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Influence of Fuel Moisture Content, Packing Ratio and Wind Velocity on the Ignition Probability of Fuel Beds Composed of Mongolian Oak Leaves via Cigarette Butts

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Abstract: Cigarette butts are an important human firebrand and account for a significant amount of man-made fires. To better address forest fires caused by cigarette butts, the influencing factors governing the ignition probability of cigarette butts can be used to establish a prediction model. This study obtains the influencing factors of the ignition probability of cigarette butts in order to establish a prediction model by constructing fuel beds composed of Mongolian oak leaves with varied fuel moisture content and packing ratios. A total of 2520 ignition experiments were then conducted by dropping cigarette butts on the fuel beds to test the burning probability of the fuels under varied wind speeds. Moisture content, wind speed, and their interaction significantly influenced ignition probability. In the absence of wind, the ignition probability is zero. The maximum moisture content of Mongolian oak leaves that could be ignited by cigarette butts was 15%. A logistic model and self-built model for predicting the ignition probability were established using these results; the mean absolute error values for the two models were 2.71% and 1.13%, respectively, and the prediction error of the self-built model was lower than that of the logistic model. This is important research to mitigate the threat of forest fires due to cigarette butts given the frequent occurrence of these events.

Keywords: cigarette butts; ignition probability; fuel

1. Introduction

As global natural disasters, forest fires can release huge amounts of energy in a short amount of time and seriously damage the structure and function of ecosystems [1], leading to a significant loss of forest resources and soil erosion, the endangerment of the wild animals, damage to water resources and increased forest fire management costs, et al. [2]. Forest fires are caused by humans, lightning, and other natural causes, with man-made fires accounting for the vast majority, especially in populated regions [3–5]. Heilongjiang province, in Northeast China, endures severe forest fires, with the area burned in the province being among the highest of provinces in China [6], according to historical data, since 2005, Heilongjiang province has experienced an average of 69.2 forest fires per year, with an average burned area of 1045.24 ha. When forest fires occur in Heilongjiang Province, they cause serious damage to the ecosystem and forest resources and pose a threat to people's safety. According to a survey [7], anthropogenic fires account for 64.5% of forest fires in Heilongjiang Province, and controlling the province's man-made fire frequency is therefore very important. Anthropogenic fires are caused by fire sources that ignite the fuel, such as agricultural burning, cigarette butts, and prescribed burning. As such, it is very important in the field of forest fire prevention to study the ignition mechanism of fire sources.

Cigarette butts are a special forest firebrand, accounting for a significant percentage of the total number of fire sources [8,9]. According to the historical forest fire data, the forest fire caused by cigarette butts in Heilongjiang province accounts for 20.6% of the man-made fire. When a cigarette butt is dropped, it first makes fuel smolder, which is difficult to identify from an observation tower, allowing the forest fire to spread before smoke is discovered and before the fire can be fought in the optimal time [10]. The ignition probability of cigarette butts is not fixed but rather is affected by the characteristics of the fuel and environment conditions. When the forest environment is hot and dry, it will decrease the fuel moisture content, and the ignition probability will significantly increase. Therefore, investigations into the response of the ignition probability of cigarette butts and the environmental characteristics needed are of great significance for the prediction and management of forest fires due to cigarette butts. While cigarette butts have received little scientific attention in terms of the conditions that cause a fire to start. Previous studies have suggested that the wind speed and moisture content of the fuel bed have a significant effect on the ignition probability of cigarette butts. For example, Hoffheins [11] found that the ignition probability of grass and fine fuel via cigarette butts has a very significant relationship with wind speed; when wind speed is roughly 3 $m \cdot s^{-1}$, the ignition probability is close to 100% for all types of fuel. Markalas [12] used ignited cigarette butts when the moisture content was 4.5%–6.5% on a fuel bed of pine needles and grass and found the ignition probability via cigarette butts was zero when no airflow was applied, but increased to 3.3% and 10% under windy conditions for pine needles and grass, respectively. Satoh et al. [13] lit dry leaves with cigarette butts and found that when the wind speed exceeded 4 $m \cdot s^{-1}$, the cigarette butts were automatically extinguished and the ignition probability dropped, but when wind speeds increased from 0 to 1 $m \cdot s^{-1}$, the ignition probability increased from 0% to 23%. Dainer [14] conducted a study of the ignition probability of hay via cigarette butts and found that, when wind speed increases and moisture content decreases, the ignition probability increases. Some researchers also believe that the structure of the grass bed has a large impact on the ignition probability [15,16]. Ignition probability is also greatly influenced by the location that the cigarette butt comes in contact with the fuel bed, with Lawson et al. [17], for example, believing that if a cigarette butt has good contact with the fuel, there is a higher ignition probability.

Although there are fewer studies of cigarette butts as a fire source, many other related ignition probabilities of fire sources have been studied and can provide a reference for studying the ignition probability of cigarette butts. Fuel can be ignited by fire sources depending on many factors, including fire size and state (flaming, glowing), environmental conditions (temperature, relative humidity, wind speed), and fuel bed characteristics (moisture content, packing ratio, fuel arrangement, temperature, porosity) [18–21]. Fuel moisture content is the most significant variable affecting ignition probability and is inversely related to the ignition probability [22–26]. The effect of wind speed on the ignition probability is complex and related to firebrand statue (flaming and glowing), the type of wind, and the position of the firebrand in the bed layer. For example, glowing firebrands can only ignite fuel when airflow is applied [27–31]. Ganteaume et al. [31] found that when airflow is oblique or turbulent, the ignition probability increases. Additionally, there may be a dual influence of wind speed on ignition probability, as airflow can increase the oxygen concentration and promote ignition but also reduce ignition by reducing the fuel temperature [24]. Packing ratio also has a significant influence on ignition probability; Banksia (*Banksia ericifolia* L.f.) and Witch hazel (*Leptospermum laevigatum* F. *Muell*) leaves, for example, cannot be ignited because they are very small and form highly dense fuel beds. The packing ratio of these fuel beds is too high to allow sufficient oxygen for combustion [24].

Although studies on the ignition probability of cigarette butts have been performed, the situations created by different fuel types ignited by the same firebrand have not been identical, and the ignition probability of cigarette butts has not been investigated for Chinese fuel types. Heilongjiang is the province hardest hit by forest fires in China with its annual fire area ranked first in the country [6]. Mongolian oak (*Quercus mongolica*) is an important broad-leaved tree in this region. Its leaves have a large surface area and this fuel therefore easily curls and can form a very thick fuel bed, which greatly influences forest fires. The aim of this study is to determine the ignition probability of a fuel bed composed of Mongolian oak leaves via cigarette butts, to analyze the influence of wind speed, moisture content, and the packing ratio of fuel beds on the ignition probability of cigarette butts, and to establish a forecasting model to provide a basis for forest fire prediction.

2. Materials and Methods

The study area is the Maoer Mountain Forest Farm in the city of Harbin, Heilongjiang Province with geographical coordinates ranging from 127°40′–127°34′ E, 45°24′–45°33′ N, as shown in Figure 1. The highest altitude of the area is 805 m, and the average altitude is 300 m. The annual average temperature is 2.8 °C. The annual mean precipitation is 723 mm, and is mainly concentrated in July and August. The forest type is predominantly the natural secondary forest formed by the destruction of the original forest and is the typical distribution area of broad-leaved red pine (*Pinus koraiensis*) forest in the temperate zone of China. The vegetation mainly includes Mongolian oak poplar (*Poplus dividiana* L.), white birch (*Betula platyphylla* Sukaczev.), and so on.

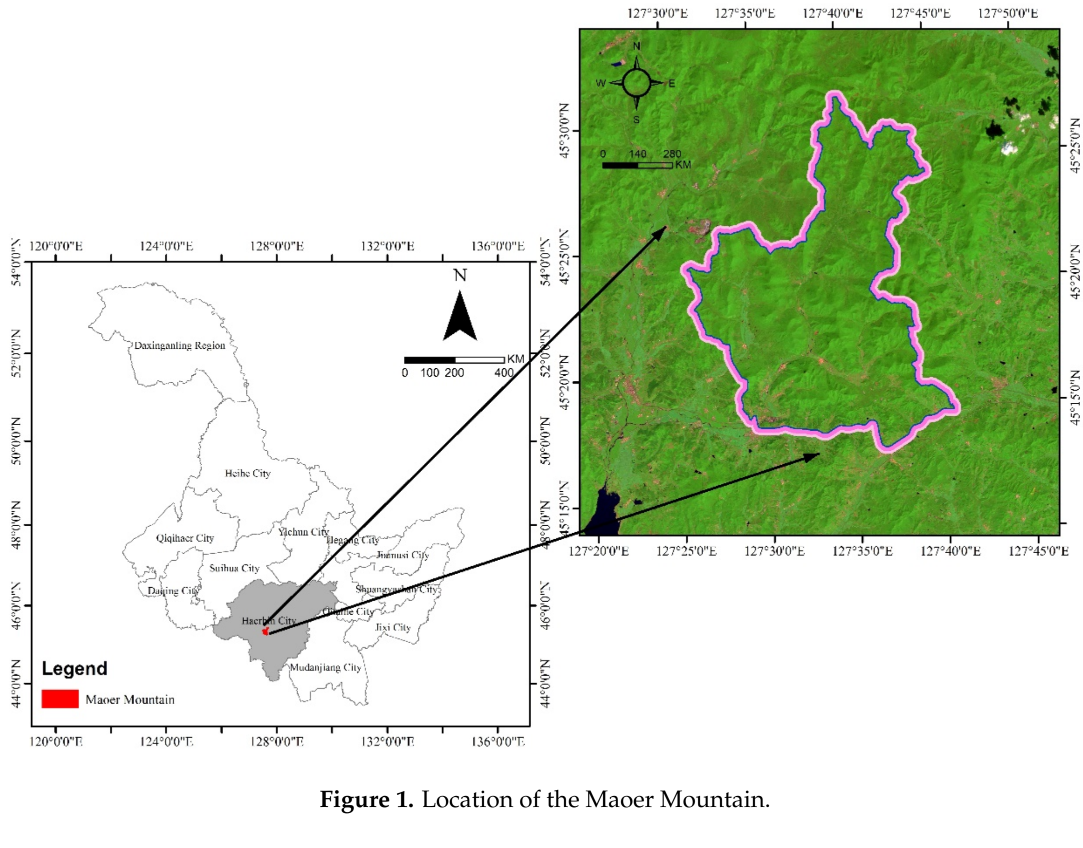

Figure 1. Location of the Maoer Mountain.

In May 2014, Mongolian oak leaves which fell in the autumn of the previous year were collected from the Mongolian oak forest in the Maoer Mountain Forest Farm. The information of the forest stand is shown in Table 1. The structure of the leaves remained completely intact. The collected leaves were laid flat in the laboratory and prepared for burning.

Table 1. The information of the forest stand.

Forest Type	Location	Evaluation (m)	Mean DBH (cm)	Mean Height (m)	Canopy Density
Quercus Mongolica	Up slope	544	23	24.4	0.45

2.1. Preparation of Burning Bed

The fuel beds used in the burning tests must be prepared in advance and must meet the natural conditions of the field bed. Fuel bed preparation mainly consisted of preparing the packing ratio and moisture content.

2.1.1. Packing Ratio

The quantity of fuel has a significant effect on the ignition probability [32] and it is therefore necessary to ensure that the fuel involved in the burning experiments is complete and conforms to the actual situation in the field. Therefore, we investigated the height and packing ratio of the surface fuel of Mongolian oak forests. We found the minimum, average, and maximum packing ratios to be 0.0383, 0.0638, and 0.0893, respectively, and the average height to be 4 cm. Hence, the packing ratio of the fuel bed was set to three levels: 0.0383, 0.0638, and 0.0893.

The packing ratio is the ratio of the bulk density of the fuel bed to the density of the particles; the fuel bed density is the ratio of the fuel mass to volume, and the particle density of the Mongolian oak leaves was 548.3 kg·m^3 [33]. The length, width, and height of the fuel bed were 17 cm, 17 cm, and 4 cm, respectively, for a bed volume of 1.16×10^{-3} m^3. According to the selected fuel bed packing ratio, the volume and particle density of the Mongolian oak broadleaves can be obtained at different packing ratios corresponding to the fuel mass. Table 2 shows the mass of the Mongolian oak leaves at different packing ratios.

Table 2. Mass of the Mongolian oak leaves with different packing ratios for a fuel bed height of 4 cm.

Packing Ratio	Bulk Density (kg·m^3)	Mass (g)
0.0383	21.0	24.4
0.0638	34.6	40.1
0.0893	49.0	56.8

2.1.2. Moisture Content

To determine the moisture content gradient, it is necessary to determine the maximum bed moisture content of Mongolian oak leaves that can be ignited by cigarette butts. Luke [34] found that when the surface fuel moisture content is above 35% it is difficult to ignite fuel beds, therefore, we chose to begin at 35% and decrease the moisture content of the fuel bed in 5% intervals, in addition to varying the wind speed and packing ratio. Fuel beds with each specific moisture content and packing ratio were put into contact with cigarette butts 30 times under different wind speeds. As long as there was a flame that could spread, the moisture content of the Mongolian oak leaves was considered to be ignited by the cigarette butts, and based on this test, the maximum moisture content of the Mongolian oak leaves that can be ignited by cigarette butts is 15%. Thus, the moisture contents of the fuel beds were set at 0%, 5%, 10%, and 15%.

The fuel bed with each specific moisture content then needed to be prepared. Mongolian oak leaves were placed in an oven and dried at 105 °C until the mass no longer changed. The dry weight was recorded as W_D, and the leaves were placed on the ground. According to the moisture content formula: $M = \frac{W_H - W_D}{W_D} \times 100\%$ (where M = moisture content of the fuel bed and W_H = wet weight of the fuel), the wet weight of the fuel at the moisture content required for the test was obtained, and recorded as W_H, where $W_H - W_D$ is the mass of water that must be added. The leaves were then placed onto the floor of the laboratory and the required water was quickly and evenly sprayed on the surface of the leaves before the fuel was sealed in a plastic bag for 24 h to allow it to absorb the water completely [35,36]. The fuel beds were then prepared with the moisture content required for the burning test. Before each ignition test, a subsample of fuel was taken and its moisture content was tested with a rapid moisture meter.

2.2. Setting the Wind Speed

The fuel bed is blown away and the burning test cannot be performed when airflow exceeds 6 $m \cdot s^{-1}$, therefore, the maximum wind speed used in this test was 6 $m \cdot s^{-1}$. With an interval of 1 $m \cdot s^{-1}$, starting from 0, seven wind speed velocities were established. For the experiment, a constant temperature blower (Philips HP8226/05, Philips, Shanghai, China) was selected as the wind source, and the wind speed was obtained by adjusting the distance between the blower and the fuel bed.

2.3. Burning Experiment

For the burning test, a 17 cm long by 17 cm wide by 5 cm high uncovered iron frame was used as the burning bed and is shown in Figure 2. The bed layer was prepared with different fuel moisture contents and packing ratios.

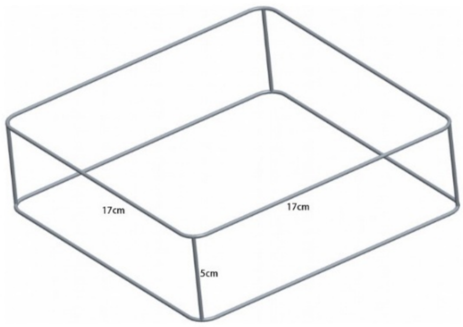

Figure 2. Diagram of the fuel bed.

The cigarette butts selected for the test were the Zhongnanhai brand (Beijing cigarette factory, Beijing, China) and had a length of 5 cm (with filter) and 2 cm (without filter) and a diameter of 0.7 cm. The cigarette butts generally fall from 1.5 m, thus, for a better simulation, the cigarette butts were thrown from a height of 1.5 m into the corresponding wind speed point on the fuel bed. The fuel bed moisture content, packing ratio, and wind speed were used as classification conditions, and each fuel bed combination of moisture content, packing ratio, and wind speed (84 combinations) was ignited via cigarette butts 30 times, for a total of 2520 burning tests. In each burning test, cigarette butts were considered to have ignited the fuel bed when there was a flame that could sustainably spread; this was marked as one, or otherwise marked as zero. The entire burning process was recorded with a digital camera (Panasonic HDC-TM900, Panasonic, Osaka, Japan). The experimental apparatus used is shown in Figure 3.

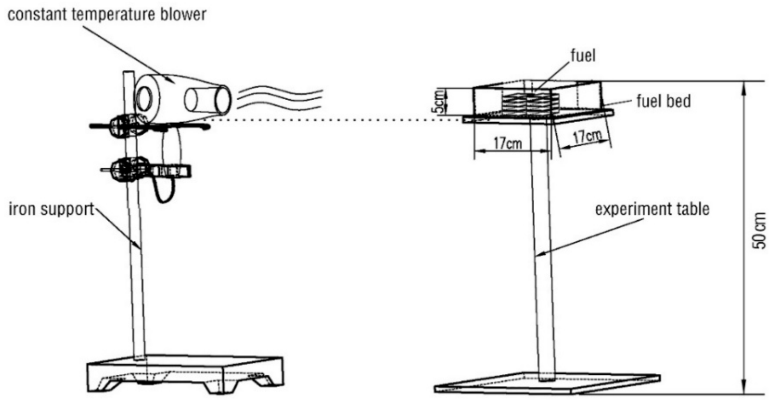

Figure 3. Diagram of the experimental apparatus.

2.4. Data Analysis

2.4.1. Analysis of Variance

Each bed's moisture content, packing ratio, and wind speed ratio (84 combinations) were tested with 30 burning tests, and each match has a corresponding ignition probability for cigarette butts, for 84 match ratios. The variance of the ignition probability was analyzed by Statistica 10.0 (Publisher: Statsoft, Tulsa, OK, USA), with the moisture content, packing ratio, and wind speed as the independent variables so that variables that significantly influence ignition probability could be determined.

2.4.2. Analysis of Influencing Factors

According to the analysis of variance, the significant influencing factors were obtained, and the manner in which these factors affect the ignition probability of cigarette butts was then analyzed. If all of the factors had a significant impact, we chose different levels of any two factors as a classification variable and analyzed how the remaining factor alone affects the ignition probability. For example, to analyze the effect of moisture content on the ignition probability, the levels of packing ratio and wind speed were used as classification variables and a scatter plot was drawn using moisture content as the independent variable and the ignition probability as the dependent variable for different packing ratios and wind speeds. According to the scatter plot, the effect of the moisture content on the ignition probability can be analyzed. The other two-factor analysis methods used were the same as for moisture content.

If there was only one factor that had no effect on the ignition probability, the burning test as a categorical condition in the test is meaningless. Therefore, this insignificant factor is removed, and the arithmetic mean of the ignition probability of each gradient of the insignificant factors is calculated under different combinations of the remaining two factors, in addition to the arithmetic mean value as the new ignition probability in different combinations of the two significant factors. A scatter plot was plotted with one of the factors as the independent variable and the ignition probability as the dependent variable at different gradients of the other factor. The effect of the factor on the ignition probability was then analyzed using the scatter plot.

If only one factor had a significant effect, the arithmetic mean of the ignition probability of this factor was calculated at different levels. A scatter plot was then made with the factor as the independent variable and the ignition probability as the dependent variable so that the effect of the factor on ignition probability could be analyzed.

2.4.3. Establishing a Probability Prediction Model for Cigarette Butts

We chose two methods to establish an ignition probability prediction model: A logistic prediction model and a self-built prediction model.

(1) Logistic prediction model: The logistic prediction model is widely used in probability modeling of forest fires [6,37–39]. In the logistic regression model, two types of discriminant problems were evaluated. The first type was cigarette butts that can ignite the fuel (assigned a value of 1); the other type was fuel that cannot be ignited by cigarette butts (assigned a value of 0). The fuel bed moisture content, packing ratio, and wind speed were taken as independent variables, and a logistic prediction model was established using a stepwise regression method in Statistica 10.0:

$$LogitP = b_0 + b_1 X_1 + b_2 X_2 \cdots + b_m X_m \quad (1)$$

The prediction model of the ignition probability of cigarette butts lighting the Mongolian oak leaves is:

$$P = \frac{e^{b_0 + b_1 X_1 + b_2 X_2 \cdots + b_m X_m}}{1 + e^{b_0 + b_1 X_1 + b_2 X_2 \cdots + b_m X_m}} \quad (2)$$

(2) Self-built prediction model: The logistic prediction model is widely applied to examine the ignition probability of forest fires, but is purely statistical and has no physical significance. Therefore, the self-built model used in this study is based on analysis of the mechanism of the influencing factors, and the appropriate model form is the model with the minimum mean absolute error (MAE).

According to the analysis of variance, moisture content, and wind speed significantly affect ignition probability. First, the model was established with wind speed as the independent variable and ignition probability as the dependent variable for each moisture content. Select functional forms (p = a/(w − b)ˆ2 + c, p = (wˆa)exp(1 − wb), p = (w + a)exp(b − w), etc., where p = ignition probability of cigarette butts; w = wind speed; a, b, and c = model parameters) were used as the model, where the MAE value of the best model form is the smallest. Then the model was established with the parameters of the previous model as the dependent variable and moisture content as the independent variable. The equation $y = de^{-fmc}$ was used as the model form (y = parameters of the previous model, mc = moisture content, d and f = model parameters). Finally, the parameter models were substituted into the previous model to obtain the ignition probability prediction model with wind speed and moisture content.

(3) Model comparison: The MAE values of the two models were calculated. The MAE is the arithmetic mean of the absolute value of the difference between all individual actual and predicted values. The MAE can better reflect the actual predicted error, and the method to calculate it is shown in Equation (3). The predictive effects of the two models with MAE were compared, where a smaller MAE indicates a better model.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|M_i - \hat{M}_i\right| \quad (3)$$

where M_i is the actual ignition probability (%), $\hat{M}_i$ is the predicted ignition probability (%), and n is the number of samples.

To further compare the prediction efficiency of the two models, two-thirds of the data were chosen for logistic and self-built modeling and one-third for data validation, in triplicate. The MAE values of the modeling data for the two models, the validation data in triplicate, and a t-test were performed. If $p < 0.05$, the prediction efficiency for the small MAE model was significantly better than that of the other model.

3. Results

3.1. Analysis of Variance

As seen in Table 3, the moisture content of the fuel bed, wind speed, and their interaction had a significant effect on the ignition probability of cigarette butts, and the packing ratio of the fuel bed had no significant effect on ignition probability.

Table 3. Analysis of variance of moisture content, packing ratio, and wind speed on ignition probability of cigarette butts.

Variables	Sum of Deviation Squares	Degree of Freedom	Mean Square Error	*f*	*p*
Moisture content	442.328	3	147.4427	5.57333	0.001595
Wind speed	923.545	6	153.9242	7.24821	0.000004
Packing ratio	3.175	2	1.5873	0.05031	0.950964
Moisture content ×Wind speed	541.0053	18	30.0558	2.58207	0.003528
Moisture content×Packing ratio	110.053	6	18.3422	0.65927	0.682588
Wind speed ×Packing ratio	104.233	12	8.6861	0.35818	0.973128

3.2. *Analysis of Influencing Factors*

The packing ratio of the fuel beds had no significant effect on the ignition probability of cigarette butts, as a result, the same fuel bed moisture content and wind speed were combined with three different packing ratios. Therefore, the arithmetic mean of the ignition probability of the three packing ratios under the same fuel moisture content and wind speed was calculated as the ignition probability under the ratio of moisture content and wind speed. There were 28 matching groups (4 × 7).

3.2.1. Influence of Fuel Moisture Content

The interaction of moisture content and wind speed had a significant effect on fire probability. For each wind speed, scatter plots with moisture content as the independent variable and the average ignition probability as the dependent variable were obtained, see Figure 4. As seen in Figure 4, the ignition probability of cigarette butts was zero when the wind speed was 0 $m{\cdot}s^{-1}$ and 6 $m{\cdot}s^{-1}$. When the wind speed was 1–5 $m{\cdot}s^{-1}$, the ignition probability decreased with increasing moisture content, and the relationship between moisture content and wind speed increased from the exponential form to the linear, and then exponential form.

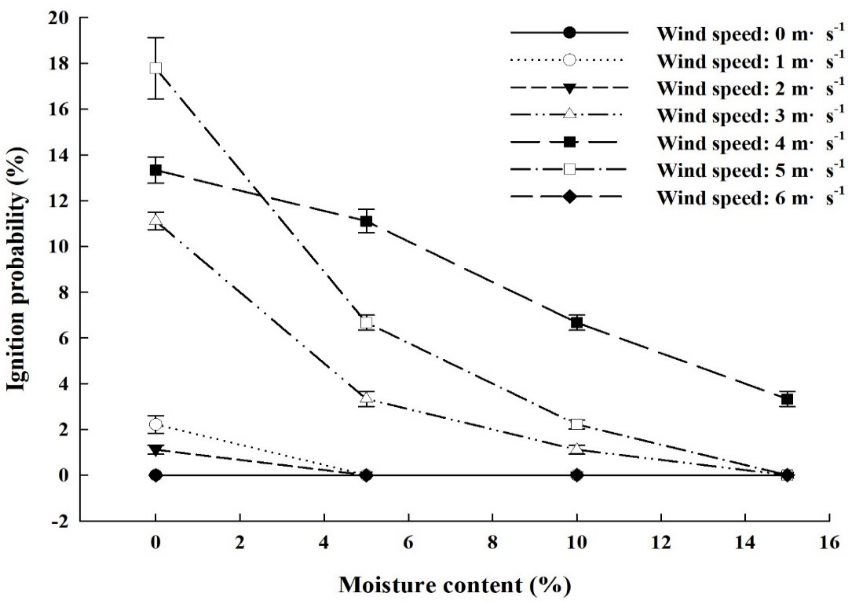

Figure 4. The ignition probability of cigarette butts for different fuel moisture content levels at each wind speed.

3.2.2. Influence of Wind Speed

For each moisture content level, scatter plots with wind speed as the independent variable and average ignition probability as the dependent variable were obtained, see Figure 5. For each moisture content level, with an increase in wind speed, the ignition probability of cigarette butts first increases and then decreases, reaching the maximum at the optimum wind speed.

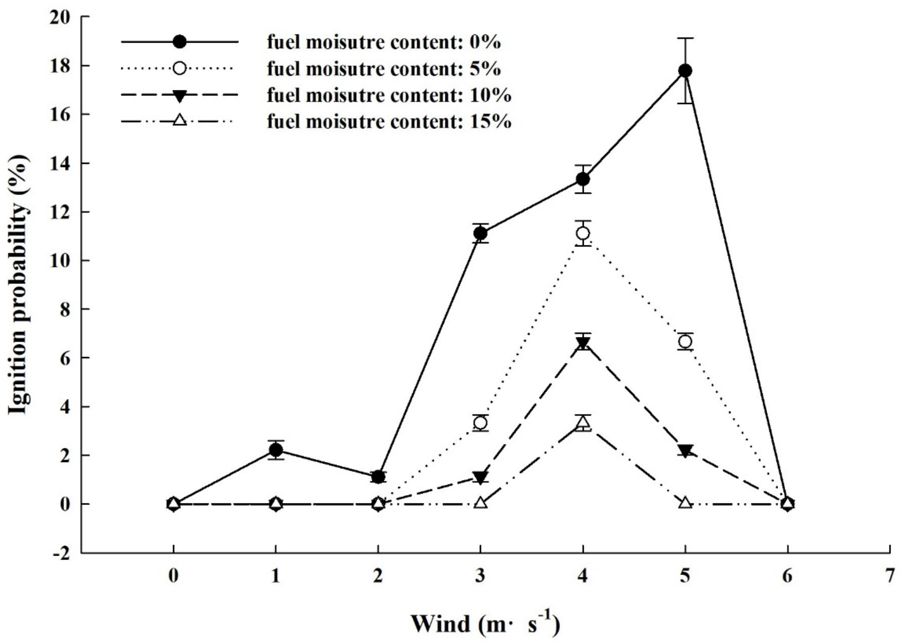

Figure 5. The ignition probability of cigarette butts for different wind speed levels at each moisture content level.

3.3. Establishing the Probability Prediction Model for Cigarette Butts

3.3.1. Logistic Prediction Model

We chose the backward regression method to remove the non-significant variables one-by-one in order to obtain the optimum logistic prediction model (i.e., the model in which non-significant variables are excluded). The parameters of the model are given in Table 4, and there is a significant correlation between fuel bed moisture content and wind speed in the model.

Table 4. Parameter estimation of best logistic regression model.

Independent Variable	Estimation Coefficient	SE	Wald Chisquare	*p*
Constant	−3.653	0.302	145.879	0.000
Moisture content	−0.168	0.028	37.767	0.000
Wind speed	0.287	0.066	18.761	0.000

The logistic prediction model for cigarette butts and Mongolian oak leaves is shown in Equation (4):

$$P = \frac{e^{(-3.653\,-\,0.168\,\times\,X_1\,+\,0.287\,\times\,X_2)}}{1\,+\,e^{(-3.653\,-\,0.168\,\times\,X_1\,+\,0.287\,\times\,X_2)}}\,\times\,100\% \quad (4)$$

In this case, X_1 is the fuel bed moisture content (%, 0–15), X_2 is the wind speed (m/s, 0–6), and P is the ignition probability (%).

3.3.2. Self-Built Prediction Model

The form of the best model that was observed is $p = \mathrm{a}/(w - \mathrm{b})\hat{}2 + \mathrm{c}$, and the parameters of the model are given in Table 5.

Table 5. Parameters of the self-built prediction model.

Moisture Content (%)	a	b	c	MAE (%)
0	14.9428007982143	4.52865123102806	0.70358893892208	2.53
5	4.58321739881847	4.34591632079375	0.28913413203429	0.64
10	1.4817479664095	4.26605163925396	0.151176534925172	0.19
15	$4.9885393103194 \times 10^{-9}$	3.99367219674002	−0.0000400391398211602	0.11

As the fuel bed moisture content increases, the parameters a, b, and c exponentially decrease. For each parameter, the fuel bed moisture content is used as the independent variable and the parameter is the dependent variable. The equation $y = d \times e^{-f \times mc}$ is used as the model form (y = parameters of the previous model, mc = moisture content, d and e = model parameters). The model parameters are shown in Table 6.

Table 6. Parameters of the self-built prediction model.

	a	b	c
d	14.9561268005343	4.53842102319753	0.705080271836714
f	0.238722311097891	0.00783275222656424	0.177530057824552

Based on parameters a, b, c, d and f, the final prediction model for the ignition probability of cigarette butts is obtained, see Equation (5), and is related to the moisture content and wind speed. The MAE value was 1.13% and the fitting is shown in Figure 6.

$$P = \frac{14.9561268005343 \times e^{(-0.238722311097891 \times X_1)}}{(X_2 - 4.53842102319753 \times e^{(-0.00783275222656424 \times X_1)})^2 + 0.705080271836714 \times e^{(-0.177530057824552 \times X_1)}} \quad (5)$$

In this case, X_1 is the fuel bed moisture content (%, 0–15), X_2 is the wind speed (m/s, 0–6), and P is the ignition probability (%).

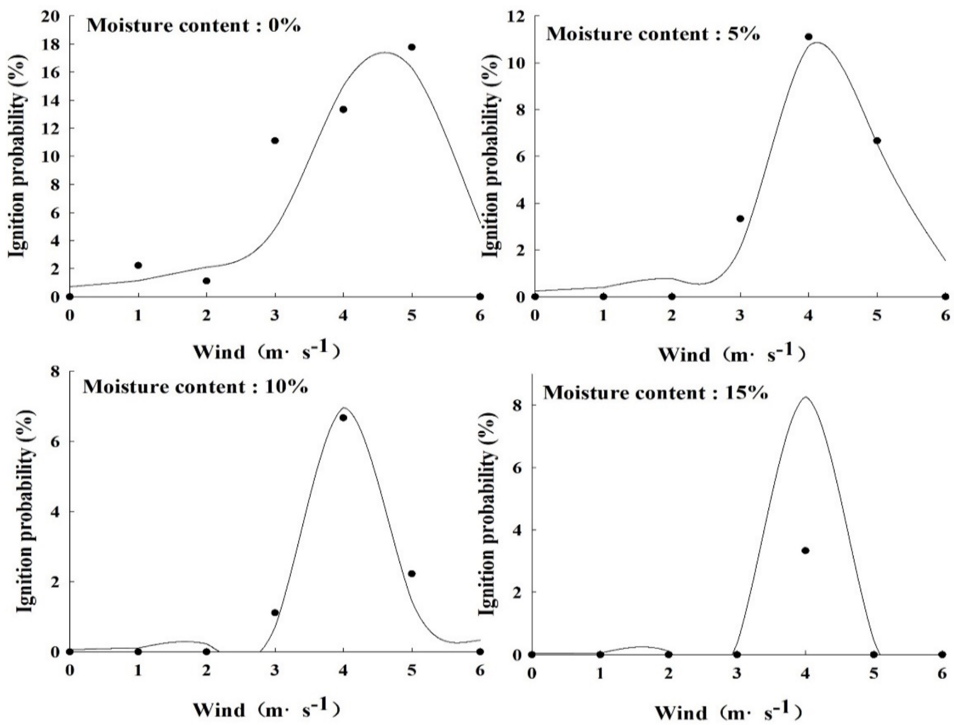

Figure 6. Ignition probability fitting curves of the self-built model.

3.3.3. Model Comparison

The MAE values of the logistic model and the self-built model were 2.71% and 1.13%, respectively. The prediction error of the self-built model was lower than that of the logistic model.

Two-thirds of the data was chosen for logistic and self-built modeling and one-third for data validation, in triplicate. For the logistic model, the MAE values of the three sets of validation data were 3.06%, 2.95%, and 3.10%. For the self-built model, the MAE values of the three sets of validation data were 1.85%, 1.35%, and 1.79%. A *t*-test was performed for the MAE values of the two models, the results of which are shown in Table 7. It can be seen that $p < 0.01$, indicating that the MAE difference between the two models was significant and that the prediction effect of the self-built model was significantly better than that of the logistic model.

Table 7. The *t*-test results of the two models.

	Mean	SD	t	df	p
Self-built model	3.04	0.08			
Logistic model	1.66	0.27	11.74	2	0.007

4. Discussion

4.1. Moisture Content

We found the maximum moisture content of Mongolian oak leaves that can be ignited by cigarette butts to be 15%. Satoh et al. [13] found that when the moisture content of leaf fuel beds is above 14%, cigarette butts cannot ignite the beds, which is similar to the results of this study. Blackmarr [22] found that the maximum moisture content of fuel that can be ignited is 16%–18% and mainly related to the fuel type. The ignition probability of cigarette butts in the present study was inversely proportional to the fuel moisture content, which is the finding as reported in previous studies [22–26]. The ignition process is divided into three phases: (1) In the fuel preheating stage, as the fuel temperature rises, water evaporates; (2) in the fuel pyrolysis stage, fuel continues to undergo thermal pyrolysis, breaking down into combustible volatiles; and (3) in the combustion phase, flammable volatiles in contact with the air form flammable mixtures, and fuels are ignited when the combustion limits are reached. The amount of heat provided by the cigarette butt is fixed, so as the fuel moisture content increases, the energy needed for ignition increases, and the cigarette butt energy is not sufficient to complete the three stages of combustion.

4.2. Wind Speed

The ignition probability was zero when the wind speed was 6 $m{\cdot}s^{-1}$, as cigarette butts cannot stay on the fuel bed surface and thus heat transfer is not possible. This result is different from that reported by Gavriil et al. [8], who considered the minimum wind speed to blow away a cigarette butt to be 4.5 $m{\cdot}s^{-1}$. The result of this study was greater than 4.5 $m{\cdot}s^{-1}$, mainly because the Mongolian oak leaves are curled and the fuel bed has gaps, so the cigarette butt remained on the bed and was not easily blown away.

We found that no matter what the moisture content of the fuel bed, the fuel cannot be ignited by a cigarette butt without wind. Previous studies have also found that glowing firebrand can only ignite fuel in the presence of airflow [27–31]. Cigarette butts are a glowing source, and wind is the necessary condition for a flame to turn from glowing to flaming. Plucinski et al. [24] reported that wind speed increases the probability of firebrands converting from glowing to flaming, and the effect of wind on the ignition probability of glowing firebrands is an effect on the fire source itself, not the fuel. However, for the cigarette butts selected in this study, in a certain wind speed range, the airflow cannot induce cigarette butts to ignite. The impact of wind on the ignition probability affects the fuels, inducing the transition from glowing to flaming.

For each fuel moisture content level, with an increase in wind speed, the ignition probability of cigarette butts first increased and then decreased, reaching a maximum probability at the optimum wind speed. Wind will increase the concentration of oxygen in the reaction zone, accelerating the combustion reaction, and increasing the ignition probability, but it will also reduce the temperature of the fuel that does not participate in the reaction and reduce the ignition probability. Thus, there may be an optimal wind speed for the ignition probability [21,24]. Some reports indicate that for glowing firebrands, with an increase in wind speed, the ignition probability will increase [11,14,31,40]. The reason for the difference is the selected wind speed range; within a certain range, the ignition probability increases with an increase in wind speed, but not infinitely. When wind speed exceeds the optimum value, the ignition probability will decline.

4.3. Packing Ratio

We found that the packing ratio of the fuel bed has no significant effect on the ignition probability. Satoh et al. [13] ignited Japanese oak leaves with cigarette butts and found that the ignition probability reached 50% when the cigarette butts were inserted into a fuel bed with a high packing ratio. However, it has been suggested by others that a packing ratio that is too large will reduce the ignition probability [24]. The effect of the packing ratio on the probability of ignition is different primarily because an increase in the packing ratio can reduce the heat loss of the fuel and increase the ignition probability, but can also reduce the oxygen concentration at the same time and thereby reduce the ignition probability. Thus, the influence of the packing ratio on the ignition probability has a duality, and different studies (different fuel types, firebrand types, packing ratio ranges, etc.) may present different results [41].

4.4. Interaction of Moisture and Wind

The form of the best model we found was $p - a/(w - b)$ˆ2 + c; a/c in this equation represents the maximum value of the ignition probability for each moisture content level, and b represents the wind speed corresponding to the maximum ignition probability for each moisture content level. As seen in Figure 7, an increase in the moisture content is correlated with an optimum wind speed decrease. The influence of wind speed on the ignition probability of cigarette butts exhibits a duality, where the increase in moisture content and the influence of wind speed on the cooling of the fuel gradually takes over. This discovery also reveals that, for cigarette butts, when the wind speed exceeds a certain threshold, the probability of ignition decreases, not because the cigarette lighter gets extinguished, but because the temperature and flammable gas concentration of the reaction zone are decreased.

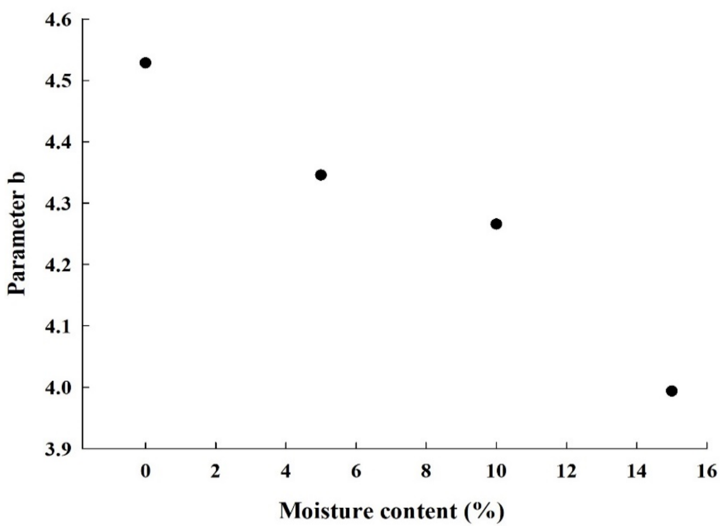

Figure 7. Parameter *b* of the self-built prediction model varies with the moisture content.

4.5. Fire Source Management

In this study, a total of 2520 tests were conducted and ignition occurred only 72 times, yielding a total ignition probability of 2.9%. Markalas [12] found that when wind was present and the cigarette butts had no filter, the ignition probability was 3.3% for needles and 10% for hay. Danier [14] found that cigarette butts ignited the hay in 33% of cases. The results of these studies are higher than that of the current study, probably owing to the number of burning tests, type of cigarette butts, fuel type, and fuel bed characteristics used. The ignition probability of cigarette butts in this study was only 2.9%, which is very low. However, forest fires caused by cigarette butts in Heilongjiang Province account for the vast majority of man-made fires [7], indicating obvious loopholes in the management of firebrands in Heilongjiang Province, especially cigarette butts. Our research provides an ignition probability model for Mongolian oak leaves that were ignited by cigarette butts in Heilongjiang Province, with an MAE of the self-built model of only 1.13%. According to the wind speed and moisture content of fuel beds at present, the probability of the ignition of Mongolian oak leaves via cigarette butts can be obtained, and the corresponding fire source management response mechanism can be put forward to reduce the number of forest fires.

5. Conclusions

This present study has shown that the ignition probability for Mongolian oak leaves ignited by cigarette butts is significantly correlated with the moisture content and wind speed, but not related to the packing ratio. In the absence of wind, the ignition probability was zero. The maximum moisture content of the Mongolian oak leaves that can be ignited by cigarette butts was 15%. The maximum moisture content of the fuel bed that can be ignited via cigarette butts first increased and then decreased when the wind speed was between 1 $m{\cdot}s^{-1}$ and 5 $m{\cdot}s^{-1}$. For different fuel bed moisture contents, the ignition probability increased and then decreased as wind speed increased, and the optimum wind speed decreased with increases in moisture content. The prediction model established in this study is significantly better than the logistic prediction model, which reveals the influencing factors for the ignition probability of cigarette butts and its mechanisms.

The results presented in this paper can further the understanding of the ignition mechanism of this fire source (cigarette butts). Nevertheless, there are currently very few reports of ignition tests in firebrand research; such experiments would be helpful for future research into this problem. In the future, a wider variety of fuel types should be tested, including needles, grasses, and mixtures of leaves and needles, to improve the prediction model for cigarette butts and provide a stronger basis for forest fire prediction.

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References

1. Wotton, B.M.; Martell, D.L.; Logan, K.A. Climate change and people-caused forest fire occurrence in Ontario. *Clim. Chang.* **2003**, *60*, 275–295. [CrossRef]
2. Hu, H.Q. *Forest Fire Ecology and Management*; China Forestry Press: Beijing, China, 2005; p. 4.
3. Kruger, F.J.; Bigalke, R.C. Fire in fynbos. In *Ecological Effects of Fire in South African Ecosystems*; Springer: Berlin, Germany, 1987; pp. 67–114.
4. Cardille, J.A.; Ventura, S.J.; Turner, M.G. Environment and social factors influencing wildfires in the Upper Midwest, United States. *Ecol. Appl.* **2001**, *11*, 111–127. [CrossRef]
5. Prestemon, J.P.; Butry, D.T. Time to burn: Modeling wildland arson as an autoregressive crime function. *Am. J. Agric. Econ.* **2005**, *87*, 756–770. [CrossRef]

6. Chang, Y.; Zhu, Z.; Bu, R.; Chen, H.; Feng, Y.; Li, Y.; Hu, Y.; Wang, Z. Predicting fire occurrence patterns with logistic regression in Heilongjiang Province, China. *Landsc. Econ.* **2013**, *28*, 1989–2004. [CrossRef]
7. Li, S.; Wu, Z.; Liang, Y.; He, H.S. Drivers of human-caused fire occurrence and its variation trend under climate change in the Great Xing' an Mountains, Northeast China. *Chin. J. Appl. Ecol.* **2017**, *28*, 210–218.
8. Xanthopoulos, G.; Ghosn, D.; Kazakis, G. Investigation of the wind speed threshold above which discarded cigarettes are likely to be moved by the wind. *Int. J. Wildland Fire* **2006**, *15*, 567–576. [CrossRef]
9. *1991–1997 Wildland Fire Statistics*; USDA Forest Service, Fire and Aviation Management: Washington, DC, USA, 1998.
10. Zhang, Y.L.; Zhang, H.; Jin, S. Study on probability of *Pinus koraiensis* needles fire lighted by burning cigarette end based on Logistic regression. *J. Cent. South Univ. For. Technol.* **2005**, *35*, 45–51.
11. Hoffheins, F.M. Fire hazard tests with cigarettes. *J. Frankl. Inst.* **1933**, *216*, 777–778.
12. Markalas, S. Laboratory experiments on the roll of burning cigarette-ends as ignition cause of forest fires. *Criminol. Public Policy* **1985**, *3*, 139–160.
13. Satoh, K.; Zhong, Y.L.; Yang, K.T. *Report of National Research of National Research Institute of Fire and Disaster*; Japan Society of Mechanical Engineers: Tokyo, Japan, 2003.
14. Dainer, J. Can Cigarette Butts Start Bushfires? Ph.D. Thesis, University of Technology, Syndey, Australia, 2003.
15. Countryman, C.M. *Ignition of Grass by Cigarettes*; Forest Service Contract 43-9AD6-1-617; Pacific Southwest, Forest and Range, Experiment Station: Riverside, CA, USA, 1982.
16. Countryman, C.M. Ignition of grass fuels by cigarettes. *Fire Manag. Notes* **1983**, *44*, 3–7.
17. Lawson, B.B.; Frandsen, W.E.; Hawkes, B.C.; Dairymple, G.N. *Probability of Sustained Smoldering Ignition for Some Boreal Forest Types*; Natural Resources Canada, Canadian Forest Service, Northern Forestry: Edmonton, AB, Canada, 1997.
18. Lautenberger, C.; Fernandez-Pello, A.C. Modeling ignition of combustible fuel beds by embers and heated particles. *For. Fires* **2008**. Available online: http://cpl.berkeley.edu/publications/lautenberger_forest_fires_2008.pdf (accessed on 25 June 2017).
19. Manzello, S.L.; Cleary, T.G.; Shields, J.R.; Yang, J.C. On the ignition of fuel beds by firebrands. *Fire Mater.* **2010**, *30*, 77–87. [CrossRef]
20. Hadden, R.M.; Scott, S.; Lautenberger, C.; Fernandez-Pello, A.C. Ignition of Combustible Fuel Beds by Hot Particles: An Experimental and Theoretical Study. *Fire Technol.* **2011**, *47*, 341–355. [CrossRef]
21. Ellis, P. The likelihood of ignition of dry-eucalypt forest litter by firebrands. *Int. J. Wildland Fire* **2015**, *24*, 225–235. [CrossRef]
22. Blackmarr, W.H. *Moisture Content Influences Ignitibility of Slash Pine Litter*; USDA Forest Service, Southeastern Forest Experimental Station: Washington, DC, USA, 1972.
23. Albini, F.A. *Stop Fire Distance from Burning Trees, a Predictive Model*; General Technology Report INT-56; USDA Forest Service, Intermountain Forest and Range Experiment Station: Washington, DC, USA, 1979.
24. Plucinski, M.P.; Anderson, W.R. Laboratory determination of factors influencing successful point ignition in the litter layer of shrubland vegetation. *Int. J. Wildland Fire* **2008**, *17*, 628–637. [CrossRef]
25. Chuvieco, E.; González, I.; Verdú, F.; Aguado, I.; Yebra, M. Prediction of fire occurrence from live fuel moisture content measurements in a Mediterranean ecosystem. *Int. J. Wildland Fire* **2009**, *18*, 430–441. [CrossRef]
26. Ellis, P. Fuelbed ignition potential and bark morphology explain the notoriety of the eucalypt messmate 'stringybark' for intense spotting. *Int. J. Wildland Fire* **2011**, *20*, 897–907. [CrossRef]
27. Keetch, J. *Smoker Fires and Fire Brands*; USDA Forest Service, Applacachian Forest Experimental Station Technical: Washington, DC, USA, 1941.
28. Bunting, S.C.; Wright, H.A. Ignition Capabilities of Non-Flaming Firebrands. *J. For.* **1974**, *72*, 646–649.
29. Ellis, P. The Aerodynamic and Combustion Characteristics of Eucalypt Bark: A Firebrand Study. Ph.D. Thesis, Australian National University, Canberra, Australia, 2000.
30. Manzello, S.L.; Cleary, T.G.; Shields, J.R.; Yang, J.C. Ignition of mulch and grasses by firebrands in wildland-urban interface fires. *Int. J. Wildland Fire* **2006**, *15*, 427–431. [CrossRef]
31. Ganteaume, A.; Lampinmaillet, C.; Guijarro, M.; Hernando, C.; Jappiot, M.; Fonturbel, T.; Vega, J.A. Spot fires: Fuel bed flammability and capability of firebrands to ignite fuel beds. *Int. J. Wildland Fire* **2009**, *18*, 951–969. [CrossRef]

32. Bianchi, L.O.; Defosse, G.E. Ignition probability of fine dead surface fuels in native Patagonia forests of Argentina. *For. Syst.* **2014**, *23*, 129–138.
33. Chu, T.F. Study on Fire Behavior of Fuel Bed of Mongolian Oak Broadleaf Under No-Wind and Zero-Slope Conditions Thesis. Master's Thesis, Northeast Forest University, Harbin, China, 2011.
34. Luke, R.H.; Mcarthur, A.G. Bush fires in Australia. *Eur. J. Surg. Oncol.* **1978**, *22*, 354–358.
35. Frandsen, W.H. Ignition probability of organic soils. *Can. J. For. Res.* **1997**, *27*, 1471–1477. [CrossRef]
36. De Groot, W.J.; Wardati; Wang, Y. Calibrating the fine fuel moisture code for grass ignition potential in Sumatra, Indonesia. *Int. J. Wildland Fire* **2005**, *14*, 161–168. [CrossRef]
37. Garcia, C.V.; Woodard, P.M.; Titus, S.J.; Adamowicz, W.L.; Lee, B.S. A logit model for predicting the daily occurrence of human caused forest-fires. *Int. J. Wildland Fire* **1995**, *5*, 101–111. [CrossRef]
38. Andrews, P.L.; Loftsgaarden, D.O.; Bradshaw, L.S. Evaluation of fire danger rating indexes using logistic regression and percentile analysis. *Int. J. Wildland Fire* **2003**, *12*, 213–226. [CrossRef]
39. Martínez, J.; Vega-Garcia, C.; Chuvieco, E. Human-caused wildfire risk rating for prevention planning in Spain. *J. Environ. Manag.* **2009**, *90*, 1241–1252. [CrossRef] [PubMed]
40. Pérezgorostiaga, P.; Vega, J.A.; Fonturbel, M.T.; Guijarro, M.; Hernando, C.; Diez, C.; Martinez, E.; Cabaret, C.L.; Blanc, L.; Colin, P.Y. Capability of ignition of some forest firebrands. In *Forest Fire Research and Wildland Fire Safety: Proceedings of IV International Conference on Forest Fire Research/2002 Wildland Fire Safety Summit, Coimbra, Portugal, 18–23 November 2002*; IOS Press: Amsterdam, The Netherlands, 2002.
41. Zhang, Y.L. Burn Probability of Fuelbed Composed of Mongolian Oak and Pinus Koraiensis Leaf Ignited by Cigarette Ends. Master's Thesis, Northeast Forest University, Harbin, China, 2016.