

Review

Forest Fuel Drying, Pyrolysis and Ignition Processes during Forest Fire: A Review

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Abstract: Forest ecosystems perform several functions that are necessary for maintaining the integrity of the planet's ecosystem. Forest fires are thus a significant danger to all living things. Forest fire fighting is a foreground task for modern society. Forest fire prediction is one of the most effective ways to solve this urgent issue. Modern prediction systems need to be developed in order to increase the quality of prediction; therefore, it is necessary to generalize knowledge about the processes occurring during a fire. This article discusses the key features of the processes prior to forest fuel ignition (drying and pyrolysis) and the ignition itself, as well as approaches to their experimental and mathematical modeling.

Keywords: forest fuel; forest fire; heating; moisture evaporation; pyrolysis; ignition; physical and mathematical modeling



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1. Introduction

To ensure the normal further functioning of biogeocenoses and the entire planet, it is necessary to conduct research in terms of forest fire fighting. Wildfires are already becoming commonplace in forested countries around the world [1–4]. Every forest fire brings with it significant losses of various types: human, economic, forest resources reduction, and biogeocenoses destruction [5–7]. Many research groups worldwide are working on developing various schemes for monitoring and extinguishing forest fires, and conducting mathematical and physical experiments to study the influence of external conditions and the type of forest on the firing process. The data obtained have already been used to combat natural disasters [8–11]. However, further research is necessary to summarize the already known data on the topic and fill the existing “niches” in this area. Only after receiving a complete picture of the forest fires features, will it be possible to resist them effectively. To accurately predict the occurrence of forest fire and further spread, it is necessary to generalize knowledge about the processes happening during a fire. The following sequence of phases stands out [12]: 1. Forest fuel heating and drying with the water vapor release; 2. Drying and beginning of combustion, where the water vapor and resins are released; 3. Ignition of gases and flaming combustion, followed by the water vapor, smoke, carbon dioxide release; 4. Carbonization and coal afterburning.

Drying, pyrolysis, and ignition of forest fuel are of particular importance in the case of the prediction of forest fires. The knowledge of these process patterns allows for both improving of the forecast accuracy and developing a set of measures to slow down or stop these processes, which will avoid ignition. This article discusses the key features of the drying, pyrolysis, and ignition processes, as well as approaches to their experimental and mathematical modeling.

2. Summary

The main tasks of the forest fires theory can be generally classified as follows [13]: (1) Estimation, monitoring, and prediction of forest fire danger; (2) Modeling the prop-

agation of the surface or crown forest fire front; (3) Development of methods for forest fires localizing and extinguishing; (4) Assessment of the consequences of forest fires; (5) Development of the reforestation methods.

Field observations of forest fires, for example, in Eastern Siberia and the Far East of the Russian Federation, show that currently there are no methods of extinguishing forest fires that could be successfully applied. A forest fire typically ends when a fire front collides with a natural or man-made obstacle, such as a riverbed, road, clearing, or mountain range. Wildfire usually continues until the entire forest area is burned out or long heavy rains begin.

The most rational way to fight forest fires is to prevent them. In this context, a significant role is assigned to methods of estimation, monitoring, and prediction of forest fire danger. Knowing the expected level of forest fire danger allows forest fire fighting services to concentrate fire extinguishing forces in places with the maximum forest fire probability.

Based on the goals and objectives of information processing on forest fire danger, the following types of information processing can be distinguished (this information is schematically shown in Figure 1) [14]:

1. Assessment of the current level of the forest fire hazard (allows for obtaining up-to-date information on the forest fuel characteristics and forest fire danger factors, as well as conducting qualitative and quantitative analysis to estimate the forest fire danger level using special scales).
2. Monitoring the forest areas state in the context of forest fire danger (designed to track daily changes in assessing the forest fuel properties, factors, and indicators of forest fire danger in order to identify temporal and spatial trends in the change in the forest fire danger level).
3. Prediction of forest fire danger (the most important type of information processing, which is intended for predictive modeling of forest fire conditions based on estimated and monitoring information on the factors and indicators of forest fire danger).

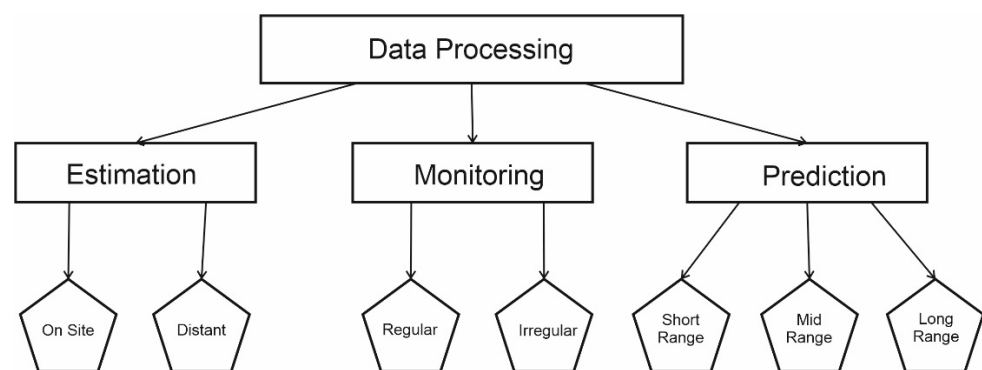


Figure 1. Types of information processing on forest fire danger.

There are different types of predictions [14]:

1. Short-range prediction assumes the calculations of the parameters for the next day period using estimated and monitoring information.
2. Medium-range prediction proposes to calculate the required parameters and the level of the forest fire danger for a 5–7 days period. In this case, predicted information for the days of the previous period can be used in addition to estimated and monitoring information.
3. Long-range prediction enables using retrospective data for previous fire seasons. However, the reliability of such type predictions is the lowest. This is especially important to understand in the context of global climate change.

Probabilistic, statistical, deterministic, empirical methods of the prediction of the forest fire danger can be distinguished [15–19]. There are also prediction methods based on

artificial intelligence technologies [20]. In the last decade, the approach of deterministic–probabilistic prediction of forest fire danger has been intensively developed at Tomsk Polytechnic University [21]. This integrated method combines a probabilistic prediction of factors of forest fire danger and scenario modeling based on deterministic mathematical models of drying, pyrolysis, and ignition of forest fuel [22–24]. Improvement of the deterministic–probabilistic approach has necessitated the analysis of published developments in this area. Within the framework of this article, it is proposed to consistently analyze the methods of studying forest fuel drying to assess its forest fire maturation. Moreover, it is necessary to consider the thermal decomposition of forest fuels, since this stage is characterized by the release of gaseous combustible products. These products largely determine further ignition and flame combustion stages. A separate section of the article is devoted to studies of forest fuel ignition. This stage is decisive in the forest fire occurrence. The scheme of forest fire stages is shown in Figure 2. The scheme of deterministic–probabilistic prediction of forest fire danger is shown in Figure 3.

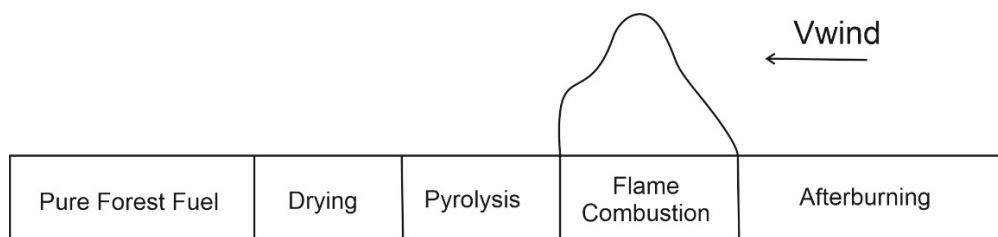


Figure 2. Scheme of the forest fire stages.

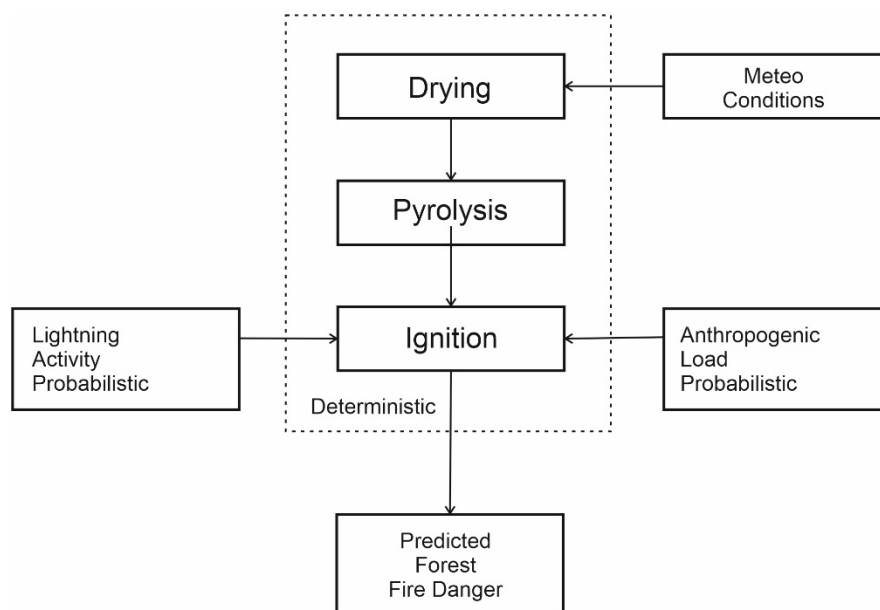


Figure 3. Deterministic–probabilistic prediction of forest fire danger.

3. Forest Fuel Drying

The drying process is one of the key processes in the study of the nature of forest fuel combustion. This stage is crucial since it is followed by the process of thermal decomposition of the substance, which is one of the precursors of possible ignition. The study of the laws governing the evaporation of liquid from forest fuel will make it possible to determine the number of measures that are expedient to stop this process.

Drying of forest fuel means the evaporation of water from it. Moisture in the sample can be free and bound. Free moisture is usually considered as a layer of water on the material surface. The saturated vapor pressure and the saturated vapor pressure above the water’s flat surface are equal in this case. Such moisture can be removed easily. The

situation is different with bound moisture. In this case, the bonds with the material are stronger. The removal of such moisture is a multi-stage and energy-intensive process.

The form of bond between moisture and material significantly affects the characteristics of the drying process. In this regard, the Soviet scientist P.A. Rebinder developed a classification of the relationship between moisture and material. The amount of work expended to evaporate 1 mole of moisture was taken as the main criterion. According to this classification, there are three types of bonds between moisture and the material [25,26]:

1. Mechanical bond is the weakest one, which requires 100 Joules of energy to break. Mechanical moisture includes moisture from micro and macro capillaries. The macrocapillaries only fill when they come into contact with the material, and the microcapillaries can also absorb moisture from the environment.
2. Physicomechanical bond takes 3000 Joules of energy to remove moisture. This type of bond includes adsorptive (firmly adhered to the surface) and osmotically (inside cells) bound moisture.
3. Chemical bond is the strongest, which requires 5000 Joules of energy to break. In this case, a chemical reaction or heating to high temperatures is required to remove moisture. This moisture is not removed during normal drying.

The key issue in the study of forest fuel drying is to determine the thermokinetic and thermophysical properties, as well as moisture content of the material under study. Also, it is necessary to define typical times characteristic features of this process. Forest fuel moisture content is one of the main parameters that affect the duration of the drying process. This parameter can vary widely depending on the fuel hygroscopicity, its cellular structure, and thermophysical properties. The importance of determining the fuel moisture content is explained by its influence on the thermophysical properties of the sample itself and on the processes of fuel drying and ignition. Therefore, it will be more difficult to ignite forest fuel with high moisture content, since a large amount of heat is required for moisture evaporation. Moreover, water vapor helps to reduce the ignition potential, combustion temperature and can dilute oxygen. Thus, the ignition may not occur at all, or it will take a much longer amount of time.

The fuel moisture content (FMC) reflects the ratio of the water contained in the sample to its dry mass and is determined by the formula [27]:

$$M = \frac{w_t - w_d}{w_d},$$

where w_t and w_d —biomass weight before drying and after its end, respectively.

Drying speed is calculated as:

$$\eta = \frac{M_{t_1} - M_{t_2}}{t_1 - t_2},$$

where M_{t_1} , M_{t_2} —biomass moisture at time t_1 and t_2 , respectively.

The moisture ratio of biomass is calculated by formula:

$$\eta = \frac{M_t - M_e}{M_0 - M_e},$$

where M_t —current biomass moisture content, M_0 —initial biomass moisture content, M_e —equilibrium moisture content.

Five typical models are widely used to describe the kinetics of biomass drying [27]:

1. The Newton model $\varphi = \exp(-kt)$
2. The Page model $\varphi = \exp(-kt^n)$
3. The modified Page model $\varphi = \exp[-(kt)^n]$
4. The Henderson and Pabis model $\varphi = a \exp(-kt)$
5. The Logarithmic model $\varphi = a \exp(-kt) + c$

where t —drying time, k, n, a, c —model parameters.

In the research devoted to the development of the systems of forest fire hazard prediction, several options for determining the FMC have been proposed. Fieldwork, the use of calibrated sticks, and the calculation of meteorological danger indices are the most common ones; none are universal because of their features. Fieldworks involve the collection of samples in various types of forest areas and further determination of moisture in laboratory conditions [28]. The fuel moisture content is measured experimentally using the thermogravimetric analysis method. This method involves obtaining thermogravimetric curves characterizing dependences of weight loss (in grams or percent) on the environment temperature. Experiments are carried out using special equipment (thermobalance), which makes it possible to record the mass loss of the sample over time [29]. It is noted that the optimal mode for obtaining adequate results is long-term drying (about 72 h) at relatively low temperatures (about 80–85 °C) [30]. The disadvantages of the fieldworks method include its laboriousness (it takes a lot of time to collect samples and conduct research) and large financial costs [31]. The use of calibrated sticks involves the determination of the FMC based on the dynamics of changes in the mass of calibrated wooden rods [32]. This method allows us to get away from the problem of high labor costs and instant estimation of the indicator. However, in this case, measurements are of a local nature, and calibration samples can quickly become unusable [31]. The meteorological danger indices (MDIs) method assumes the FMC calculation based on weather conditions instead of direct measurements [33]. This method is quite adaptive, but it does not allow for the physiological characteristics of the plants. Thus, it leads to less accuracy with respect to living fuels. It is also possible that errors appear due to incorrect determination of the parameters, which serve as the basis for the calculation of moisture [31].

Nowadays, remote sensing technology is widely used to determine FMC. This technology makes it possible to level the main difficulties of the previous methods, as well as to provide a wide spatial and temporal coverage [34]. For example, hyperspectral and multispectral remote sensing technologies use empirical dependences of fuel moisture spectral indicators, which can differ from region to region. The FMC can be judged by the hyperspectral signals in the spectral regions with high water absorption. Wide spectral variations due to moisture changes include variations in near-infrared (NIR) and shortwave infrared (SWIR) [35]. The use of spectral technologies involves the calculation of coefficients, based on which the FCM can be subsequently estimated. These include Normalized Difference Vegetation index (NDVI) [36,37], Normalized Difference Infrared index (NDII) [37], Leaf Water Content index (LWCI), Tasseled Cap 'Wetness', Integral, and Spectral Derivatives [37,38].

Radiative transfer models (RTM) are another promising direction in remote sensing. Such models are grounded in physical laws that provide a connection between the obtained spectral characteristics and properties of forest fuel [39]. In this case, the radiation transfer equation, which is attenuated by absorption and scattering or enhanced by backscattering, is applied. However, the accuracy is limited within the emitting medium, which must be continuous and homogeneous. If the medium is a combination of several different phases (for example, a mixture of gases, solid particles, residues of decomposing fuel, etc.), the accuracy is significantly reduced [40]. Difficulties also arise with the parameterization of these models, since the input parameters strongly depend on the external conditions and forest fuel properties. However, an approach of randomly changing these parameters in the specified ranges can be used to bypass this limitation [41]. The RTM technology is now considered in the context of a promising, but not widely used approach. However, cases of its application as well as technical solutions to improve the accuracy of this method have already been described in the literature [42–46].

A mixture of living and dead fuels usually burns during a wildfire. Therefore, there is a need to identify the patterns of moisture change for both species. The process of moisture evaporation from living and dead fuels will be different [30]. So, in the case of living fuel, moisture moves to the surface layer due to diffusion and capillary forces. The water release

to the surface itself occurs owing to the tensile pressure caused by the water potential. But water moves to the surface of dead fuel due to the processes of diffusion and evaporation from the cell walls. As a result, moisture forms a film on the surface and then begins to evaporate. In addition, the moisture content of living fuels changes gradually during the day, while dead fuels quickly react to in environmental conditions changes. Consequently, the estimation of the fuel moisture content contributes to a more accurate prediction of the occurrence of a forest fire. The concepts of Live Fuel Moisture Content (LFMC) and Dead Fuel Moisture Content (DFMC) are introduced in the literature to differ the peculiarities of the moisture evaporation for dead and live fuels. Empirical [47–49] and process-based models [50–53] are used to assess these indicators. Empirical models are based on statistical data from field observations on FMC ratios and input data (weather conditions, fuel type, terrain features) [54]. In process-based models, attempts are made to model the processes occurring in fuel based on experiments and theoretical principles [54].

Living forest fuels can be divided into grasses and herbaceous plants or into morphological parts of plants (leaves, needles, small branches, etc.). LFMC is much more difficult to measure in terms of meteorological indicators because of the ability of plants to adapt to drought and to consume moisture accumulated in the soil. The previously described remote sensing method is often used to determine LFMC [55–58].

Dead forest fuels are subdivided into subclasses depending on the moisture content, which is calculated with 1, 10, 100, and 1000 h time lags (shifts). Time lag characterizes the amount of time taken to evaporate about 63% of the initial moisture content. According to the time lag concept, dead forest fuels can be attributed to one of the following subclasses [59]:

1. Class (moisture content is approximately equal to the environment moisture content. This class includes dead herbaceous plants that form the forest floor, as well as round wood fuel with a diameter of up to 6 mm).
2. Class (moisture content ranges from 1 to 60%. This group includes round wood fuel with a diameter in the range from 6 to 25 mm or a layer of forest floor up to 20 mm thick).
3. Class (moisture content ranges from 1 to 50%. These include round wood fuel with a diameter of 25 to 75 mm, as well as forest floor with a thickness of 20–100 mm).
4. Class (moisture content ranges from 1 to 40%. These include wood fuel with a diameter of 75 to 203 mm, as well as forest floor with a thickness of more than 100 mm).

The determination of DFMC is especially important because dead fuel cannot regulate and replenish its moisture level like living fuel can. This means that it is more susceptible to drying out and more fire hazardous [60,61].

The concept of equilibrium moisture content (EMC) was also introduced to study the processes of vapor exchange, adsorption, and desorption [62]. The equilibrium moisture content of forest fuel means the moisture content that an element will reach if it will be left in considered environmental conditions for a sufficient amount of time. This parameter may depend on specific environmental conditions and on the change of the current sample moisture rate towards equilibrium. During simulations, equilibrium moisture is described as a function of temperature, relative humidity, and sometimes the forest fuel type. The most famous models using this exponent belong to Simard [63], Van Wagner [64], Anderson [65], and Nelson [66]. Scientists have developed their models based on empirical data, trying to allow for adsorption and desorption processes.

However, the use of the equilibrium moisture content parameter is complicated by the hysteresis nature of the wetting and drying modes. In this regard, the authors began to propose other approaches to the description of processes. So, several vapor exchange models appeared, which were based on data on the humidity and temperature of the environment. But the final result of the calculations was the actual moisture content in the forest fuel. In this case, attempts were also made to parameterize the drying process to increase the accuracy of the results. Also, a behavioral model using rainfall as input was suggested. All the obtained models need to be improved and have a limited scope of application [62].

Experimental work in the field of drying is aimed at determining the values of the moisture content of various types of fuel, drying characteristics, and establishing the regularities of the various environmental factors that influence the moisture content. For example, the influence of external environmental parameters (wind speed, relative humidity, air temperature) on the fine fuel moisture content was considered using a special climate-controlled chamber [67]. As a result, it was found that the intensity of moisture loss during the experiment was uneven. The initial stage is described with a rapid moisture loss. Subsequently, the drying process is stabilized to exponential decay. The obtained data made it possible to develop the corresponding prediction equations reflecting the rate of moisture content change and equilibrium moisture content for fine fuels with respect to absorption and desorption processes.

The influence of drying temperature on the mass change in three widespread dead forest fuel samples (eucalyptus leaves, grass, pine needles) was described in [68]. The moisture content was determined at various temperatures (from 60 to 105 °C). It was noted that the values of the masses of dried fuel within the range were about 3.5%, which is significant in the context of forest fire hazard prediction.

The moisture content of typical forest fuels was assessed at the beginning of the fire hazardous season in [69]. The studies tested samples collected in various types of forests with different reliefs. It was concluded that the moisture content decreases in the series “birch-aspen-pine-oak”. These results are explained by differences in the wood structure of these species. It was also noted that the land topography insignificantly affects the moisture content of the sample.

The kinetic parameters of drying and pyrolysis of some forest fuels typical for taiga zone on the territory of Russia, are given in [70]. In the course of research, it was identified, that several types of forest fuel have uniform values of kinetic constants.

Information about the drying process is used to formulate criteria for forest fire occurrence. For example, the Nesterov empirical drought index is widely used in Russia [71]. The index is calculated based on daily synoptic data (temperature, humidity, daily precipitation). It relies on a simple mathematical model describing a weighted difference between temperature and dew point. However, this index does not consider such important factors as the type of forest fuel and its thermophysical and thermokinetic properties, wind speed, and soil type [72]. The index is calculated according to the formula:

$$NI = \sum_{i=1}^W (T_i - T_{d,i}) T_i,$$

where T_i , $T_{d,i}$ —air temperature and dew point at the time between 13:00 and 15:00 local time of the current day (°C); W —the number of days on which the amount of precipitation was less than 3 mm [73].

As can be seen from the formula, the index is calculated based on the weather conditions in the previous days. According to the obtained index value, 5 levels of fire hazard are distinguished: no fire risk ($NI < 300$), low risk ($301 < NI < 1000$), medium risk ($1001 < NI < 4000$), high risk ($4001 < NI < 10,000$), and extremely high risk ($NI > 10,000$) [73].

There is also a Modified Nesterov index, and similarly, the Zhdanko index [74]. In this case, a scaling coefficient is added to the previous formula. This coefficient allows controlling changes in precipitation on the day the index is calculated. In this case, the formula is applied for calculations [75]:

$$MNI_i = \left(MNI_{i-1} + \sum_{i=1}^W (T_i - T_{d,i}) T_i \right) \cdot K(n),$$

where $K(n)$ —a scaling factor for accounting for precipitation. It is taken equal to one if there were no rainfall, or equal to zero if the amount of precipitation was more than

19 mm. There are also intermediate values of this coefficient depending on the amount of precipitation [75].

Another commonly used method for assessing potential fire hazards is the Keetch–Byram drought index (KBDI). It represents the net effect of evapotranspiration and precipitation on the creation of cumulative moisture deficits in the topsoil. KBDI is trying to measure the amount of rainfall required to replenish the soil in a field. The index is calculated by the formula [76]:

$$DQ = \frac{[203.2 - Q][0.968 \exp(0.0875T + 1.5552) - 8.30]d\tau}{1 + 10.88 \exp(-0.001736R)},$$

where Q —moisture deficiency (mm), T —daily maximum temperature ($^{\circ}\text{C}$), $d\tau$ —time increment (1 day), R —annual precipitation (mm).

The index ranges from 0 to 800. Zero corresponds to no moisture deficit and 800 to a maximum drought. KBDI is based on daily rainfall and maximum air temperature observations. The KBDI value of each new day is calculated using the data for the previous day [77].

Furthermore, the Canadian Forest Fire Weather Index System (CFFWIS) uses information about fuel moisture content. This prediction system includes an FWI system consisting of six components calculated on the meteorological data basis for each day. The first three components reflect the moisture content of different fuels: thin (litter), weakly compacted organic material (“duff”), and deeper organic layers/fuels with a large surface [78].

The Angstrom index proposed by Swedish scientists is also used to assess the fire hazard. This index is one of the simplest ways to assess drought. By analogy with the Nesterov index, five levels of fire hazard are distinguished depending on the index value [79]. The index is calculated by the formula [80]:

$$B = 0.05H \cdot \left(\frac{T - 27}{10} \right),$$

where H —relative humidity (%); T —air temperature ($^{\circ}\text{C}$) [80].

The issues of both comparing the accuracy of indices and their applicability on a specific territory are discussed [81–84].

Thus, modern research devoted to the study of the drying process indicates a direct relationship between the moisture content of the fuel and its further ignition. Among the main directions of current research, one can single out the determination of the parameters of this process for various forest fuel types, as well as the development of mathematical models of drying.

4. Forest Fuel Pyrolysis

The fuel pyrolysis investigation is a foreground task in the context of prediction of the forest fire hazard. This process is a kind of “conductor” to the ignition of the material since during decomposition gaseous volatile substances that support combustion are released into the atmosphere.

During pyrolysis, the reaction of thermochemical decomposition of the initial substance (biomass) into solid, liquid, and gaseous fractions occurs in the absence of oxygen [85]. It is necessary to know the composition of the considered fuel in order to reveal its pyrolysis mechanism. Typical forest fuel mainly consists of three main polymers (cellulose, hemicellulose, lignin) in different percentages, as well as extractive and mineral substances [86]. This means that the forest fuel pyrolysis will proceed similarly to its main components decomposition.

Cellulose is a part of cell walls and is a linear homopolysaccharide of cellobiose monomers, consisting of two β -glucopyranose units. According to thermogravimetric studies, cellulose decomposition includes three stages with corresponding temperature ranges. At temperatures below $300\text{ }^{\circ}\text{C}$, intermediate decomposition products (active cellulose or anhydrocellulose) are mainly formed [87]. Active decomposition is observed at

300–390 °C during depolymerization reactions. Here, about 80% of volatile compounds and anhydro-oligosaccharides are formed [88,89]. The charring process takes place at the temperature of 380–800 °C.

Hemicellulose promotes the binding of cellulose microfibrils to the cell wall. This substance has low thermal stability and different structure and composition. Usually, xylan is its main component. Hemicellulose decomposition occurs at 200–350 °C with main peaks at temperatures of 290 and 310 °C. The degradation of hemicellulose is quite similar to cellulose. Dehydration occurs at low temperatures (<553 K) with further depolymerization at higher temperatures [88].

Lignin is a complex three-dimensional polymer of phenylpropane units. The main stage of lignin decomposition occurs at temperatures of 200–450 °C [90]. Dehydration predominates at relatively low temperatures, but the formation of different lignin monomers occurs at higher temperatures. Monomers decomposition happens at temperatures higher than 700 °C. After that, the released products enter the vapor phase. This substance is more stable than previous ones. Therefore, in this case, the proportion of char and aromatics formed is also higher [91].

Thus, studies show that the complex polymer structure of the main components of forest fuel entails a variety of possible reactions and products with an increase in temperature. In general, it is considered that there are three main stages of decomposition: the release of water and carbon oxides from the matrix, the main intensive decomposition, and then a slow decomposition [92].

The pyrolysis process modeling is a rather complex and multifaceted task since it is necessary to allow for the variations in the chemical composition of the biomass, the ongoing reactions, and its products. There are three main groups of models that consider this process on three different levels: mechanistic, network, and kinetic [93].

The purpose of mechanistic models of pyrolysis is to reveal the mechanism of this process depending on the ongoing reactions paths and the resulting components without any groupings and generalizations [93]. As a rule, these models are based on force field (molecular mechanics) or ab initio methods [93]. Such models are not widely used in research since it is possible to simulate only the decomposition of only one specific component. However, there are still studies devoted to the decomposition of cellulose in the literature [94–96].

Network models describe the volatiles release mechanism as the subsequence of depolymerization and repolymerization reactions, accompanied by external and internal mass transfer. These models are used mainly for coal fuels, but there are adoptions for biomass paying attention to structural changes of the material. In this case, it is possible to conduct a quantitative analysis of volatile gases, tar, and coke during pyrolysis. However, the effect of inorganic impurities on pyrolysis is not considered here [93]. Typical examples of network models are Bio-FG-DVC (Functional Group Depolymerization Vaporization Crosslinking) model [97], Bio-FLASHCHAIN model [98], and Bio-CPD (Chemical Percolation Devolatilization) model [99].

Kinetic models describe the pyrolysis of biomass and forest fuel in general. This type of model is the most appropriate one in the context of forest fire investigation. Such models provide good convergence of results with a small set of input parameters that can be obtained experimentally. The simplest example of the kinetic model is the one-stage global kinetic model, which describes the biomass conversion into semi-coke and volatiles [100]. The Arrhenius equation is the basis of this model [101]:

$$\frac{dV}{dt} = A \exp\left(-\frac{E}{RT}\right)(V_{\infty} - V),$$

where A , E , R —Arrhenius equation kinetic coefficients, t —time, T —the particle temperature, V —the normalized mass of volatiles, and V_{∞} —the final value of V .

Such models are typically used with heat transfer and volumetric reaction models. For example, a one-dimensional mathematical model of pyrolysis based on the global kinetic

model is considered in [102]. The suggested model took into account the variability of thermophysical properties as well as different radiative heat flux and boundary conditions. The global kinetic model does not fully cover all pyrolysis peculiarities, but it is suitable for approximate calculations and estimates. For example, using this model, the parameters of the cellulose pyrolysis process were estimated at low heating temperatures [103]. Additionally in the literature, kinetic models are subdivided according to the reaction mechanism into two large types: lumped and distributed. In lumped models, it is assumed that the various biomass components are combined into three large classes: gas, tar, and char. Within the framework of this concept, several options for the primary material decomposition and secondary reactions of volatile products are proposed [104]. In addition, pyrolysis can be described as a set of parallel reactions [93]. Such an approach allows for the experimental and numerical data agreement to be increased, as well as to predict released components amount.

Thus, the thermogravimetric analysis of pyrolysis products leads to the creation of a three independent reactions model. It is suitable for volatiles released during the wood and sawdust pyrolysis [105]. In this model, the biomass decomposition is described by the decomposition of its main components without any interaction between them. The kinetic equation linking the fugitive emission at time t with the activation energy and preexponential value can be written for each component:

$$\frac{d(V_i/V_i^*)}{dt} = k_{0i} e^{-\frac{E_i}{RT}} \left(1 - \frac{V_i}{V_i^*}\right)$$

where V^* —the total volatile mass available for each component in the primary biomass. The total volatile biomass release is determined by linear correlation.

A modification of the parallel reactions model taking into account the volatilization of products is described in [106]. The added equations allowed obtaining a set of kinetic parameters for pyrolysis in an inert and oxidizing environment. The influence of substance heating and ignition rate is also considered. Similar studies were carried out for other biomass types with the subsequent model correction and description of the main regularities [107–110]. However, the combination of such models with heat and mass transfer equations makes calculations rather laborious. This fact makes complicates the applications of this model [92].

The model of competing reactions is mostly used to describe forest fuel pyrolysis [100,111]. The model represents a set of primary and secondary reactions combined in a narrow temperature range using three competing reactions. Despite the fact that such models are capable of giving rather good predictions, it becomes complicated to choose the appropriate kinetic parameters, since it is difficult to track the active material separation from volatiles and char [92,112–115].

Detailed lumped kinetic models are also often used. Such a model is more mechanistic compared to classical lumped kinetic models. It mainly focuses on biomass structure; the removing volatiles process with the permanent gases, condensable vapors (resins) and a solid residue (char) formation; and threading secondary gas-phase reactions. Biomass pyrolysis is assumed as a linear combination of components decomposition in accordance with their proportions without taking into account their interaction [116].

The literature describes a model developed by the Ranzi group, which allows predicting the total yield of pyrolysis products for a limited number of reactions using optimal computing power. However, there are limitations in obtaining some kinetic parameters due to the forced fitting of the parameters [117]. Vinu and Broadbelt also proposed a more elaborate model in their studies, reflecting an understanding of various competing reactions in the rapid pyrolysis of cellulose and other glucose-based carbohydrates using a unified microkinetic model [118].

Distributed models describe pyrolysis products formation by an infinite number of independent parallel reactions with different activation energies specified using different distribution functions [104]. The distributed activation energy model (DAEM) assumes

that pyrolysis occurs through reactions with different activation energies. The activation energy distribution can be described by a continuous function. This type of model was initially used for solid fuels, but then it was adapted to biomass [119]. DAEM can imitate mass loss over the entire conversion rate more accurately compared to other models. The model can be described by the equation:

$$1 - X = \begin{cases} \int_0^\infty \exp\left[-\int_{T_0}^T \frac{A}{\theta} \exp\left(\frac{-E}{RT}\right) dT\right] f(E) dE, & \text{first order } (n = 1) \\ \int_0^\infty [1 - (1 - n) \left(-\int_{T_0}^T \frac{A}{\theta} \exp\left(\frac{-E}{RT}\right) dT\right)]^{\frac{1}{1-n}} f(E) dE, & \text{nth order } (n \neq 1) \end{cases}$$

where: E —the activation energy, θ —the heating rate, A —the frequency factor, R —the ideal gas constant, n —the reaction order, T —absolute temperature, T_0 —the initial temperature, $(1 - X)$ —represents remaining mass fraction $f(E)$ —the initial distribution function of activation energies [120].

The kinetic parameters for DAEM can be calculated using distribution-free methods or distribution-fitting methods. The distribution-free method first determines the E and α correlation using the isoconversion method. Then $f(E)$ is determined by differentiating the ratio between α and E . The distribution-fitting method is the dominant method, which is based on the presupposition of $f(E)$ and further obtaining parameters by the TG simulation according to numerical methods. These methods achieve a fine fit (usually greater than 0.99) [121]. DAEM models are actively used in practice [122–125].

Different distribution types can be used to assess $f(E)$. For example, Gaussian, logistic and exponential distributions were tested to determine the convergence between numerical and experimental data for spruce powder pyrolysis in [125]. It is noted that the greatest agreement was provided by the combination of the exponential and Gaussian distributions, and the use of DAEM allows one to distinguish between the heating rates of the components.

In modern realities, it is of interest to compare various approaches to modeling pyrolysis and select the most successful options for a specific type of heating and forest fuel [126–128]. Thus, two competing models, namely the linear model and the Arrhenius model, were evaluated for pyrolysis in the physical modeling of fires in grass fuel [127]. Lucerne hay was used as a sample. The results also show that the linear model is independent of the score and interspecific variation.

The efficiency of three previously proposed schemes of pyrolysis reactions of wood (birch) was assessed in the reproduction of thermogravimetric experiments with birch wood [128]. The remaining parameters of the model were determined from laboratory calorimetric experiments. The results show that a one-stage first-order reaction scheme provides good heat rate predictions in comparison with more complex models. The source of thermal input parameters (direct measurement or inverse simulation) did not significantly affect predictive power. Numerical simulations were performed using a fire dynamics simulator (FDS) pyrolysis program. The developed computer program can be applied as a stand-alone solution for pyrolysis to simulate material behavior on a small and laboratory scale, and also to study the phenomenon of conjugate flame propagation, taking into account spatially varying boundary conditions.

Furthermore, there is a research direction in the literature devoted to the study of the pyrolysis process during liquid evaporation [129–131]. These developments contribute to a deeper understanding of the processes occurring directly during pyrolysis and its suppression.

Consequently, in the course of the pyrolysis process, gaseous decomposition products of the substance are released into the atmosphere and subsequently cause fuel ignition as well as support the combustion. The researchers note that the pyrolysis patterns directly depend on the biomass composition. There are also discussions in the literature about the mathematical description of the reactions taking place during this process. Further research

is necessary to determine the thermophysical and kinetic parameters of this process for various forest fuel types.

5. Forest Fuel Ignition

Forest fuel ignition is considered the last stage before starting the fire. It affects the level of forest fire hazard along with the drying and pyrolysis process. Currently, the ignition process is studied within the multiphase reacting media mechanics. Now the literature describes various ignition models, taking into account the properties of the material, environmental parameters, as well as the features of the ignition source. It is advisable to consider the identified features of the forest fuel ignition.

The ignition process depends on the type of ignited material and environmental conditions. The forest fuel ignition is considered as the ignition of condensed systems. A condensed system is understood as a substance in a liquid or solid-state with a short-range or long-range order of atoms [132]. There are several ways to ignite condensed matter. Conductive ignition describes ignition when a high-temperature medium contacts a relatively cold substance. Radiant ignition assumes the condensed matter ignition by the transfer of energy from incandescent particles or gases. The cause of convective ignition is the interaction between a condensed substance and burning gases, which are often products of thermal decomposition of this very substance [133]. Various models were built taking into account the laws of these ignition paths, for example, gas-phase, heterogeneous, and solid-phase.

When studying the ignition process, it is necessary to pay attention to the determination of the ignition delay time. This parameter makes it possible to assess the susceptibility of forest fuel to be ignited. A technique for estimating the ignition time of solid materials is presented in [134]. It is based on the suggestion that the time to ignition is proportional to the squared time integral of the incident heat flux. This relationship can be easily demonstrated for classic ignition timing solutions. Thus, the ignition time can be easily calculated using incident heat flux onto the sample (calculations of the gas phase) and the experimental results. The proposed approach can be effective when used in the simulation of ignition in a forest fire.

The ignition of forest fuel from the Mediterranean region is studied in [135]. Thermal analysis showed that several factors influence flammability. However, the amount of decomposing cellulose between 320–370 °C is a decisive factor. Moreover, the mass of formed volatiles at 120–160 °C affected this process.

Intermittent and continuous ignition of *pinus radiata* needles (live, dead, a mixture of dried and re-moistened needles) is studied in [136]. The ignition delay times with the corresponding confidence intervals were obtained depending on the applied heat flux. The higher values of temperatures, ignition delay times, and heat fluxes are characteristic for live fuels in the case of spontaneous continuous ignition. Rewetting also affects the critical heat flux.

In addition, the spontaneous ignition of pine needles as an ideal heating source was considered in order to establish the relationship between the incident radiation heat flux and the reverse ignition time [137]. A quasilinear relationship was typical for a thermally thin solid fuel. A linear dependence between the mass loss rate and the decreasing heat flux was found. Changes in temperatures and mass rate were analyzed for different heat fluxes values.

The process of ignition of thin natural fuel (pine needles) by simulating a lightning discharge with a long current was experimentally studied in [138]. The logistic regression was used to predict the likelihood of ignition. It was found that burning time and the energy of the simulated discharge required for pine needle ignition increase with an increase in the fuel moisture content. Visual observation showed that the ignition proceeded through a very special process, including three stages, other than ignition from firebrands or flame emission: the discharge heating, thermal feedback, self-sustaining flame. Experimental

research on ignition was carried for various forest fuels in order to determine their ignition susceptibility [139].

Experimental studies of ignition of forest fuels with heated particles have been carried out [140–143]. Such particles can be formed as a by-product of the operation of infrastructure facilities (from power lines, hot work at specialized factories, railways), cars (exhaust system operation, overheating of the brake system), pyrotechnics, etc. These particles can migrate over long distances and become a potential cause of fire [144–146]. Firebrands are mainly formed when fuels are burned in wildlands or directly in the event of a fire. These firebrands are then carried by the wind to areas with non-burning fuels.

The spruce needles and birch leaves ignition by a heated to high temperatures particle is considered in [147]. The linear dependence of the ignition delay times on the initial particle temperature was determined. When the particle temperature equals 1300 K, the ignition delay time does not depend on the heating source size. A complex of interrelated diffusion and convective processes takes place both in the porous structure of the material and above it.

The results of studying the needles ignition using firebrands are presented in [148]. It is noted that the fuel layer porosity affects the heat flux value required for ignition. An analytical expression was obtained within small ignition delay times for the correlation of the ignition time inversion with the heat flux. The developed model made it possible to evaluate the effective properties of forest fuel.

Another important parameter in the ignition process is the heat release rate. This parameter helps in determining other quantities, such as flame and plume geometry, and in predicting their propagation. The heat release rate is not determined directly but is calculated on the basis of experimentally determined values using calorimetric methods [149,150].

The contribution of radiant and convective flow components were assessed in [150] for the case of the ignition of the forest layer located at a slope. The obtained data served as the basis for calculations of the radiation and convection fractions emitted into the environment. The convective fraction decreases from 74.9% to 61.1% at a slope of 20°, while the total radiation fraction varies from 25.1% to 38.9% and increases with fuel loads.

The experimental results of the heat flux effect on particles of the *Cistus monspeliensis* plant are presented in [151]. The results show that there is a limit in a particle size limit, after which the heat release rate has a different behavior during combustion. This change means the difference in fuel flammability. The obtained data can be used for further simulation of the combustion processes for plants of this class.

Moreover, there are articles where experimental and mathematical approaches are used to the study of the ignition process with solid particles [152–154]. Thus, the forest fuel ignition by heated particles made of stainless steel and aluminum is considered in [154]. The ignition type (flaming, smoldering, or its absence) was also determined. The provided videogram reveals the surface layer smoldering after a particle falls on it. Ignition in this case is influenced by fuel, particle, and environmental parameters. Similar studies were carried out for wood [155,156].

A mathematical model of the forest fuel ignition by a heated metal particle is considered in [157]. According to the mathematical statement, a heated particle falls on the forest fuel layer with heterogeneous wood inclusions in it. The problem of thermal conductivity with appropriate boundary conditions is solved. The pyrolysis reaction was taken into account. As a result, typical temperature changes were obtained, and the dynamic of the heating of the surface and deeper layers was estimated. Heating is mainly caused by heat transfer along the vertical coordinate. The presence of inclusions does not have a significant effect on heat transfer processes.

A three-dimensional mathematical model of the ignition of the forest fuel layer by another heated element made of forest fuel material (pine twigs and pine bark) was suggested in [158]. The element length is the main affecting factor in the ignition beginning. A pine twig poses a greater threat to the start of a fire than pine bark. The calculated and

experimental times of layer ignition are in good agreement. Additionally, the ignition of a forest fuel layer is investigated in [159].

Less research is devoted to the combustion of deciduous fuel under various types of heating [160,161]. These studies allow for characterizing the fuel behavior as a stage sequence. In addition, the initial FMC influence on ignition was estimated. Typical temperature distribution and weight loss changes with time were obtained. These results supplement the available data on forest fuel combustion. There are also models of heat transfer in a plant element, which permit the study of the sample behavior within various forest fire scenarios and the temperature changes in it [162].

A qualitative and quantitative analysis of the combustion of representative California chaparral samples (manzanita, scrub oak, hoary leaf ceanothus, and chamise) was carried out in [163]. The experimental setup simulated the situation where the forest fuel was in the front of a forest fire. It was assumed that heat energy from the fire front was transmitted in two ways (convection and radiation). The ignition and combustion process was recorded using a video camera. Surface temperature data for specimens (except for *Adenostoma flaviculatum*) were obtained using type K thermocouples.

The qualitative analysis investigated the effect of specimen shape and orientation on ignition. Samples of chamise were examined separately from broad leaves to study the effects of shape and orientation. The leaves were found to burn in a similar pattern for broadleaf species when cut in similar shapes. Round samples ignite around the perimeter of the sample, and then flame spreads towards the center. Squared samples were ignited first at the corners with further flame spread along the perimeter. A significant influence of the sample orientation was also noticed. Wide leaves held horizontally exhibit a completely different combustion pattern than when upright. When vertically oriented above the flame burner plane, the leaves were ignited at the edge closest to the flame. Also, there were small bubbles in the central part of the horizontally oriented broad leaf before the ignition. When the moisture content of the manzanita sample exceeded 100%, these bubbles burst prior to combustion to form a crater on the surface. The chamise plant consists of small needles and a stem. The tips of the needles were ignited first. In the case of a vertical position, the needles closest to the ignition source were ignited first and then the flame moved upward.

Qualitative experiments made it possible to determine the approximate place of ignition, where the thermocouples were subsequently located for quantitative analysis. As a result, ignition temperature and delay times for the manzanita and scrub oak samples were determined. The ignition temperature obeys the normal distribution law. The influence of the moisture content on the ignition temperature and ignition delay time was noted.

Experimental studies of ignition were conducted for 14 types of living samples, focusing on the moisture effects during combustion [164]. For this purpose, the released moisture mass during ignition was compared to the original one. It was noted that the ignition of the samples mainly occurred at the end of local evaporation. One of the reasons for retained moisture is due to localized ignition, showing that combustion and evaporation occur simultaneously on a global scale. Ignition could have occurred at the needle tip, while the bulk of the moisture has still remained in the inner sample layers. In addition, the physical features of the living specimen can affect moisture since it could not escape beyond the outer boundaries of the sample. The outer cells had to undergo pyrolysis first. The profiles of mass and temperature changes were constructed and analyzed. Temperature profiles have a plateau at 200–300 °C for the leaf perimeter and a 100 °C and 140 °C plateau for the inner leaf part. All this leads to the conclusion that in the case of living fuel there is a remained after the leaf ignition. This statement contradicts the classical combustion model.

Mathematical modeling of pyrolysis and combustion of vertically oriented manzanita leaves (*Arctostaphylos glandulosa*) was carried out in [165]. During the simulation, the moisture content of the sample was varied, which corresponded to different leaf states (live and dead). During the study, the fuel was exposed to a hot gases stream, which corresponded to a real experimental setup. There is a satisfactory agreement with previously published experimental data. The dynamics of the heat release rate confirmed that the

increase in humidity delays the ignition time. Modeling has shown that thermal, impulse, and concentration boundary layers are formed on the leaf edges. These layers played a significant role in leaf heating and pyrolysis. An evaporation front was found inside the leaves, extending inward from the edges. A significant amount of liquid remained in the leaf after the fire. The analysis of the sample mass change as well as and the phase dynamics is presented.

It is important to note that current research shows differences in the lower limits of coniferous and deciduous forest fuels. According to suggestions made, this fact is explained by the difference in the transverse dimensions of the individual forest fuel elements (needles and leaves). Thus, the leaf area significantly exceeds the area of the needles, which leads to a difference in the areas of heat removal. This leads to differences in ignition delay times of about 2.5 times. This means that the deciduous element, placed in a litter consisting mainly of needles, can cause a fire and the development of a forest fire. Therefore, the peculiarities of the deciduous forest fuel ignition need to be revealed.

In sum, it can be concluded that the ignition process is influenced by the fuel type (coniferous or deciduous species, living and dead fuels), the method of heat supply (impact from a heat flux, carbon flow fall). It is also worth noting the presence of research gaps regarding the ignition patterns of deciduous fuels. Experimental and theoretical studies of this process are currently being carried out. Scientists have noted that different forest fuel types are ignited in different ways. Therefore, further research is required to obtain all the ignition patterns for different cases.

6. Discussion

A detailed analysis of research in the field of drying forest fuel shows a sufficient variety of approaches to accounting for fuel moisture content in the context of the prediction of the forest fire danger. The main approaches are presented in Table 1.

Table 1. Research on forest fuel drying.

Number	Type	Reference	Input Data	Index
1	Empirical (Fieldworks, calibrated sticks)	[28,31,32,63–66]	Forest fuel samples from the forest area under study	FMC (living and dead), EMC
2	Remote sensing	[31,36–38]	Satellite data, forest fuel reflectance in the near-infrared, shortwave infrared, and red bands	NDVI, NDII, LWCI
3	Radiative transfer models	[39,42–46]	Satellite data, forest fuel spectral characteristics and properties	FMC
4	Meteorological index	[71–80]	Daily synoptic data (temperature, humidity, daily precipitation)	Nesterov Index, Modified Nesterov index, Keetch-Byram drought index, Angstrom index

It is clear that each method has its own advantages and disadvantages. Even the simplest Nesterov index [166] is still used in the Russian Federation as a state standard for determining forest fire danger [167]. In fact, The Canadian and American methods for prediction of the forest fire danger are also devoid of the physics of the process. Therefore, they do not take into account the physical processes of moisture evaporation from the standpoint of the general theory of heat and mass transfer [168,169]. However, the Canadian method is successfully applied not only in Canada but also in the territory of other countries. For example, the Canadian method is used in the European EFFIS system [170]. The results of a study of various methods for predicting forest fire danger in Southern Europe including an analysis of the Canadian method suitability for this area were published in 2000 [171]. As a result, this method was shown to perform better when analyzing historical data from Southern Europe. However, the concept of the Canadian method is based on the

postulate of equilibrium moisture content. It should be noted that the processes of moisture evaporation from forest fuel are non-equilibrium and this fact must be taken into account when developing new methods for describing the drying process.

Kinetic mathematical models of Newton, Page, and other researchers are closer to real processes [27]. However, this similarity is based on mathematics, but not on the physics of the moisture evaporation process. In addition, attempts are known to assess the moisture content of forest fuel using remote sensing data, for example, based on NDVI, NDII [36,37]. These are quite promising approaches. However, their application is actually limited to crown forest fires, since the optical systems installed on satellites do not allow for obtaining information about the moisture content of the forest fuel ground layer. RTM studies [39] should be mentioned here. Developments based on the Keetch–Byram index [76] also do not take into account the real physical processes of forest fuel humidification and drying in real conditions, and ignore the provisions of the general theory of heat and mass transfer [169].

Mathematical models of forest fuel layer drying were developed at the beginning of the 21st century in Tomsk. A kinetic scheme using the Hertz–Knudsen law served as the basis for these models [172]. Mathematical models of various complexity and dimensions have been developed and partially verified with experimental data [173–176]. Such models are quite promising and physically grounded. However, preliminary observations of ground forest fuel show that it is necessary to develop new mathematical models that would allow for the spreading of the moisture evaporation front into the depth of the forest fuel layer. It will be presumably the most promising mathematical model for forest fuel drying for the further development of a deterministic–probabilistic approach to the prediction of the forest fire danger. Although the kinetic mathematical models suggested by Tomsk scientists have already been used within the framework of the deterministic–probabilistic approach [177].

Another important addition can be made. The use of physically-based mathematical models requires a substantial amount of computing and random access memory resources for their software implementation. It is shown that parallel computations on multiprocessor computing systems can be used in this case. For example, the SPMD computation model can be applied using the Message Passing Interface (MPI) library [178]. It should be noted that no approaches to modeling the forest fuel drying based on artificial intelligence have been found.

As for the pyrolysis of forest fuels, first of all, studies that consider dry organic matter as a single substance can be distinguished [179]. Other researchers approach differently and isolate components, namely cellulose, hemicellulose, and lignin [88–91]. Typically, pyrolysis is simulated using the mechanistic, network, and kinetic mathematical models [88]. The article discusses these types of mathematical models in sufficient detail. Table 2 provides information on the main mathematical models for the pyrolysis of forest fuels.

Table 2. Research on modeling of the forest fuel pyrolysis.

Number	Type	Reference	Dry Organic Matter	Stages
1	Mechanistic models	[93–96]	considered as a multicomponent substance (cellulose, hemicellulose, and lignin). The components pyrolysis can be considered separately	All the reaction paths and the formed components are considered.
2	Network models	[93,97–99]	considered as a multicomponent substance (cellulose, hemicellulose, and lignin). Components have different macromolecular structure	Sequence of stages (depolymerization, repolymerization, external transport, internal transport)
3	Kinetic models	[100–127]	considered as a single substance	Lumped and distributed, global and detailed, one-stage, tree independent reactions and competing reactions

From the point of view of prediction of the forest fire danger, the most important question is not which model to use, but rather choosing the dry organic matter concept. The authors of the article believe that considering the dry organic matter as a single substance is the most promising practical approach. The proportion of dry organic matter can be determined prior to modeling [180]. But assessing the proportion of cellulose, hemicellulose, and lignin can be a non-trivial task. Therefore, when developing a deterministic–probabilistic approach, it is advisable to mathematical models of pyrolysis, which use the kinetic scheme of dry organic matter decomposition without taking into account component composition.

It should also be noted that the computational complexity of algorithms that implement mathematical models of pyrolysis is quite high. It is shown that it is necessary to use parallel computations on multiprocessor computing systems [181]. By analogy with modeling of the drying process, coarse-grained parallelization methods can be used in the SPMD model with MPI.

As it has been already noted, ignition is a key stage in a forest fire. According to Figure 4, various ignition sources that lead to the ignition of forest fuels can be distinguished. From the point of view of mathematical modeling of the forest fuel ignition based on deterministic models and the general theory of heat and mass transfer, as well as chemical physics, three types of boundary conditions can be distinguished that will simulate a particular ignition source. Namely, the boundary conditions of the first kind (constant temperature), the second kind (radiant heat flux), and the third kind (convective heat flux) can be used. Mathematically, the whole variety of ignition sources is reduced to these three boundary conditions. Although, the ignition of a forest fuel by heated particles or firebrands can also be modeled using boundary conditions of the fourth kind on the line of contact of a heated particle with a finite supply of heat and the surface of a forest fuel [182]. In addition, mathematical models for the ignition of forest fuels can be divided according to the location of the leading exothermic reaction. Solid-phase, heterogeneous, and gas-phase mathematical models can be distinguished [183].

Analysis of literature sources shows that many publications are devoted to the experimental study of forest fuel ignition. This is largely due to the forest fuel diversity in different forest areas in different countries of the world community. Such studies can be used to verify mathematical models of forest fuel ignition.

Within the framework of the deterministic–probabilistic approach to predicting forest fire danger, it is necessary to link the ignition delays and the probability of forest fuel ignition and, as a consequence, the probability of a forest fire occurrence. In addition, prospects are emerging for the development of a new physically grounded classification system for forest fuels based on systems of linear algebraic equations linking the ignition delays with the thermophysical and thermokinetic characteristics [184]. As a result of cluster analysis in the hyperspace of the properties of forest fuels, groups of forest fuels can be identified that have similar properties in the context of forest fire danger. It should be noted that all existing classifications of forest fuels are descriptive [185].

In sum, it should be concluded that the most promising mathematical models of drying, pyrolysis, and ignition of forest fuels, use real physicochemical mechanisms and postulates of the general theory of heat and mass transfer and chemical physics [169,183].

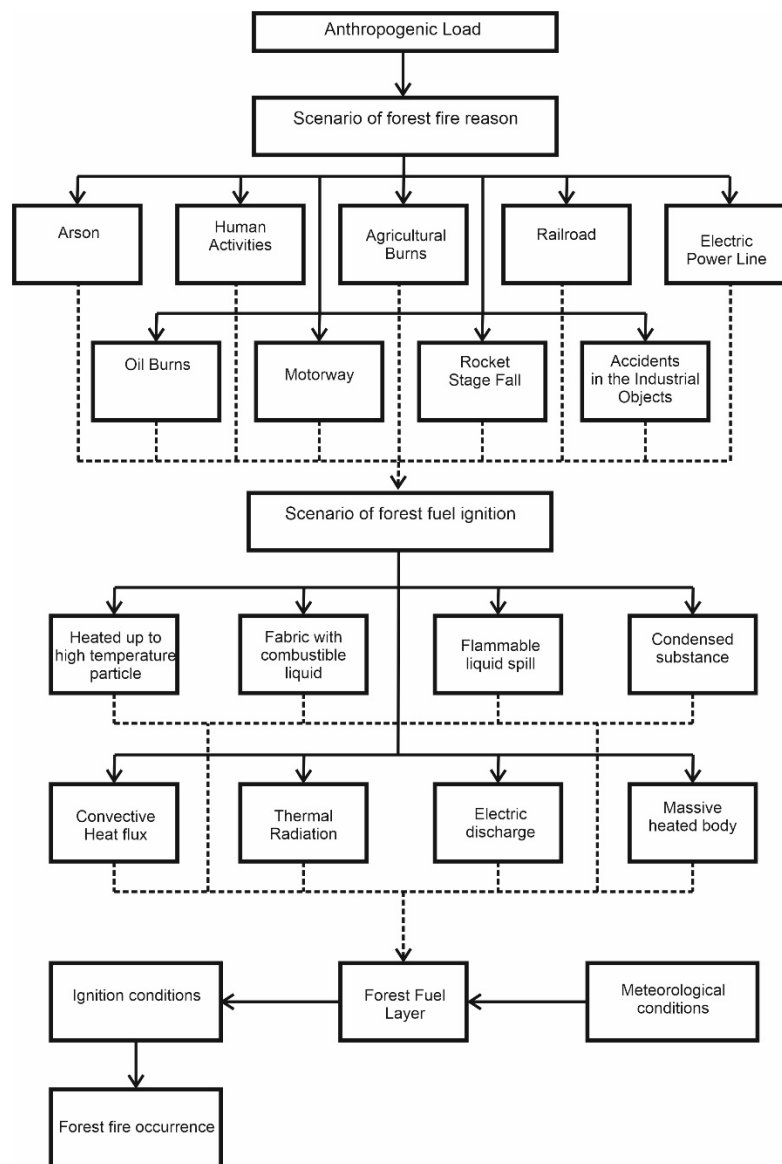


Figure 4. Ignition of forest fuel by human-made sources.

7. Conclusions

The analysis of literary sources on this topic have shown that scientists around the world are interested in studying the features of the processes occurring in forest fuels immediately before and during a forest fire.

The analyzed studies show that the processes of drying and pyrolysis largely determine the further ignition of forest fuels. Therefore, it is reasonable to continue research, as well as to apply the knowledge gained both in predicting the occurrence and spread of the forest fire itself and in predicting possible consequences. It is necessary to focus on the establishment of the regularities of drying, pyrolysis, and ignition of various types of wood fuel, in order to have a complete picture of possible outcomes in the future when the forest is exposed to unfavorable environmental factors.

It should be noted that the research carried out makes a significant contribution to solving the problem of combating forest fires. The results obtained can be applied both in prediction systems and in the development of fire extinguishing methods.

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