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Study on the Limit of Moisture Content of the Sub-Surface Fires Converted to the Surface Fires in the Boreal Forests of China

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Abstract: A sub-surface forest fire is a type of smoldering combustion with a slower spread rate, longer combustion time, and lower combustion temperature compared with flame combustion. Sub-surface fires are usually accompanied by surface fires, and the surface fires' conversion from sub-surface fires has great uncertainty. Therefore, there are considerable difficulties in monitoring and fighting sub-surface fires. However, there are few studies on the conversion from sub-surface fires to surface fires, and the mechanism and influencing factors of the conversion remain unclear. This study focuses on *Larix gmelinii* forests, which are representative of the boreal forest of China and hot spots of sub-surface fires, studies the moisture content limit of sub-surface fires' conversion to surface fires by simulating a smoldering experiment, and establishes a monitoring model of sub-surface fires and an occurrence probability prediction model of sub-surface fires' conversion to surface fires. The results showed that the moisture content limit of the conversion was 25% in the grass–*Larix gmelinii* forest and *Ledum palustre*–*Larix gmelinii* forest and 20% in *Rhododendron dauricum*–*Larix gmelinii* forest. There was a significant positive correlation between the time and temperature caused by the smoldering. The monitoring model of the sub-surface fires based on the surface temperature and moisture content had a good fitting effect ($p < 0.01$). The occurrence probability prediction model of the sub-surface fires' conversion to surface fires, based on a logistic regression model, had high prediction accuracy (AUC = 0.987). The lower the moisture content of the humus, the closer the smoldering came to the surface and the higher the probability of conversion. This research could contribute to the study of the mechanism of sub-surface fires' conversion into surface fires.

Keywords: sub-surface forest fires; moisture content limit; surface forest fires; conversion mechanism

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1. Introduction

In recent years, with the intensification of climate change and the greenhouse effect, the frequency and duration of forest fires around the world have shown an obvious increasing tendency, seriously threatening the ecological environment, human life, and property [1]. Forest fires include flame combustion and smoldering combustion. The former refers to surface fires and crown fires, and the main fuels are trees, shrubs, and herbs above the surface. The latter refers to sub-surface fires, and the main fuels are humus or peat below the surface [2]. Compared with flame combustion, the spread of smoldering combustion is much slower, lasts longer, even for weeks or months, and is of a lower temperature, but more pollutants and harmful gases are emitted at the same time [3,4]. These characteristics can easily result in neglect of sub-surface forest fires during monitoring and rescue, and the relevant studies are inadequate [5]. The extreme haze events in Southeast Asia caused by the large area of smoldering peat fires in 1997 made people truly realize the serious threat posed by sub-surface fires to the environment and the economy [6,7]. Large-scale sub-surface fires have successively occurred in various countries over the years, such as eastern North Carolina in the United States in 2008 [8], the outskirts of Moscow in Russia in 2010 [9], and the large-scale peat fires in Southeast Asia in 2015 [10]. Therefore, a better understanding of the mechanism of sub-surface fires in forests plays a very important role in reducing the damage and has gradually attracted the attention of relevant scholars in recent years.

Sub-surface fires happen very rarely in isolation and are mostly accompanied by surface fires; smoldering combustion is more likely to occur than flame combustion and continues to burn under low-temperature, high-humidity, and low-oxygen conditions [11]. When surface fires are extinguished, the intensity of the embers is too weak to cause flame combustion but can cause smoldering combustion, which is difficult for rescue personnel to detect, and smoldering may continue slowly and spread at a rate of 0.5 m per week [12]. In addition, due to strong concealment, sub-surface fires are difficult to find even with advanced remote sensing monitoring [13], so sub-surface fires may not be detected for a long time and even form overwintering fires [14]. Unlike surface fires and crown fires, sub-surface fires can spread both horizontally and vertically [15] and will quickly turn into surface fires when they spread to regions with thin humus layers or cracks. Since the high randomness of fire conversion has made it difficult to predict the occurrence of surface fires converted from sub-surface fires, it is hard for forest fire prevention departments to respond quickly, so sub-surface fires are likely to develop into canopy fires or even large-scale forest fires. At present, few studies have been conducted on the conversion from sub-surface to surface fires; the existing studies are either based on computer simulations or use polyurethane foam as a research material [16–18]. The mechanism and influencing factors of this complex conversion process are still unclear, and there is a need for more studies. Moisture content could affect the occurrence, development, and spread of combustion, thus playing a prominent role in the smoldering process of sub-surface fires [19,20]. Researchers have conducted a series of studies on the smoldering characteristics and combustion dynamics mechanisms of sub-surface fires under different moisture content conditions as well as the effects of moisture content on the occurrence, combustion temperature, and spread rate of sub-surface fires [12,21–25]. The limit of sub-surface fires' smoldering is a new research direction, and studies on the mechanism and limit of the transformation between sub-surface fires and surface fires are rarely reported [26,27], which requires further research.

Peat layers in high northern latitudes are the most abundant in the world [28], but due to their extremely high moisture content, it is difficult for smoldering to begin in the original peat except under extreme drought conditions [29,30]. The warming climate and lower groundwater levels have a larger effect on the humus or peat accumulated on the shallow layers of boreal forests than on the original peat [31], resulting in higher ground temperatures in the forest, so the occurrence, frequency, and damage of sub-surface fires have increased significantly in recent years [32].

Considering the limitations of existing research and the danger of sub-surface fires transforming into surface fires, this study focuses on the *Larix gmelinii*-dominated boreal forest of northeastern China, which is frequently subject to sub-surface fires. The aims of the study are to improve the understanding of the mechanism of smoldering in open fire transformation and to provide scientific support for the management of sub-surface fires via simulated ignition experiments. Thus, the research objectives are (1) to quantify the critical moisture content conditions for the transition from sub-surface fire to surface fire; (2) to develop a monitoring model to predict sub-surface fires based on surface temperature; and (3) to establish a probability prediction model for the transformation of sub-surface fires into surface fires.

2. Methods

2.1. Study Area

Since the coniferous forest of the boreal forests is the hot spot of the sub-surface fires [32], the Genhe Forestry Bureau (Figure 1) of the Daxing'an Mountains in Inner Mongolia (120°41′30″–122°42′30″ N, 50°25′30″–51°17′00″ N) was selected as the study area. The terrain and landform exhibit a northeast high, southwest low pattern, resembling hilly topography. The average elevation is 1000 m, with predominantly gentle slopes of less than 15 degrees [33,34]. Within a cold temperate zone, this region has a humid forest climate with short summers and long winters. The annual average temperature is −5.5~8 °C; the rainfall is mainly concentrated in July and August. The vegetation, primarily ligneous plants, belongs to the East Siberian and Mongolian flora. Due to the cold climate, the annual precipitation is between 450–500 mm [34], and the presence of moist soil and permafrost limits the growth of broadleaved trees. The hardy *Larix gmelinii* has become the dominant species in this region, forming a cold–warm location-type coniferous forest belt.

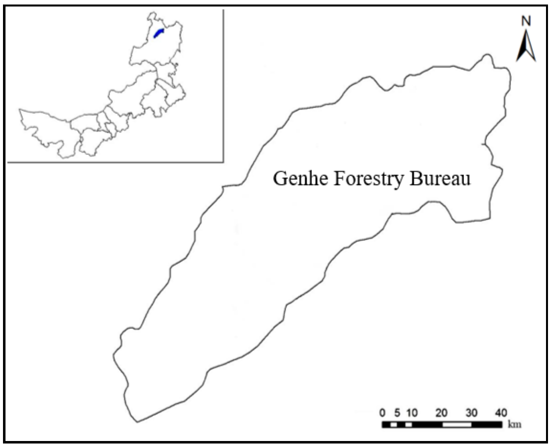

Figure 1. Study area.

2.2. Sampling and Processing

The study was focused on the main fuel types in the *Larix gmelinii* forest of the Forestry Bureau, including the grass-*Larix gmelinii* forest, the *Ledum palustre-Larix gmelinii* forest, and the *Rhododendron dauricum-Larix gmelinii* forest (Figure 2). The soil was excavated and the thickness of the underground fuel layer was measured. Three sets of 50 cm × 50 cm quadrats each were established diagonally on the 3 sample plots. All the underground fuels of the quadrats were collected and transported to the laboratory [24].

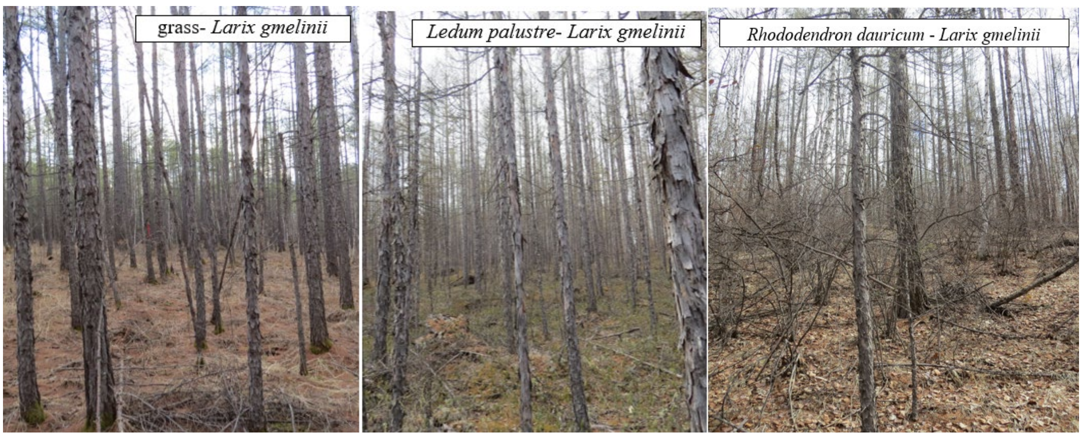

Figure 2. Experimental plot.

In this study, 4 moisture content levels (10%, 15%, 20%, and 25%) of the fuels were selected. The fuels were placed in a cool and ventilated place to dry naturally. The moisture content (MC) was measured every 6 h (MC = (wet weight − dry weight)/wet weight) until the appropriate moisture content was obtained. Samples of fuels with different moisture contents were placed in sealed plastic bags for the simulating smoldering experiment.

The moisture content was measured of the 3 samples prior to the smoldering experiment using the rapid moisture monitor, with the average value being used as the experimental moisture content of the corresponding sample.

2.3. Simulating Smoldering Experiment

The simulating smoldering experimental equipment of the study was a self-assembled sub-surface fire temperature acquisition system, consisting of a smoldering furnace, thermocouple, data acquisition module, and laptop. Fuels with different moisture contents were put into the smoldering furnace separately, and a small hole was drilled every 3 cm on the side of the furnace from top to bottom. The Type K thermocouple was inserted into the middle of the humus through the drilled holes. The thermocouples and data acquisition module were connected by compensation wires, and the temperature variation data of the humus combustion were transmitted back to the laptop at 10 s intervals. The far-infrared heating plate was placed under the smoldering furnace, and the heating temperature was set at 500 °C. The power supply was switched off after heating for 2 h. The schematic diagram of the experimental equipment is shown in Figure 3.

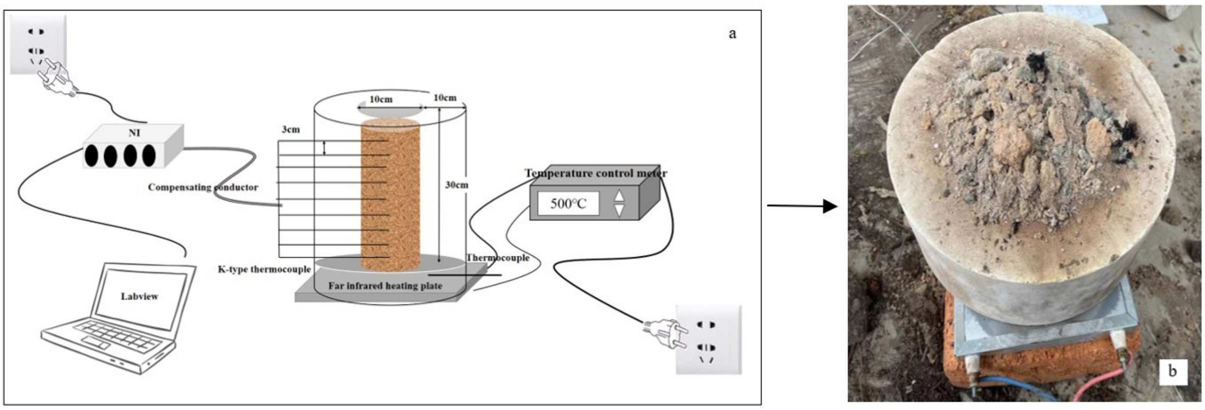

Figure 3. Simulating smoldering experiment: ((**a**) schematic diagram of the experimental equipment; (**b**) fuel after smoldering).

2.4. Data Processing and Analysis

The variation diagrams of smoldering temperature according to the data of the sub-surface fire temperature acquisition system were drawn. There was a collapse of the surface fuel during the smoldering experiment, and since the depth of 3 cm is close to the surface, the temperature at 3 cm depth could be well representative of the change in surface temperature. Therefore, temperature data of the 3 cm depth, recorded by the thermocouple was considered as the surface temperature. An equation was established to show the relationship between surface temperature and time by means of regression analysis, and the monitoring model of the peak temperature, time, and depth of the smoldering based on surface temperature and moisture content.

The occurrence probability prediction model of the sub-surface fires converted to the surface fires represented a logistic regression model. Based on the logistic regression model, the occurrence probability prediction model of the sub-surface fires converted to surface fires was established according to moisture content and depth. The dependent variable of the logistic regression model is discontinuous, which could be a binomial or multinomial function. Independent variables could be continuous or categorical variables. When the temperature of the fuels reached 300 °C, there would be obvious smoldering [27]. Therefore, this study indicated that when the peak temperature of 3 cm was less than 300 °C, the conversion from the sub-surface fires to the surface fires is difficult and, conversely, the conversion is easy. If the occurrence probability of sub-surface fire is P, then the nonoccurrence probability of sub-surface fire is $(1 - P)$ and can be expressed as [35]:

$$\ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n$$

where β_0 is a constant, independent variable, x_n is driving factors, and β_n is the coefficient of their variables.

In the study of the occurrence probability prediction, the ROC (receiver operating characteristic) has been widely used in the evaluation of the accuracy and the determination of the threshold value. The AUC (area under the curve) of the ROC curve can be used to evaluate the accuracy of the prediction model. The value of AUC ranges from 0.5 to 1 [35,36]. The higher the value of the AUC, the better the sensitivity, specificity, and accuracy of the prediction model [35,36].

3. Results

3.1. Limit Moisture Content of Sub-Surface Fires Converted into Surface Fires

As shown in Figure 4, the smoldering sub-surface fires of the main fuels in the *L. gmelinii*-dominated boreal forest of China could easily turn into surface fires when the moisture contents were low. The grass-*L. gmelinii* forest and the *L. palustre-L. gmelinii* forests were easily converted to surface fires when the moisture contents of humus were 10%, 15%, and 20%. When the moisture content was 25%, although the surface temperature reached 197.56 °C and 184.70 °C, respectively, the duration of the temperature was short and the surface fuel did not burn, the temperature only reflected the upward heat transmitted from the deep smoldering, and conversion to the surface fires was difficult. The smoldering time of fuel from *R. dauricum-L. gmelinii* forest was significantly longer than the grass-*L. gmelinii* forest and the *L. palustre-L. gmelinii* forest, the conversion to the surface fires when fuel moisture contents of 10% and 15% was easy, but the conversion was difficult when the moisture content was 20%. Smoldering temperatures with different moisture contents were all high, the peak smoldering temperature of fuel from grass-*L. gmelinii*, *L. palustre-L. gmelinii*, and *R. dauricum-L. gmelinii* forests were 750.67 °C, 746.34 °C, and 789.39 °C, respectively, and there were two peak smoldering temperatures in the deep smoldering.

We divided the variations of the surface temperature into three stages. The smoldering was difficult to monitor in the first stage when the surface temperatures were below the room temperature (25 ° C); the variation of the surface temperature was intensified in the second stage when the surface temperatures were higher than the room temperature (25 °C) but lower than the evaporation temperature (100 °C), namely evaporation stage; the moisture began to dry in the third stage, when the surface temperatures were over 100 °C, and reached the peak temperature of the smoldering. Variation of the surface temperatures caused by the smoldering of the fuel from grass-*L. gmelinii* forest and the *R. dauricum-L. gmelinii* forest took a longer time, and the longest times were 3.59 h and 3.54 h, when the moisture content was 15% and 20%, respectively. The temperature variation of the fuel from *L. palustre-L. gmelinii* forest occurred fast, with 0.99 h of smoldering with a moisture content of 10% causing changes in the surface temperatures. This indicated that the smoldering of the *L. palustre-L. gmelinii* forest could be detected in a short time.

The smoldering time for the evaporation of moisture of different fuels increased with the increasing moisture content. The smoldering time of the fuel from grass-*L. gmelinii* forest and the *L. palustre-L. gmelinii* forest was the longest with a moisture content of 25%, being 9.83 h and 4.24 h, respectively; while the smoldering time of the *R. dauricum-L. gmelinii* forest was the longest with a moisture content of 20%, reaching 15.96 h. With the increase in moisture contents, the duration of the surface combustion stage decreased. The surface combustion time was 1.52 h and 2.55 h when the moisture content of fuel from the grass-*L. gmelinii* forest was 10% and 15%, and only 0.86 h when the moisture content was 20%. The combustion time of the fuel from *L. palustre-L. gmelinii* forest was even shorter, only 0.57 h with a moisture content of 20%. The combustion time of the fuel from *R. dauricum-L. gmelinii* forest was longer, reaching 0.94 h and 2.21 h when the moisture content was 10% and 15%, respectively.

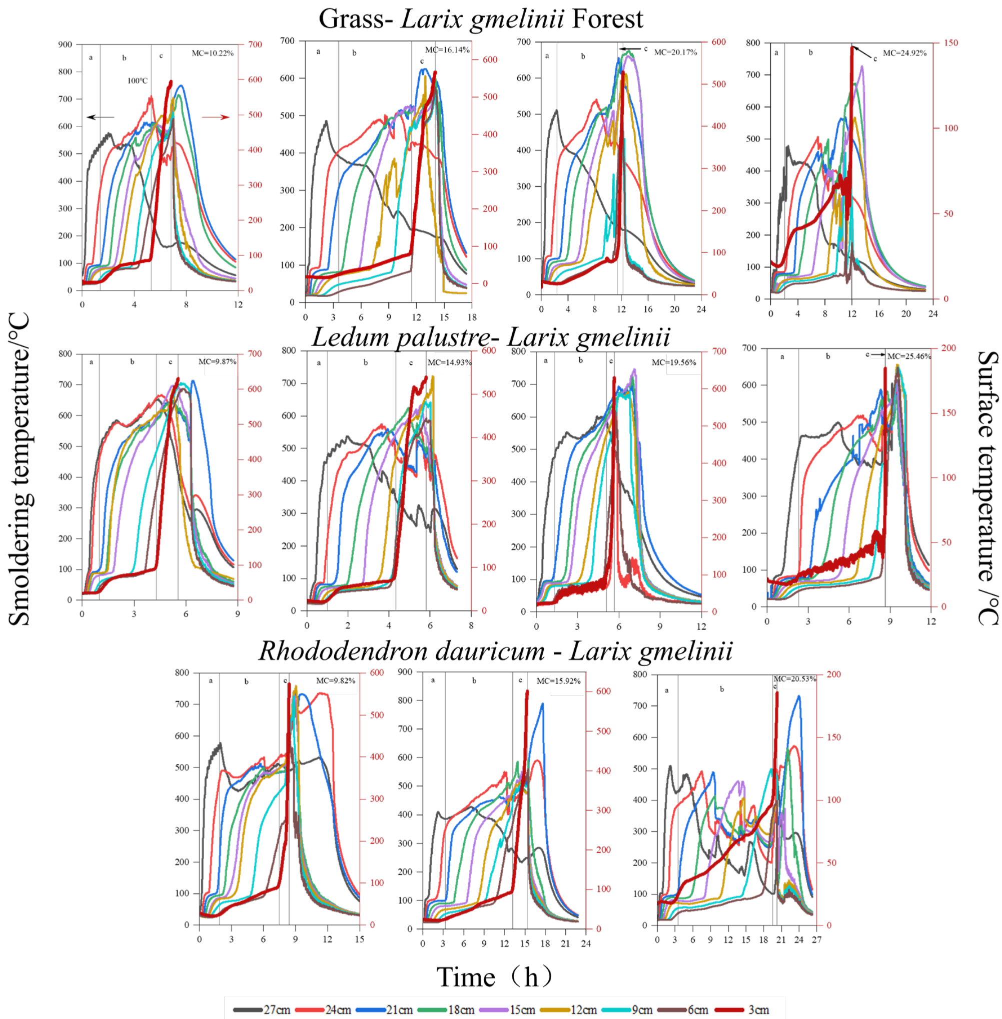

Figure 4. Temperature variation of the smoldering sub-surface fires: ((a) the surface temperature is lower than the room temperature; (b) the surface temperature is higher than the room temperature but below 100 °C; (c) the surface temperature is above 100 °C and rises to the peak combustion temperature).

3.2. The Monitoring of the Sub-Surface Fires

Variation of the surface temperatures caused by the smoldering was an important basis for the monitoring of the sub-surface fires. The fitting results of the temperature and time in the evaporation stage and combustion stage were shown in Figure 5 with the moisture contents that could lead to the conversion of sub-surface fires to surface fires. According to the results, there were significant positive correlations between temperature and time at the two stages, as the equation fitted was effective and precise ($p < 0.01$, $R^2 > 0.78$).

With surface temperature and moisture content set as independent variables, the peak smoldering temperature, and the depth and time of peak smoldering temperature as dependent variables, the monitoring and warning models of the sub-surface fires were established (Table 1). The monitoring and warning models of grass-*L. gmelinii* forest, the *L. palustre-L. gmelinii* forest and the *R. dauricum-L. gmelinii* forest all had great fitting effects; the independent variables (surface temperature and moisture content) both passed the significance test ($p < 0.01$). The peak smoldering temperature was positively correlated with the surface temperature, and negatively correlated with the moisture content; the depth was negatively correlated with both surface temperature and moisture content, and the time was positively correlated with both surface temperature and moisture content.

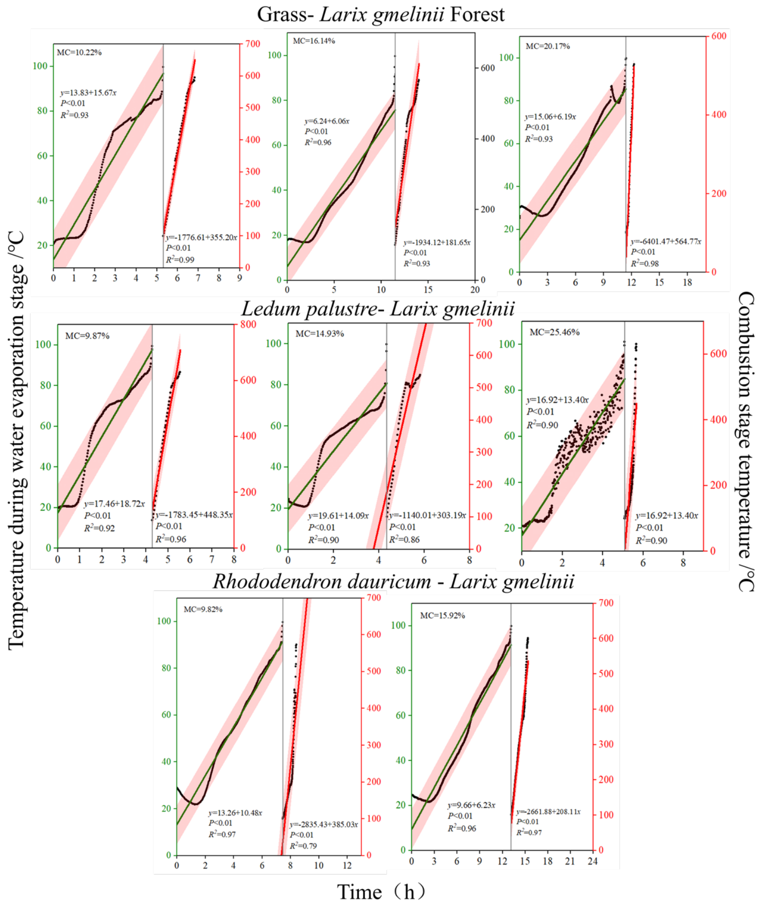

Figure 5. The fitting results of surface temperature and time.

Table 1. The monitoring and warning models of the sub-surface fires.

Fuel Type	Parameter	Independent Variable	Standard Error	Significance	*p*-Value	Equation
Grass-*Larix gmelinii* forest	Peak temperature/°C	Constant	3.58	<0.01	<0.01	$y = 519.19 + 0.46x_1 - 4.52x_2$
		Surface temperature	0.008	<0.01		
		Moisture content	0.18	<0.01		
	Depth/cm	Constant	0.189	<0.01	<0.01	$y = 28.04 - 0.008x_1 - 1.18x_2$
		Surface temperature	0.0001	<0.01		
		Moisture content	0.009	<0.01		
	Time/h	Constant	0.1	0.044	<0.01	$y = 0.2 + 0.02x_1 + 0.22x_2$
		Surface temperature	0.0002	<0.01		
		Moisture content	0.005	<0.01		
Ledum palustre-Larix gmelinii forest	Peak temperature/°C	Constant	5.83	<0.01	<0.01	$y = 515.34 + 0.51x_1 - 4.57x_2$
		Surface temperature	0.01	<0.01		
		Moisture content	0.28	<0.01		
	Depth/cm	Constant	0.09	<0.01	<0.01	$y = 27.66 - 0.02x_1 - 0.06x_2$
		Surface temperature	0.0001	<0.01		
		Moisture content	0.004	<0.01		
	Time/h	Constant	0.07	<0.01	<0.01	$y = -0.53 + 0.008x_1 + 0.17x_2$
		Surface temperature	0.0002	<0.01		
		Moisture content	0.003	<0.01		
Rhododendron dauricum-Larix gmelinii forest	Peak temperature/°C	Constant	3.39	<0.01	<0.01	$y = 505.29 + 0.46x_1 - 6.15x_2$
		Surface temperature	0.01	<0.01		
		Moisture content	0.19	<0.01		
	Depth/cm	Constant	0.16	<0.01	<0.01	$y = 33.49 - 0.03x_1 - 0.54x_2$
		Surface temperature	0.0001	<0.01		
		Moisture content	0.009	<0.01		
	Time/h	Constant	0.14	<0.01	<0.01	$y = -5.30 + 0.04x_1 + 0.64x_2$
		Surface temperature	0.0001	<0.01		
		Moisture content	0.008	<0.01		

x_1: surface temperature; x_2: moisture content of humus.

3.3. Occurrence Probability Prediction Model of the Sub-Surface Fires Converted to the Surface Fires

The two independent variables (mention the independent variables here) both passed the significance test ($p < 0.05$), the selected regression equation had a good fit (R^2 = 0.73), and the moisture content and depth were negatively correlated with the probability of occurrence (Table 2). The regression equation is as follows:

$$P = \frac{1}{1 + e^{-\ (11.168 - 0.665x_1 - 0.804x_2)}}$$

where P is the probability of the sub-surface fires converted to the surface fires; x_1 is the moisture content of humus; and x_2 is the depth.

Table 2. Logistic regression fitting of the probability of sub-surface fire spreading to the surface in Genhe Forestry Bureau.

Parameter	Standard Error	Significance	R^2
Constant	6.131	0.040	
Moisture content	0.324	0.045	0.73
Depth	0.402	0.039	

The ROC curve was drawn according to the probability of sub-surface fires turning into surface fires predicted by the model; the AUC value of the area under the curve was 0.987, indicating that the model has a high prediction accuracy (Figure 6).

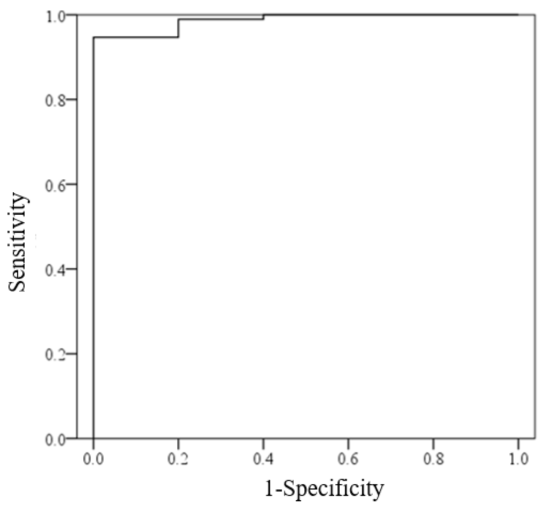

Figure 6. ROC curve of the occurrence probability prediction model of sub-surface fires spreading to the surface. The horizontal and vertical coordinates in the figure represent the false positive rate and true positive rate, which refer to the error prediction rate and correct prediction rate of sub-surface fire transforming into surface fire.

According to the odds ratio (a value used to measure the degree of the dominant influence of an independent variable) (Table 3), the influence of moisture content of humus (1.944) on the probability of the sub-surface fires converted to the surface fires was greater than that of depth (0.448). Moisture contents being the same, the probability of conversion from sub-surface fires to surface fires increased by 0.448 times when the depth decreased by 3 cm; depths being the same, the probability increased by 1.994 times when the moisture content decreased by 5%.

Table 3. Odds ratio of logistic regression for the probability of sub-surface fires spreading to the surface (upper and lower limits are 95% confidence intervals).

Independent Variable	Coefficient	Lower Bound	Upper Bound
Moisture content	1.944	1.029	3.670
Depth	0.448	0.204	0.984

4. Discussion

There are few records on the frequency and extent of damages caused by sub-surface fires in the historical forest fire data, which leads to an illusion that sub-surface fires rarely occur. In recent years more studies have shown that sub-surface fires are not absent, but latent, and intertwined with the surface fires, so they are often ignored. This study clarified the moisture content limit of the conversion from sub-surface fires to surface fires of the boreal forests of China by simulating the smoldering experiment and revealed the conversion process of the smoldering combustion to flame combustion. Although there may be some deviations from the actual fires in the experimental results, the study of the mechanism of the conversion is of critical importance.

4.1. Smoldering Sub-Surface Fires Converted to Surface Fires

While smoldering in peatlands has received a lot of attention due to substantial carbon emissions [7,37], the damage caused by smoldering in boreal forests must not be ignored [38]. With higher permeability and global warming, dry underground fuel (humus or peat) layers are more likely to cause serious smoldering sub-surface fires [39]. Sub-surface fires can cause serious damage to forest landscapes when they are converted to surface fires or even crown fires [40]. The lower the moisture content of the main fuels in the boreal forests, the higher the probability of sub-surface fires turning into surface fires. Smoldering is maintained by the heat released by itself [41], so the lower the moisture content, the less heat is taken for evaporation, the more heat remains, which leads to the greater possibility of spreading to the surface. With the increase in moisture content, evaporation will carry away a part of the heat, so the combustion temperature around the surface will decrease [42]. However, the acceleration of temperature increase, indicates that the moisture content within a certain range can promote smoldering, which is in agreement with the conclusions of previous studies [23]. However, when the moisture content of humus is too high, the smoldering will be suppressed, indicating that large amounts of water are needed to extinguish the smoldering [43]. Inadequate use of water will not just cause failure in preventing the spread of sub-surface fires, but also promote smoldering combustion.

In the boreal forests of China, the sub-surface fires of the grass-*L. gmelinii* forest and the *L. palustre*-*L. gmelinii* forest could easily turn into a surface fire with the moisture contents of humus being 10%, 15%, and 20%, but the conversion was difficult with the moisture content over 25%. The upward spread rate of the *L. palustre*-*L. gmelinii* forest was the highest, indicating that smoldering can be detected in a short time, enabling sub-surface fires to be extinguished more quickly. The combustion temperature of the grass-*L. gmelinii* forest was the highest, and the high temperature of humus near the surface layer could be maintained for a long time. Therefore, relatively wet fuels or a small amount of rainfall cannot effectively prevent the conversion of sub-surface fires, as the long time duration of high temperature can dry the fuels [32], which might lead to a higher risk of surface fires in the grass-*L. gmelinii* forest. The moisture content limit of conversion from the sub-surface fires to the surface fires in the *R. dauricum*-*L. gmelinii* forest was 20%, which was lower than that of the other two fuels. But the smoldering in *R. dauricum*-*L. gmelinii* forest could last for a long time, and the concealment was much higher than the others. When the smoldering was found, it was likely to have been spread for a long time, causing greater damage to the soil structure and plant roots. Although it was difficult for sub-surface fires converted into surface fires with high moisture contents, the smoldering temperatures of deep layers can be still high, and the smoldering could spread not only vertically but also horizontally [44].

This would further increase the concealability of sub-surface fires. When sub-surface fires spread to regions with low moisture content or thin humus, they would still turn into surface fires. Furthermore, due to the long-term accumulation of combustible emissions, there might be extreme fire behaviors of deflagration when the fires encounter air, seriously threatening the safety of rescue personnel [45,46].

4.2. Sub-Surface Fires Monitoring Based on the Variation of Surface Temperature

Sub-surface fires are different from surface fires and canopy fires, the intensity and risk of their occurrence can be reduced through fuel treatment [47]. Due to the particularity of underground fuels, the prediction of occurrence and effective monitoring are the best ways to reduce the damage caused by sub-surface fires as much as possible. Due to the strong concealability, it is very difficult to detect smoldering, and previous monitoring methods are all based on experience. Recently, studies have shown that emissions of smoldering can be used as the basis of monitoring [48], but the quantitative data are few, and further exploration is necessary. This study found that the spread of smoldering sub-surface fires is slow and it would take a long time to spread from the deep layer to the surface, but smoldering can cause variations of surface temperature before turning into surface fires. There are many kinds of temperature measurement tools, and thus the detection of temperature is easy, so we conclude that the variations of surface temperature can be used as an important basis for monitoring.

Smoldering of the fuel from the *L. palustre*-*L. gmelinii* forest was easily detected by the variations in surface temperature. The variation of surface temperature took 0.99 h with the moisture content of 10%, and 1.31 h when the moisture content was 20%. This resulted from the fact that the fuels of the *L. palustre*-*L. gmelinii* forests are mostly composed of incompletely decomposed plant roots, branches, and leaves, so the large voids within humus and the high oxygen content may contribute to the upward spread of heat, which significantly reduces the difficulty in monitoring and rescue work. The fuels of the grass-*L. gmelinii* forest and the *R. dauricum*-*L. gmelinii* forest are mostly composed of completely decomposed humus and plant roots, the organic matter being abundant, so the spread of smoldering is slow, and variation of the surface temperature might take a long time. The longest time taken for the variation of surface temperature in the grass-*L. gmelinii* forest was 3.59 h, and 3.54 h for that of the *R. dauricum*-*L. gmelinii* forest. This greatly added to the difficulty in monitoring and the damage of the sub-surface fires, so the monitoring should also be assisted with the soil-cutting method. The study also found that the smoldering temperature of deep layers fluctuated greatly, and there were two temperature peaks. This was because when the sub-surface fire spread to the surface, the increased supply of oxygen to the deeper layer, together with fallen fuels, resulted in more intense smoldering [49]. Therefore, individuals should never rush into the fire site recklessly. Firefighting and rescue work should be carried out in an orderly manner after good protective measures have been taken and the surface temperature reduced; otherwise, temperature rise and ground collapse will significantly heighten the risk of the work [50].

4.3. Occurrence Probability Prediction Model of the Sub-Surface Fires

Neglect of the sub-surface fires has resulted in a lack of data on occurrence, burned area, and time; hence, research publications on the prediction models are scarce. Previous studies used indirect factors such as groundwater level, drought index, humus code, and drought code in the Canadian fire risk rating system to predict the occurrence of sub-surface fires [50–53]. Although the research results can partly contribute to the prediction of sub-surface fires, the accuracy and applicability of the models still need improvement.

Sub-surface fires can be caused by surface fires or lightning strikes [54], but the sub-surface fires cannot be converted into surface fires in a short time, and this obvious lag made it difficult to predict the conversion. Based on the logistic regression model, this study established the occurrence probability prediction model of the sub-surface fires converted to surface fires with moisture content and depth, achieving high prediction accuracy (ACU = 0.987). Due to its strong applicability, the logistic regression model has been widely used in predicting forest fires [55,56]. Although the simulation results might be somehow different from the actual conditions, the humus of the actual forest was used in the experiments. Further, the experimental combustion method used also represents the extent of the actual smoldering sub-surface fires; therefore, the results of the present study can be used to explain the effect of fuel moisture content and depth on the conversion of sub-surface fires to surface fires. In addition to the moisture content and depth conditions used in this study, other studies have shown that high-intensity surface fires could cause an increase in surface temperature and decrease the moisture content of humus [57–60] which is highly likely to affect the probability of sub-surface fires transforming into surface fires. However, further studies are required to verify this. Based on surface temperature and moisture content, this study has established the monitoring models of the peak temperature, depth, and time of the smoldering. The models had a good fit and high precision, less complexity, and the independent variables were easier to obtain when compared to the previous studies.

5. Conclusions

This research is focused on the *L. gmelinii* forest in the boreal forests of China and studied the moisture content limit of sub-surface fires converted to surface fires. The results showed that the moisture content limit of the conversion was 25% in the grass-*L. gmelinii* forest and the *L. palustre*-*L. gmelinii* forest, and 20% in the *R. dauricum*-*L. gmelinii* forest. The surface temperature could be an important basis for monitoring sub-surface fires. The lower the moisture content of humus and the closer the smoldering is to the surface, the higher the probability of conversion from sub-surface fires to surface fires. This research provides a reference for the formulation of prevention and control measures for sub-surface fires in the boreal forest and contributes to future studies on the conversion mechanism of sub-surface fires to surface fires.

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