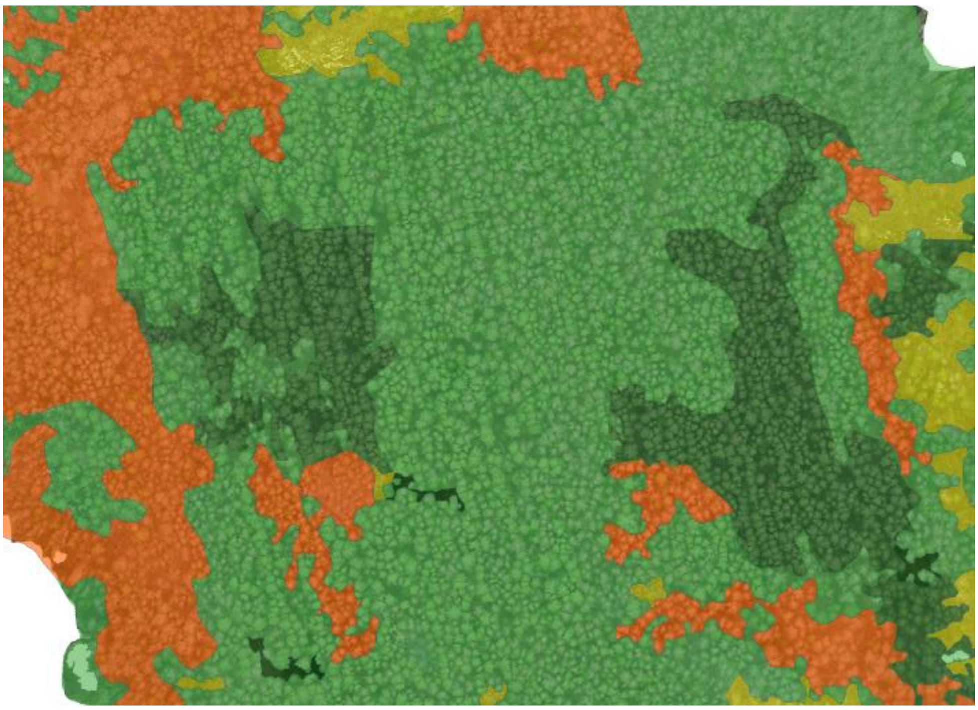


Figure 5. Assessment of fire danger in the experimental forest area using the proposed model.

The colors in Figure 5 refer to the fire hazard scale from Table 5. This example demonstrates how much the periods of fire maturity can differ for different types of FCM, and confirms the importance of considering the predominant types of FCM when assessing the fire risk of forest sites. Thus, the proposed system of forest fire hazard assessment based on modeling the process of FCM desiccation using digital twins, such as data obtained from forest monitoring by unmanned aerial vehicles, makes it possible not only to assess the fire hazard of individual forest plantation components at the time of direct monitoring but also to calculate the time after which the FCM species will reach fire maturity. An analysis of the advantages and disadvantages of the main methods for assessing forest fire hazard and their comparison with the proposed methodological approach is given in Table 7:

Table 7. Comparison of the main methodologies with the proposed methodological approach.

Methodology	Advantages	Disadvantages
Canadian Forest Fire Danger Rating System (CFFDRS–Canada)	- high accuracy; - division of vegetation into 16 categories;	- completely empirical character of the methodology; - physical properties of FCM are not taken into account; - there is no information on the distribution of fire occurrence probabilities; - the impossibility of using these techniques in other countries;
National Fire Dander Rating System (NFDRS –USA)	- the state of soil vegetation and its susceptibility to sources of fire are taken into account;	- no information on the distribution of fire occurrence probabilities; - all plants and their parts with a diameter (thickness) of more than 6 mm are excluded; - rough division of vegetation into 9 categories; - expression of fire hazard indicators in dimensionless quantities; - the impossibility of using these techniques in other countries;
Criteria for assessing fire hazard adopted in Russia—Nesterov's flammability index (Russia)	- ease of use; - small amount of required data;	- incorrect dimension of index; - physical properties of FCM are not taken into account;
Suggested methodological approach	- the state of ground vegetation and its susceptibility to sources of fire is taken into account; - the physical properties of FCM are taken into account; - provides information on the probability distribution of fires.	- methodology requires the introduction of corrections for daily fluctuations in atmospheric parameters; - methodology requires a series of experiments to determine the characteristics of different types of forest combustible materials.

5. Conclusions

As a result of the analysis of the research aimed at studying the rate of FCM drying, depending on physical properties and environmental parameters, an algorithm for calculating the moisture content and time of forest fire maturation of LGM was derived. With its help, knowing the initial moisture content, it is possible to calculate fire maturity periods for each forest plantation component. The types of FCM fire hazards concerning moisture content are described in the proposed scale of assessment of fire hazard class. Per Pearson's criterion of agreement, the significance of divergences of moisture content values, obtained through the derived dependence with experimental data on the example of pine needles, was evaluated. The conclusion about the correctness of the choice of the functional dependence of the moisture content of pine needles was made. An example of the application of the proposed model for assessing the fire hazard of forest plantations in the experimental area was demonstrated and it clearly showed how much can vary the state of fire maturity for different types of fire-prone FCM.

Based on the results of this work, it can be concluded that the proposed forest fire hazard assessment model will improve the accuracy of forest fire forecasting. Especially promising is the use of the proposed method in conjunction with digital forest monitoring data from UAVs (unmanned aerial vehicles). The images obtained as a result of flying over the area make it possible to identify the predominant types of FCM, and the data of moisture content calculations will help to assess the condition of each type of FCM and to identify the most fire-hazardous areas. Taking into account the comparison of different methodologies, shown in Table 7, the authors are planning to continue this study with the aim of further improvements of a suggested methodological approach and elimination of its disadvantages.

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Appendix A

Time, h	Experimental Moisture Content, %	Calculated Moisture Content, %	Deviations $\frac{(O_i-E_i)^2}{E_i}$	Error $\frac{\lvert E_i-O_i \rvert}{O_i} \cdot 100\%$
0	160	160	0.00	0.00
24	140	132	0.48	5.71
48	116	109	0.45	6.03
72	96	91	0.27	5.21
96	82	76	0.47	7.32
120	70	63	0.78	10.00
144	61	53	1.21	13.11
168	50	45	0.56	10.00
192	44	38	0.95	13.64
216	38	32	1.13	15.79
240	29	28	0.04	3.45
264	18	24	1.50	33.33
288	18	21	0.43	16.67
312	16	19	0.47	18.75
336	16	17	0.06	6.25
360	15	15	0.00	0.00

Time, h	Experimental Moisture Content, %	Calculated Moisture Content, %	Deviations $\frac{(O_i-E_i)^2}{E_i}$	Error $\frac{\lvert E_i-O_i \rvert}{O_i}\cdot 100\%$
384	14	14	0.00	0.00
408	12	13	0.08	8.33
432	12	12	0.00	0.00
456	12	11	0.09	8.33
480	12	10	0.40	16.67
504	11	10	0.10	9.09
528	11	9	0.44	18.18
552	10	9	0.11	10.00
576	10	9	0.11	10.00
600	10	9	0.11	10.00
	$\chi^2 = \sum \frac{(O_i-E_i)^2}{E_i}$		10.24	

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