Review

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Research Progress on Forest Ground Fires

Yufei Cao [1], Zhongliang Gao [1,*] and Wentian Yu [1]

[1] School of Civil Engineering, Southwest Forestry University, Kunming, China
* Correspondence: Zhongliang Gao, School of Civil Engineering, Southwest Forestry University, Kunming, China

Abstract: Forest ground fire is a phenomenon of spontaneous combustion that occurs in humus or peat layers, representing an extreme fire behavior. Monitoring ground fires is difficult, and large-scale spreading can result in air pollution, extensive tree mortality, soil structure damage, and other consequences, posing a threat to the ecological environment. Starting from the ignition, spreading, and critical stages of ground fires, this paper analyzes the conditions for ignition and spreading, as well as the applicability of ground fire prediction and forecasting models. It investigates the critical conditions for the transition from smoldering to flaming (StF) phenomenon and analyzes the deficiencies of ground fire prediction, forecasting, and monitoring technologies. It indicates that the type of ignition source, physicochemical properties of combustibles, and environmental factors are the main factors influencing the ignition probability and spreading characteristics of ground fires. The critical stage of the StF phenomenon is related to changes in environmental conditions and sudden changes in physicochemical properties of combustibles. Indirect prediction methods using drought indices, groundwater levels, etc., both domestically and internationally, have errors in predicting ground fire occurrences. Existing fire monitoring equipment cannot meet the monitoring requirements for ground fires. This paper proposes future research directions for ground fires, providing reference for ground fire research.

Keywords: forest ground fire; ignition probability; spreading characteristics; StF phenomenon; forest fire monitoring

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1. Introduction

Forest ground fires are the largest-scale and longest-lasting burning phenomena on Earth [1]. They essentially involve smoldering combustion in peat or humus layers and are primarily distributed in regions with thick accumulations of humus, such as tropical rainforests, high-altitude areas, and polar regions. Both northeastern and southwestern China [2], northern Europe, Russia [3], Indonesia [4], Canada, and even within the Arctic Circle are frequent areas for ground fires [5]. Compared to surface fires, ground fires exhibit characteristics such as easy ignition, low reaction temperature, slow spread rate, incomplete combustion, and the potential to transition to surface flames [6-8]. Forest ground fires can have a series of negative impacts on ecosystems, leading to large-scale carbon emissions, release of harmful substances such as CO, polycyclic aromatic hydrocarbons, and increased PM2.5 levels [9]. For instance, in 1997, ground fires in Indonesia led to a 6-14 times increase in concentrations of toxic gases such as polycyclic aromatic hydrocarbons in affected areas, resulting in higher probabilities of respiratory and cardiovascular diseases among the population [10]. Additionally, ground fires consume organic matter in the soil, causing soil compaction, altering soil physicochemical properties, changing microbial proportions in the soil, and weakening the secondary succession capability of forest areas after fires [11-13]. Ground fires can also affect hydrology in affected areas, leading to decreased groundwater levels, deterioration of water quality, and death of riverine organisms [14,15].

In recent years, due to exacerbated greenhouse effects and frequent El Niño phenomena, the frequency and scale of forest ground fires have significantly increased, resulting in an escalating level of ecological harm [16]. However, predicting and monitoring ground fires is challenging due to their specific occurrence locations and absence of surface flames, and technological development in this area is still in its infancy [17]. After ground fires occur, firefighting departments often fail to promptly detect the fires and initiate initial control measures. By the time the fires are discovered, they have already spread extensively and become difficult to control. Compared to extinguishing surface fires in forests, extinguishing ground fires is more challenging. Studies have shown that the minimum precipitation intensity required to completely extinguish peat fires is 4mm/h, with a water volume of approximately 6L/kg of peat, which is much higher than the water volume required to extinguish surface fires [18,19].

This paper analyzes the influencing conditions and experimental conditions during the ignition and spreading processes of ground fires, starting from the ignition, spreading, and critical stages of ground fires. It also explores the conditions for the occurrence of the smoldering-to-flaming (StF) phenomenon at the critical stage, highlights the deficiencies in ground fire prediction, forecasting, and monitoring technologies, and proposes future research directions for ground fires, providing reference for ground fire research.

2.Factors Influencing the Ignition Probability of Ground Fires

Compared to surface fires, ground fires do not require high-energy ignition sources; cigarette butts, embers, and flying embers can all ignite ground fires, and the range of combustible moisture content capable of ignition is wide. The ignition process of ground fires exhibits different ignition probabilities under the influence of environmental conditions such as wind speed, temperature, and humidity. Currently, characteristics of ignition sources, physicochemical properties of combustibles, and environmental conditions are the primary research focus regarding the ignition probability of ground fires.

2.1 Influence of Ignition Source Characteristics on Ignition Probability

Ignition sources can be classified into anthropogenic and natural sources. Anthropogenic sources are the predominant factors in forest fires, accounting for over 90% of all ignition sources [20]. Natural sources are heat sources generated under natural geographical conditions and typically ignite ground fires in forest fires through direct or indirect means such as lightning strikes or sunlight focusing, with complex ignition mechanisms.

In anthropogenic sources, Peng Sun et al., and others conducted indoor experiments on cigarette butt ignition of forest litter and found that the probability of cigarette butts igniting litter was only 1% to 3% and easily influenced by environmental factors [21,22]. Moreover, the randomness of cigarette butt dropping increased the uncertainty of ignition probability. If the cigarette butt ignites within combustible materials, it is more likely to accumulate heat and increase the ignition probability; otherwise, the ignition probability decreases. Apart from cigarette butts, smoldering firebrands have been found to exhibit similar mechanisms as ignition sources [23], where the ignition probability is significantly influenced by the shape and dropping mode of the fire source.

In natural sources, they can directly or indirectly ignite ground fires with complex ignition mechanisms. Wang et al. used glass balls to focus sunlight and ignite combustible materials [24], while Zhang et al. simulated lightning ignition of dry peat cakes using arc discharge currents [25], expanding the research on the ignition mechanisms of natural sources igniting ground fires. Currently, the possibility of natural sources igniting forest fires is relatively low, but with global climate change, natural sources cannot be ignored.

Flying embers are a unique phenomenon in forest fires, generating new fire points under the influence of air currents and accelerating the spread of fires [26]. Laboratory studies often simulate flying embers using high-temperature metal particles, embers, and mechanical friction. Antonio C. Fernandez-Pello et al. simulated the ignition of fuel beds by flying embers using high-temperature metal particles, embers, and mechanical friction, finding that the size of the fire source was inversely proportional to the ignition temperature of combustible materials [27]. To more intuitively study the relationship between the ignition capability of flying embers and their size and temperature, Hadden et al. conducted experiments on igniting fuel beds with high-temperature inert particles successively, and their studies all showed a similar hyperbolic relationship between particle diameter, temperature, and ignition probability, where larger fire source diameters required lower temperatures for successful ignition [28-30].

Forest fires in outdoor environments often result from the combined effects of multiple ignition sources [31,32]. Exploring the ignition probability of ground fires under the coupled effects of multiple ignition sources can more accurately reflect the occurrence of ground fires and reveal the characteristics of the ignition stage of ground fires.

2.2. Influence of Combustible Physicochemical Properties on Ignition Probability

The moisture content, density, and combustibility of combustible materials affect the probability of ground fires, reflecting changes in heat accumulation, heat transfer, and oxidation rates. Combustible materials with a certain moisture content can increase ignition temperature by evaporating water, absorbing heat, and inhibiting chemical reactions. Santana et al. found that the maximum moisture content at which forest humus could ignite was 59%, significantly higher than the maximum moisture content of combustible materials on the surface (30%) [33], indicating that ground fires can occur under conditions of high moisture content in combustible materials, posing a higher risk of occurrence than surface fires and crown fires. Density affects the ignition process by altering oxygen supply and heat accumulation within combustible materials [34]. The influence of density on the ignition probability of combustible materials is complex; high density reduces internal oxygen supply but favors heat accumulation [35], while low density has the opposite effect. Jae-Young Sohng et al. analyzed the ignition characteristics of different densities of cotton, and Zhang et al. studied the probability of cigarette butt smoldering ignition under different bed compression ratios, both finding a normal distribution relationship between ignition probability and combustible material density [22]. The ignition probability of ground fires is also related to the combustibility of combustible materials itself. Combustibility reflects the heating characteristics during the ignition process and indicates the difficulty of ignition of combustible materials [36]. Aude Ganteaume conducted ignition experiments on humus collected from different locations and found that the ignition moisture content threshold and ignition time of each humus were significantly affected by combustibility [37].

2.3. Influence of Environmental Conditions on Ignition Probability

Environmental conditions affecting ignition probability include wind speed, temperature, and humidity. Wind speed has a dual effect on the ignition probability of combustible materials. On one hand, it can reduce the moisture content of combustible materials and bring in more oxygen; on the other hand, it can carry away some combustible gases and reduce accumulated heat. Hadden et al. believe that increasing wind speed within a certain range contributes to smoldering ignition [38]. Peng Sun et al., and others found that the probability of ignition of low-energy heat sources increased with the assistance of wind [21]. Temperature and humidity primarily affect ignition probability by changing the moisture content of combustible materials [22]. As temperature increases, water evaporation leads to a decrease in the moisture content of combustible materials, making them more flammable; lower humidity leads to lower moisture content and increased flammability of combustible materials. The larger the scale of the study, the more pronounced the changes in temperature or humidity [39,40]. Therefore, in forest environments with high fire risk due to drought, high temperature, and strong winds, it is necessary to strengthen control over forest fire sources to reduce the probability of ground fires.

3. Factors Influencing the Spread of Ground Fires

The spread structure of ground fires can be divided into the unburned zone, moisture evaporation zone, pyrolysis zone, charcoal oxidation zone, and ash zone, with the spread direction being parallel horizontally and vertically [41] (Figure 1). The characteristics of smoldering propagation are mainly influenced by the oxygen content inside the combustible material and thermal conduction, with driving factors including the state of the combustible material itself and external environmental factors.

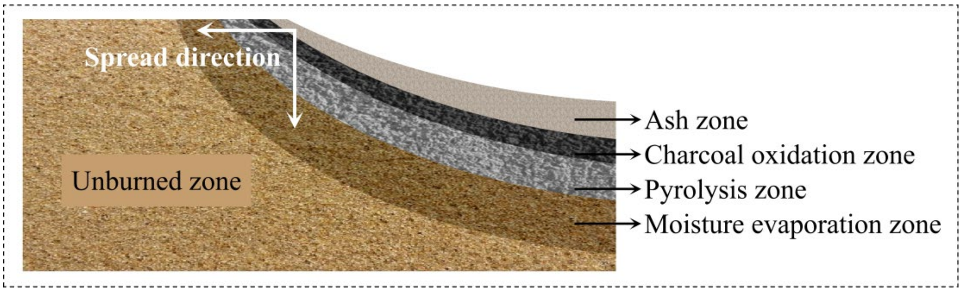

Figure 1. Structure of Ground Fire Propagation.

3.1. Influence of Moisture Content on Ground Fire Propagation Characteristics

The evaporation of moisture absorbs heat, hindering the propagation of ground fires. Even if combustible materials with high moisture content are ignited, it is difficult to sustain smoldering propagation. Due to differences in experimental conditions, different scholars have determined that the maximum moisture content range for self-sustaining smoldering of peat and humus is 90%-100% [42] and 30%-35%, respectively. Numerous experiments have shown a negative correlation between moisture content and the smoldering propagation rate of peat [43] and humus [44,45], indicating that the propagation rate decreases as the moisture content increases. However, when moisture can alter the geometric shape of the combustible material, its influence on the smoldering propagation process becomes complex. Feng He et al. found that the volume expansion of corn stalk powder upon water absorption increases the contact area between the combustible material and oxygen, accelerating oxidation [46]. They observed that at a moisture content of 29.77%, the smoldering propagation rate was highest. Similarly, Christensen et al. found that moisture causes peat expansion, leading to a decrease in bed density and organic matter mass, thereby increasing the propagation rate [41].

3.2. Influence of Inert Components on Ground Fire Propagation Characteristics

Peat and humus, located in the forest floor, tend to accumulate inert components such as minerals. The effect of inert components on smoldering propagation is twofold. On one hand, inert components affect the thickness of the ash layer, which aids in heat accumulation. On the other hand, a thicker ash layer reduces the oxygen content inside the combustible material [47]. Additionally, the relatively high specific heat capacity of inert components [48] is detrimental to ground fire propagation. Under different conditions, the sensitivity of the smoldering propagation rate to inorganic content varies. Christensen et al. found that under low moisture conditions, the influence of inorganic content on the propagation rate is small, whereas under high moisture conditions, inorganic content significantly affects the propagation rate [41].

3.3. Influence of Particle Size on Ground Fire Propagation Characteristics

Particle size affects the porosity and bulk density of combustible materials, altering the contact area between the combustible material and oxygen, and thus affecting the propagation rate and temperature variation of ground fires [49]. Peat and humus, at the same combustion depth, exhibit higher peak temperatures with smaller particle sizes. Xue Lu suggested that smaller particle sizes result in larger surface areas, leading to more efficient oxygen reaction [50,51]. Unlike the linear relationship between particle size and peak temperature, the influence of particle size on the propagation rate of ground fires is more complex [52]. Charles A. Bigelow found that when the particle size of peat exceeds 3mm, smaller particle sizes correspond to faster propagation rates [43], while the opposite is true when the particle size is less than this value. When the particle size exceeds 3mm, the chemical reaction between particles and oxygen dominates the smoldering propagation; when the particle size is less than 3mm, the propagation rate is dominated by the density of peat.

3.4. Influence of Wind on Ground Fire Propagation Characteristics

Wind affects the oxygen content and heat of combustible materials, thereby altering the propagation characteristics of ground fires. Oxygen content affects the thickness of various propagation regions. If the oxygen content of the combustible material is low, the smoldering process requires a thicker reaction front to sustain, increasing the thickness of each region [53]. Heat is the physical basis for maintaining ground fire combustion. Sufficient heat accumulation is necessary for sustaining combustion or propagation. However, the influence of wind on the propagation of ground fires is not a simple promotion or inhibition relationship but rather a game [54]. Wind brings oxygen and assists in heat transfer, accelerating the oxidation process of combustible materials, but it also takes away some heat. Therefore, there exists a critical wind speed. When the wind speed is below the critical value, oxygen brought by the wind dominates; if it exceeds this critical value, the heat loss caused by wind speed predominates, inhibiting the propagation of smoldering.

4. Conditions for Transition from Smoldering to Flaming in Ground Fires

The transition from smoldering to flaming (StF) is caused by changes in environmental conditions or abrupt changes in the physical properties of the smoldering propagation medium. After the surface fires were extinguished during the forest fire in Muli County, Liangshan Prefecture, in 2019, strong winds caused the embers to reignite, rapidly leading to surface fires developing into crown fires, resulting in casualties [55]. Once the StF phenomenon occurs, the surrounding combustible materials reach ignition conditions, causing flames to spread rapidly, resulting in significantly increased temperatures and posing serious fire safety hazards [56].

4.1. Influence of Environmental Conditions on the Transition from Smoldering to Flaming

Wind is a crucial factor in causing the StF phenomenon. Wind can increase the oxygen supply to the reaction zone, accelerate the surface charring of combustible materials, and generate combustible gases. When the reaction zone reaches the minimum ignition temperature and accumulates sufficient oxygen and combustible gases, the StF phenomenon occurs. However, wind can also enhance the convective heat loss at the smoldering front, and excessively fast wind speeds are not conducive to the occurrence of the StF phenomenon. Experiments conducted by N. Gorbach, and others on StF phenomena in forest humus showed that under conditions of positive propagation and wind speeds below 7m/s, the time of StF occurrence was negatively correlated with wind speed [55,57]. Compared to positive propagation, reverse propagation is less likely to transition to flaming and is more prone to extinguishment. The reason is that the wind in positive propagation carries heat to the unburned zone, resulting in a more efficient heating process, while in reverse propagation, the wind transfers heat to the ash zone, reducing the heat utilization rate.

External heat exchange conditions also affect the occurrence of the StF phenomenon. Xin, Li, and others wrapped the smoldering reaction device with water layers at temperatures of 20°C and 80°C, respectively. They found that under the same wind speed, the 80°C water layer had better insulation effects, which facilitated heat accumulation to reach the ignition temperature and trigger the StF phenomenon [55,57]. In summary, caution should be exercised against the occurrence of the StF phenomenon during strong winds and hot weather.

4.2. Influence of Sudden Changes in Combustible Material Physical Properties on the Transition from Smoldering to Flaming

The physical properties of combustible materials are not uniformly continuous; their moisture content and geometric shapes vary in different locations within the same area. During the propagation of ground fires, Mohamed M. Ahmed et al. and others found that the sudden increase in moisture content of combustible materials results in heat absorption [58], leading to a decrease in temperature, a slowdown in oxidation reaction rates, and oxygen accumulation. This promotes the mixture reaction of combustible gases produced by previous pyrolysis reactions, facilitating the occurrence of the StF phenomenon. Taking smoldering sawdust as an example [56], the different dry bulk densities of the combustible materials before and after the sudden change in moisture content form voids, where oxygen supply is enhanced, promoting smoldering reactions. In cracks or grooves of combustible materials, the StF phenomenon is also prone to occur. Zhang and colleagues found that smoldering wood in cracks generates a chimney effect [59], and the two smoldering surfaces in the cracks jointly heat the combustible gases, enhancing heat radiation and promoting the occurrence of the StF phenomenon. In detecting high-risk areas for ground fires, particular attention should be paid to areas where combustible materials experience sudden changes in moisture content or valleys, to prevent the occurrence of the StF phenomenon.

5. Prediction, Forecasting, and Monitoring Techniques for Ground Fires

5.1. Prediction and Forecasting Techniques for Ground Fires

Due to the strong concealment, low frequency of occurrence, and difficulty in obtaining fire data of ground fires, there is a relative lack of prediction models for ground fires. Currently, logistic regression models are established based on factors such as combustible moisture content, combustible thickness, and wind speed, derived from laboratory simulations of the ground fire occurrence process [37,60,61]. Other methods for prediction include monitoring groundwater levels and Byram drought indices. Rein et al. classified ground fire hazards based on combustible moisture content, considering the upper peat's moisture content below 115% as high hazard, between 115% and 135% as moderate hazard, and above 135% as low hazard [62]. Otway et al. [63] established an empirical model for smoldering ground fires using the Decay Moisture Code (DMC) and Drought Code (DC) from the Canadian Fire Weather Index System.

5.2. Monitoring Techniques for Ground Fires

The development of monitoring techniques for ground fires is still incomplete. Traditional remote sensing techniques such as infrared and visible light, which are suitable for monitoring forest fires with lower temperatures, have poor feasibility for detecting ground fires. The smoke generated by the combustion of deep combustibles is adsorbed by the surface layer, leading to low monitoring efficiency of reconnaissance aircraft and lookout towers [49]. Currently, the mainstream monitoring method involves using portable gas laser scanners to measure the concentrations of CO2, CO, polycyclic aromatic hydrocarbons, and other smoldering emissions, comparing them with databases to determine the location and intensity of ground fires [64]. Additionally, some scholars install small thermal sensitive components on ground animals such as crawlers and groundhogs to monitor the occurrence of ground fires [65].

6. Conclusion and Discussion

6.1. Conclusion

The ignition probability and propagation characteristics of ground fires are influenced by the type of ignition source, the physical and chemical properties of combustibles, and environmental conditions. The ignition probability is mainly affected by the shape and size of artificial ignition sources, while natural ignition sources have a smaller impact. Factors such as combustible moisture content, compactness, and combustibility affect the ignition probability of ground fires. Moisture content, inert components, and particle size affect the propagation of ground fires, and moisture content can indirectly influence propagation by changing the geometric shape of combustibles and the content of inorganic substances. Wind speed has a dual effect on ignition probability and propagation characteristics, while temperature and humidity affect the ignition probability by changing the moisture content of combustibles. The direct conditions for the occurrence of StF phenomena in ground fires are environmental conditions and sudden changes in the physical and chemical properties of combustibles. Indirect prediction of ground fires using methods such as determining drought indices and groundwater levels may lead to errors, and existing fire monitoring equipment cannot meet the needs of monitoring ground fires.

6.2. Discussion

Due to the unique spatial location and combustion characteristics of ground fires, research on ground fires is still in its early stages. The ignition probability of ground fires is affected by the characteristics of the ignition source, the state of combustibles, and environmental conditions. Currently, there are relatively mature small-scale experimental studies on single influencing factors, but experiments are difficult to simulate the ignition process of ground fires accurately. Single influencing factors are not sufficient to summarize the ignition rules of ground fires. Supported by real ground fire cases, large-scale multivariate simulation experiments should be conducted to restore real fire conditions, improve the reliability of ground fire prediction and forecasting, and establish an ground fire prediction and forecasting system. The propagation of ground fires under the influence of moisture content, inert components, particle size, and wind exhibits complex linear relationships, and changing a single influencing condition does not necessarily produce the same effect. Analyzing the functional relationship between influencing conditions and the propagation of ground fires, establishing a propagation model for ground fires, and supplementing existing monitoring technologies are necessary. To suppress the transition of ground fires to flaming, enhance emergency rescue capabilities, be vigilant about changes in fire environment conditions and sudden changes in the physical properties of combustibles, and reduce the probability of StF phenomena. In addition, ground fire research should combine modern technologies such as big data models and artificial intelligence algorithms to overcome experimental limitations.

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