*forests*

MDPI

*Article*

# Predicting the Integrated Fire Resistance of Wildland–Urban Interface Plant Communities by Spatial Structure Analysis Learning for Shanghai, China

**Manqing Yao, Deshun Zhang *, Ruilin Zhu, Zhen Zhang and Mohamed Elsadek**

College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China; 2110314@tongji.edu.cn (M.Y.); 2030156@tongji.edu.cn (R.Z.); zhang_zhen@tongji.edu.cn (Z.Z.); elsadek_m@tongji.edu.cn (M.E.)

* Correspondence: zds@tongji.edu.cn

**Abstract:** Fire is a prevalent hazard that poses a significant risk to public safety and societal progress. The continuous expansion of densely populated urban areas, exacerbated by global warming and the increasing intensification of urban heat islands, has led to a notable increase in the frequency and severity of fires worldwide. Incorporating measures to withstand different types of calamities has always been a crucial aspect of urban infrastructure. Well-designed plant communities play a pivotal role as a component of green space systems in addressing climate-related challenges, effectively mitigating the occurrence and spread of fires. This study conducted field research on 21 sites in the green belt around Shanghai, China, quantifying tree morphological indexes and coordinate positions. The spatial structure attributes of different plant communities were analyzed by principal component analysis, CRITIC weighting approach, and stepwise regression analysis to build a comprehensive fire resistance prediction model. Through this research, the relationship between community spatial structures and fire resistance was explored. A systematic construction of a prediction model based on community spatial structures for fire resistance was undertaken, and the fire resistance performance could be quickly judged by easily measured tree morphological indexes, providing valuable insights for the dynamic prediction of fire resistance. According to the evaluation and ranking conducted by the prediction model, the *Celtis sinensis*, *Sapindus saponaria*, *Osmanthus fragrans*, *Koelreuteria paniculata*, and *Distylium racemosum* + *Populus euramericana* 'I-214' communities exhibited a high level of fire resistance. On the other hand, the *Koelreuteria bipinnata* + *Ligustrum lucidum*, *Ginkgo biloba* + *Camphora officinarum* + *Ligustrum lucidum*, and *Ligustrum lucidum* + *Sapindus saponaria* communities obtained lower scores and were positioned lower in the ranking. It is emphasized that the integration of monitoring and regulation is essential to ensure the ecological integrity and well-being of green areas in the Wildland–Urban Interface.

**Keywords:** urban greening; plant community; fire resistance; spatial structure; prediction model; surface litter

check for updates

**Citation:** Yao, M.; Zhang, D.; Zhu, R.; Zhang, Z.; Elsadek, M. Predicting the Integrated Fire Resistance of Wildland–Urban Interface Plant Communities by Spatial Structure Analysis Learning for Shanghai, China. *Forests* **2024**, *15*, 1266. https://doi.org/10.3390/f15071266

Academic Editor: Mariusz Ciesielski

Received: 13 June 2024
Revised: 9 July 2024
Accepted: 10 July 2024
Published: 20 July 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

According to Global Climate Models (GCMs), a prevailing forecast for the year 2050 indicates a shift toward predominantly subtropical climates in most cities, with urban areas in tropical regions experiencing increased aridity [1]. Approximately 22 percent of these tropical cities are expected to face unprecedented climatic circumstances [2,3]. This anticipated climate change brings forth challenges such as heightened temperatures, frequent heat waves, reduced rainfall, and increased humidity, all of which contribute to an elevated risk of fires [4].

The ramifications of these climate conditions are particularly pronounced in densely urbanized areas of Chinese cities, where extensive architectural development amplifies susceptibility to fire dangers [5,6]. In this context, the Wildland–Urban Interface (WUI)

emerges as a significant focus, as greenery in these areas is particularly vulnerable due to the abundance of combustible materials and inadequate management methods [7–9]. Notably, the incidence of fires in the WUI of Shanghai surpasses that in the central metropolitan area, with suburban areas experiencing a disproportionately higher rate of fatalities and injuries resulting from these fires [10,11].

Landscape greening plays a crucial role in urban ecosystems offering multifaceted functions, including the creation of spaces crucial for disaster mitigation and risk reduction. The resilience of plant communities to the adverse effects of fire is categorically divided into two main classifications: fire resistance and fire tolerance [12]. Fire resistance refers to the ability to prevent the initiation and propagation of flames [13]. Given the escalating complexity of climate conditions, the significance of fire resistance for plant communities in the Wildland–Urban Interface (WUI) is heightened. The manifestation of fire resistance primarily occurs through a variation in species composition and spatial structure. Species classified as fire-resistant utilize various morphological features to shield essential tissues from thermal damage, thereby achieving a robust defense against fire [14,15]. Additionally, a community's spatial structure exerts influences over burning conditions, including the microclimate, ground cover plants, litterfall, and the vertical continuity of fuels. These factors collectively impact the extent of fire damage [16,17] (Figure 1).

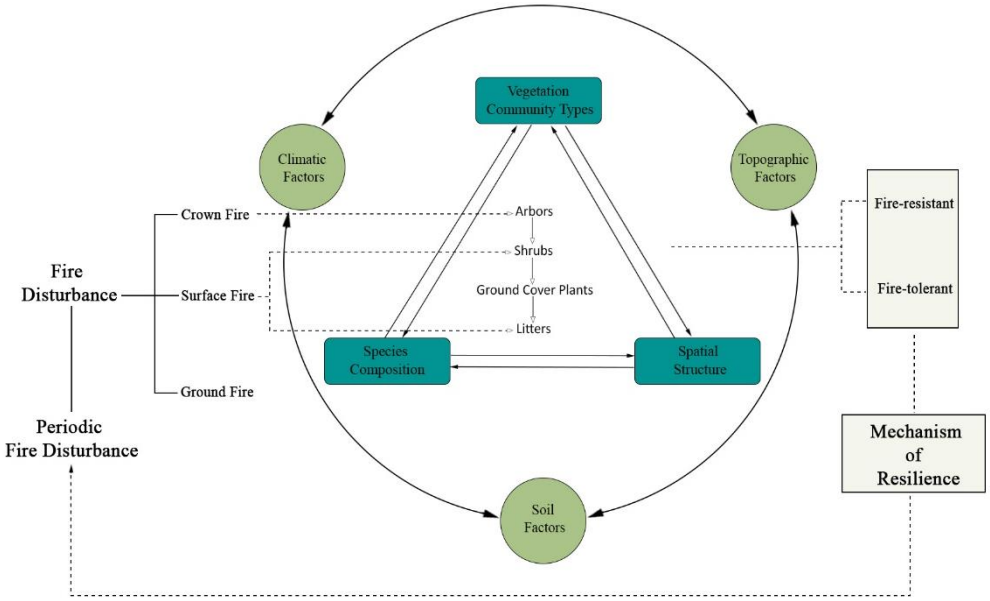



**Figure 1.** Factors shaping plant community development: influence of climate, soil, and terrain in fire-prone environments. In regions with hot and dry climates, characterized by high-temperature heatwaves and droughts with minimal rainfall, plant communities have evolved a resilience mechanism. This mechanism involves regulating the species composition, spatial structure, and community types in response to frequent fire disturbances. The plants develop characteristics that make them resistant to fire and well adapted to fire-prone environments.

Research on plant fire resistance is currently categorized into three scales: the microscopic species size, the mesoscopic community scale, and the macroscopic landscape scale. At the species scale, there is a predominant focus on the examination of fire-resistant tree species, a subject that has undergone extensive study and yielded significant results. These findings have been successfully applied in the establishment of fire-resistant forest belts and disaster-preventive green spaces, leading to substantial outcomes [18,19]. Moving to the landscape-scale, the analysis considers patches as the smallest unit of examination [20,21]. Within these patches, plants are indirectly characterized using landscape indices. Researchers explore how the distribution of landscape patches affects the occurrence and spread of forest fires [22].

Community-scale studies play a crucial role in bridging the gap between individual species and landscapes, and their significance should not be underestimated [23]. A plant community, an organized grouping of all the plants in a specific region, functions as a dynamic equilibrium system where individual plants are interconnected and influenced by their synergistic environment [24–26]. The spatial arrangement of various plant individuals within the community alters the microclimate conditions for combustion, and the combustion properties of mixed combustibles differ from those of individual components [27,28].

Currently, the community focus primarily revolves around species composition and specific characteristics related to stand structure. Researchers have examined the relationship between the community's spatial structure and the quality of combustibles [29–31]. However, existing indicators are insufficient in accurately representing community features. Therefore, additional screening is essential to develop a thorough evaluation system for community fire resistance. Scholars have endeavored to identify intuitive, straightforward indicators. For instance, a prediction model has been developed to assess the potential combustibility of a community, considering independent variables such as environmental factors and spatial structure factors [32]. Recently, there has been a growing interest among researchers to develop a model capable of accurately assessing the fire resistance of plant communities through simple measurements and visual observation.

The present study intends to investigate plant communities and their potential to bolster fire resistance within the WUI green belt in light of climate change. Through the examination of plant communities in the green belt surrounding Shanghai and surrounding spatial structure data, we assessed the fire-resistant capabilities of these communities. The assessment focused on three key elements: the quality of surface litter, spatial structural attributes, and combustion properties. We developed a comprehensive prediction model for fire resistance in these plant communities, primarily utilizing their spatial structure as a foundation. This model employs easily quantifiable tree morphological indicators to evaluate the fire resistance of a community. It eliminates the need for laborious measurements and combustion experiments conducted on surface litter.

## 2. Materials and Methods

### 2.1. Study Site

The study areas are located in Shanghai (30°40′−31°53′ N,120°52′−122°12′ E), a megacity in eastern China, characterized by a mean elevation of approximately 4 m. The region experiences a subtropical monsoon climate (Cfa type) with distinctive four-season patterns. The average annual temperature is 17.6 °C, accompanied by an average annual rainfall of 1586.5 mm. Summers in Shanghai, typically from June to September, have average temperatures ranging from 28 °C to 33 °C (82 °F to 91 °F), and can face occasional dry spells, with limited rainfall and high temperatures. During winter, Shanghai has relatively low rainfall and experiences cooler temperatures with mainly showers, while persistent rain is rare.

Twenty-one representative arboreal communities, characterized by high occurrence and undisturbed condition, were chosen in the Shanghai city green belt (Figure 2). The green belt (S20) in the 1990s, spanning 97 km with a planned area of 7241 $hm^2$, serves as the foundation for the establishment. The vegetation primarily consists of trees, and the plant community has achieved stability following an extended period of renewal and succession. Deciduous broad-leaved forests and evergreen broad-leaved forests dominate the area, with an occurrence frequency exceeding 70%. These communities consist of 18 different arboreal species distributed among 14 groups, as detailed in Table 1. The selection criteria for plots were as follows: (1) Inclusion communities commonly found in the green belt surrounding Shanghai city, spanning coniferous, evergreen broad-leaved, deciduous, evergreen broad-leaved mixed, and deciduous broad-leaved forests. (2) The chosen communities exhibited a pristine condition without noticeable signs of human intervention, such as debris clearing, branch and leaf trimming, fertilizer addition, and soil tillage, among other activities. (3) The tree growth within the communities was consistently

robust and healthy, seen by the examination of the growth of the tree's trunk, leaves, bark, and crown, while also considering the presence of pests and diseases. (4) The geomorphic characteristics of the communities consistently displayed a level landscape without noticeable slopes at a specific distance from aquatic bodies.

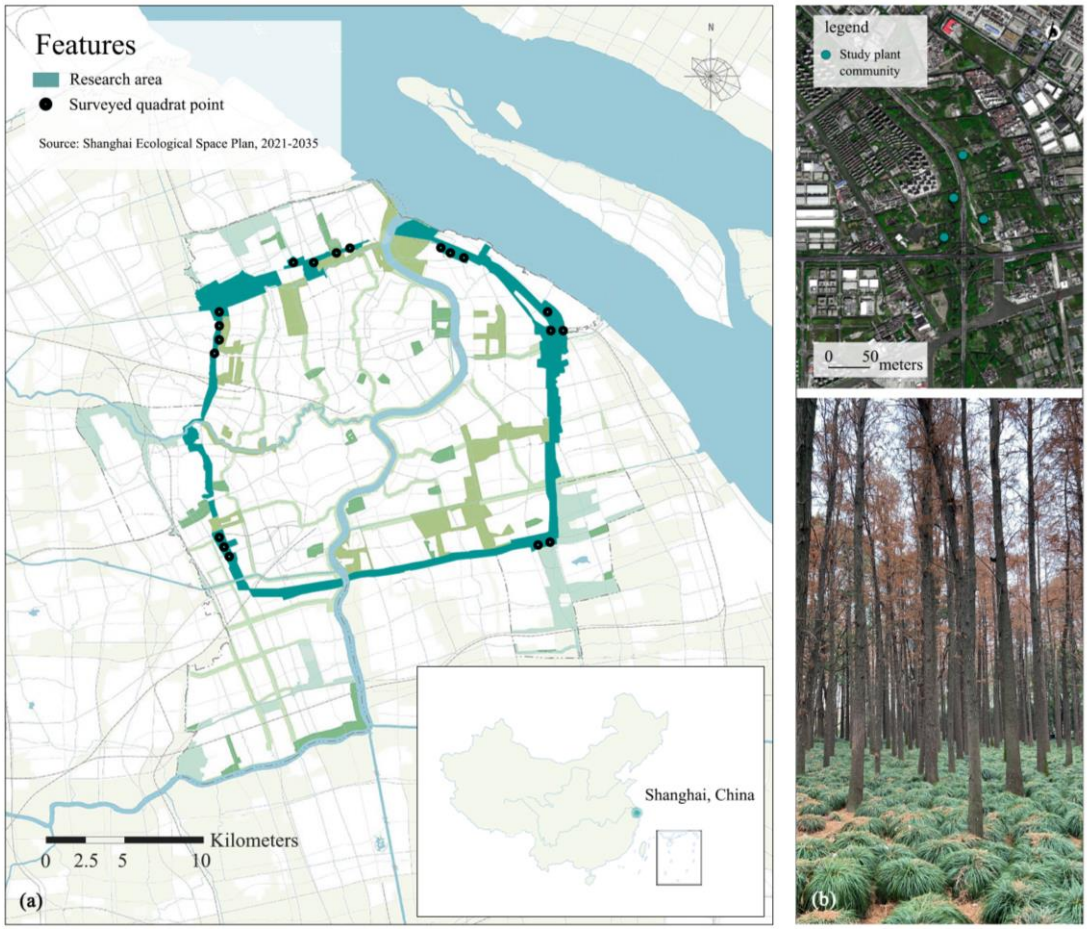



**Figure 2.** The visualization of (**a**) Map of research area and (**b**) Examples of study plant communities and on-site photos in green belt of Shanghai—dominated by deciduous and evergreen broadleaf forests.

### *2.2. Experiment and Measurement Methods*

#### 2.2.1. Plant Community Research Methods

A field survey was conducted from January to March 2022 to collect data from twenty-one representative communities. At the community level, 15 m × 15 m quadrats were established as samples to assess the extent of the green belt surrounding Shanghai. Within these quadrats, the positions of all trees were recorded, along with five indicators: the diameter at breast height (DBH), the diameter at ground level (DGL), the crown breadth, the tree height, and the branch height. Using the gathered data, eight indicators were computed: tree density, crown density, basal coverage, the average DBH, the average DGL, the average crown breadth, the average tree height, and the average branch height.

Tree height: using a laser rangefinder to measure the height of the tree from the ground root to the treetops.

Branch height: the height of a tree from the ground root to the first branching point.

Crown breadth: using the vertical visual method, using a tape measure to read the canopy width of the tree.

DBH: using a tape measure to read the diameter of the trunk of the tree at a height of about 1.3 m above the ground.

DGL: using a tape measure to read the width of a tree's stem at the horizontal position where it meets the ground.

**Table 1.** Basic information of studied communities and major species.

| Serial No. | Plant Community Name | Dominate Tree (Latin Name) | Life Forms (Arbor) |
|---|---|---|---|
| 1 | *Taxodium distichum* | *Taxodium distichum* | Deciduous/Coniferous |
| 2 | *Taxodium distichum* var. *imbricatum* | *Taxodium distichum* var. *imbricatum* | Deciduous/Coniferous |
| 3 | *Liquidambar formosana* + *Pterocarya stenoptera* | *Liquidambar formosana*<br>*Pterocarya stenoptera* | Deciduous/Broad-leaved<br>Deciduous/Broad-leaved |
| 4 | *Zelkova serrata* | *Zelkova serrata* | Deciduous/Broad-leaved |
| 5<br>6 | *Celtis sinensis*-A<br>*Celtis sinensis*-B | *Celtis sinensis*- | Deciduous/Broad-leaved |
| 7<br>8 | *Sapindus saponaria*-A<br>*Sapindus saponaria*-B | *Sapindus saponaria* | Deciduous/Broad-leaved |
| 9 | *Acer buergerianum* | *Acer buergerianum* | Deciduous/Broad-leaved |
| 10 | *Koelreuteria paniculata* | *Koelreuteria paniculata* | Deciduous/Broad-leaved |
| 11 | *Ginkgo biloba* | *Ginkgo biloba* | Deciduous/Coniferous |
| 12 | *Ginkgo biloba* + *Camphora officinarum* + *Ligustrum lucidum* | *Ginkgo biloba*<br>*Camphora officinarum*<br>*Ligustrum lucidum* | Deciduous/Coniferous<br>Evergreen/Broad-leaved<br>Evergreen/Broad-leaved |
| 13 | *Distylium racemosum* + *Populus euramericana* 'I-214' | *Distylium racemosum*<br>*Populus euramericana* 'I-214' | Evergreen/Broad-leaved<br>Deciduous/Broad-leaved |
| 14 | *Elaeocarpus decipiens* + *Liriodendron chinense* | *Elaeocarpus decipiens*<br>*Liriodendron chinense* | Evergreen/Broad-leaved<br>Deciduous/Broad-leaved |
| 15 | *Ligustrum lucidum* + *Sapindus saponaria* | *Ligustrum lucidum*<br>*Sapindus saponaria* | Evergreen/Broad-leaved<br>Deciduous/Broad-leaved |
| 16 | *Koelreuteria bipinnata* + *Ligustrum lucidum* | *Koelreuteria bipinnata*<br>*Ligustrum lucidum* | Deciduous/Broad-leaved<br>Evergreen/Broad-leaved |
| 17 | *Firmiana simplex* + *Ligustrum lucidum* | *Firmiana simplex*<br>*Ligustrum lucidum* | Deciduous/Broad-leaved<br>Evergreen/Broad-leaved |
| 18<br>19 | *Osmanthus fragrans*-A<br>*Osmanthus fragrans*-B | *Osmanthus fragrans* | Evergreen/Broad-leaved |
| 20 | *Camphora officinarum* | *Camphora officinarum* | Evergreen/Broad-leaved |
| 21 | *Ligustrum lucidum* | *Ligustrum lucidum* | Evergreen/Broad-leaved |

The study site is located in the green belt of Shanghai and is mainly covered by trees. The plant community in this area has reached a stable state after a long period of renewal and succession since the completion of the forest belt project [33,34]. The dominant types of trees in this area are deciduous broadleaf forests and evergreen broadleaf forests, with both types occurring more than 70% of the time [35].

#### 2.2.2. Surface Litter Quality Indicator Collection Methods

Within each quadrat, mechanical sampling was performed to identify the central point of a 3 m × 3 m grid. The grid encloses a rectangle of 1 m by 1 m, serving as the reference square (Figure 3a). An on-site electronic scale with a precision of 1 g was used to measure and record the weight of surface litter in the designated square. The weight of surface litter in the eight adjacent quadrats measuring 1 m × 1 m was calculated by multiplying the weight of the reference square by the quality factor (Figure 3b). The quality factor was determined through an assessment of the geographical distribution and thickness of the surface litter. To ensure the accuracy of the quality factor, a random selection of 6–7 sets of measurements were taken and modified for each quadrat of 15 m × 15 m.

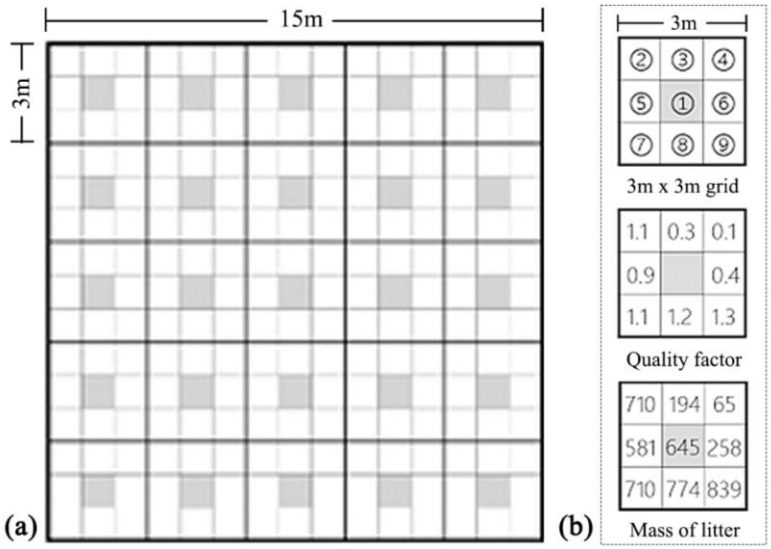



**Figure 3.** The visualization of (**a**) The central point of a 3 m × 3 m grid was selected and a 1 m × 1 m area was framed as a reference square to collect and weigh the mass of surface litter and (**b**) Take the *Camphora officinarum* community as an example.

The samples obtained from the plot were initially weighed and subsequently placed into a drying oven set at 85 °C. Once the samples reached a stable weight after drying, they were reweighed. The moisture content of the samples was determined through the following computation:

$$R = \frac{W_A - W_a}{W_A} \times 100 \quad (1)$$

where

$R$ is the moisture content,
$W_A$ is the total weight of the sample before drying (in grams),
$W_a$ is the total weight of the sample after drying (in grams).

2.2.3. Techniques for Assessing Spatial Structure Indicators

The origin coordinates were recorded using a GPS locator, with the reference point being the bottom left corner of each 15 m × 15 m quadrat. The coordinates of each arborvitae were subsequently quantified using a relative coordinate system. The distance between the two arborvitae was determined using their coordinates and computed using Equation (2). This calculation was carried out to analyze the distribution characteristics of individuals within the plant community.

$$L_i = \sqrt[2]{(x_a - x_b)^2 + (y_a - y_b)^2} \quad (2)$$

where

$L_i$ is the distance (m) between arbor-a and arbor-b,
$x_a$ and $y_a$ are arbor-a's horizontal and vertical coordinates, respectively.
$x_b$ and $y_b$ are the horizontal and vertical coordinates of arbor-b, respectively.

2.2.4. Techniques for Determining Combustion Indicators

The samples underwent drying and crushing, with a 1 g portion selected for combustion experiments on the litter. The experiments were conducted using a ZDHW-10A microcomputer high-precision calorimeter with a heat capacity of 10,169 J. Three replications were performed for each tree species of litter, and the average value was calculated.

Combustion experiments were conducted separately for each tree species, measuring the combustion indexes of the surface litter for different tree species. In the pure forest com-

munity, the combustion properties of the surface litter aligned with those of the individual tree species. In the mixed forest, the burning indexes of the community's surface litter were determined based on the quality ratios of the surface litter of different tree species.

### 2.3. Data Analysis Methods

Pearson correlation analysis and principal component analysis (PCA) were employed in this study to identify the primary elements influencing the geographical structure of plant communities [36]. Eight indicators of the spatial structure of plant communities were thoroughly examined.

The CRITIC method (criteria importance through inter-criteria correlation) is employed to determine the objective weights of indicators, using the conflict between the contrast intensity and evaluation indicators. Contrast intensity is represented by the standard deviation, indicating the variability of data. A higher standard deviation reflects greater data variability, leading to a higher weight. The conflict between evaluation indicators is based on their correlation. A strong positive correlation between measurement indicators indicates lower conflict, resulting in a lower weight. Therefore, to establish a comprehensive evaluation system for fire resistance, the CRITIC weighting approach was used to assign weights to the indicators for the three components of community fire resistance [37]. This step laid the foundation for a thorough assessment.

Stepwise regression analysis is a method commonly employed in multivariate regression analysis to establish optimal or suitable regression models, enabling a more in-depth exploration of the dependency relationships between variables. This approach is straightforward and yields regression equations with fewer variables, while retaining the most significant ones that exert substantial influence. In practice, it has proven to be effective, exhibiting high predictive accuracy. Additionally, given the interrelationships among variables in this study, stepwise regression helps mitigate multicollinearity to a certain extent. A sequential regression analysis was conducted by integrating the correlation between the key factors defining the spatial structure of the communities and the comprehensive evaluation system of fire resistance [38]. This analytical approach facilitated the development of a predictive model for plant community fire resistance. The last step involved constructing a prediction model for plant community fire resistance. This was achieved by combining the correlation between the primary factors describing the community's spatial structure and the entire fire resistance evaluation system, using a stepwise regression analysis.

SPSS 26.0 was used for statistical analysis of the data, and Origin2021 was used for graph drawing.

## 3. Results

### 3.1. Correlation Analysis of Spatial Organization Indicators in Plant Communities

The examination of the spatial structure of the community, encompassing tree density, crown density, basal coverage, DBH, DGL, crown breadth, tree height, and branch height, utilized the Pearson correlation coefficient model. The analysis revealed a significant correlation among these indicators as depicted in Figure 4.

The eight indicators mentioned above were thoroughly reduced in scale to extract the primary variables characterizing the geographical organization of the community. An initial utility test of PCA was conducted. According to the results of the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's sphericity test (Table S1), the KMO value is 0.633, more significant than the threshold of 0.5. The $p$-value is less than 0.05, indicating a significant correlation between the indicators with no covariance. These findings affirm the fulfillment of basic assumptions of PCA and the reliability of the extracted principal components.

The results of the PCA are detailed in Table S2. The eigenvalues of the first three components were all greater than 1, indicating a strong ability to comprehend the original data. Characterizing the spatial structure of the plant community involved extracting these first three principal components, which accounted for 37.246%, 30.303%, and 23.989% of the variance, respectively. The cumulative variance of the principal components was

91.538%, suggesting that they captured most of the characteristics of the community's spatial structure. The variance contribution of the significant components was 37.246%, 30.30%, and 23.9893%, respectively. The cumulative variance explained by these components was 91.538%, indicating their significant role in capturing the essence of the community's spatial structure.

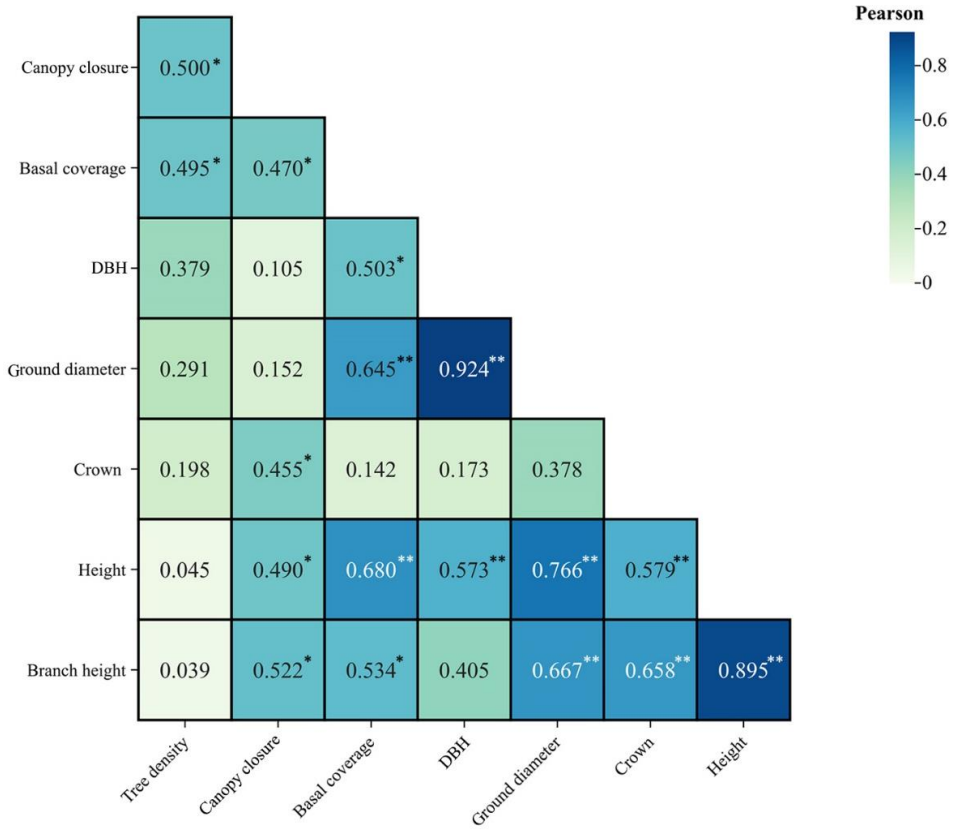



**Figure 4.** Correlation diagram of community spatial structure index. All values followed by * are significantly different at $p \leq 0.05$, and by ** are significantly different at $p \leq 0.01$.

The initial experimental data were subjected to factorial axis rotation to distribute the loadings across the three common components. The original matrix was subsequently rotated using the Kaiser normalized maximum variance approach. The results obtained after five iterations are presented in Table 2.

**Table 2.** Rotated component.

| | Component | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| DBH ($X_1$) | 0.949 | 0.034 | −0.219 |
| Ground diameter ($X_2$) | 0.936 | 0.307 | −0.080 |
| Basal coverage ($X_3$) | 0.696 | 0.147 | 0.668 |
| Height ($X_4$) | 0.661 | 0.647 | 0.227 |
| Crown ($X_5$) | 0.085 | 0.920 | −0.146 |
| Branch height ($X_6$) | 0.490 | 0.782 | 0.138 |
| Canopy closure ($X_7$) | −0.036 | 0.649 | 0.644 |
| Tree density ($X_8$) | −0.185 | −0.096 | 0.954 |

The metrics with the strongest correlation were DBH and DGL, while the basal cover and tree height also showed a significant correlation. Consequently, the metric $F_1$ was named the stem component. This factor quantifies the girth and elevation of the tree trunks within a community. A higher stem component indicates taller trees in the community, and

more robust tree stems contribute to a greater basal area. The stem component emerges as the primary determinant of the community's spatial organization, encompassing 37.246% of the variance, explaining over one-third of the original index's information.

The crown component, designated as $F_2$, is influenced by several indicators, with crown breadth showing the highest correlation, followed by branch height, crown density, and tree height. This factor measures the size and density of the community canopy. A higher crown component indicates a more extensive canopy length and a denser canopy. Additionally, a higher crown component corresponds to a greater average crown breadth and a higher density of trees in the community.

The metric $F_3$ exhibited strong correlations with tree density, basal coverage, and crown density. Consequently, $F_3$ was designated as the density component. This factor quantifies the abundance and concentration of individuals within a community across three distinct vertical height levels. A higher density component indicates a larger number of trees in the community, a higher density of trees, and superior basal coverage and crown density.

The community's spatial organization can be characterized using the aforementioned equation, incorporating the three composite components.

$$F_1 = 0.949X_1 + 0.936X_2 + 0.696X_3 + 0.661X_4 + 0.085X_5 + 0.490X_6 - 0.036X_7 - 0.185X_8 \quad (3)$$

$$F_2 = 0.034X_1 + 0.307X_2 + 0.147X_3 + 0.647X_4 + 0.920X_5 + 0.782X_6 + 0.649X_7 - 0.096X_8 \quad (4)$$

$$F_3 = -0.219X_1 - 0.080X_2 + 0.668X_3 + 0.227X_4 - 0.146X_5 + 0.138X_6 + 0.644X_7 + 0.954X_8 \quad (5)$$

where $F_1$, $F_2$, and $F_3$ represent the stem, crown, and density components, respectively. $X_1$–$X_8$ represent DBH, DGL, basal coverage, tree height, crown breadth, branch height, crown density, and tree density, respectively.

### 3.2. Assessment of Fire Resistance of a Plant Community

Surface litter, a significant combustible material within the community, profoundly influences the community's fire resistance through its quality characteristics, spatial structure attributes, and combustion properties. To establish a comprehensive evaluation system for the community's fire resistance based on surface litter, a total of 10 indicators were selected from these three aspects (Table 3).

**Table 3.** Indicators for characterizing fire resistance of plant communities from a surface litter perspective.

| Classification of Indicators | Serial Number | Indicator Name | Interpretation of Indicator | Standardized Treatment | Weighting (%) |
|---|---|---|---|---|---|
| Quality Characteristics | $X_1$ | Average Value of the Mass Per Unit Area | The average value of the mass per unit area of surface litter reflects the overall amount of combustible material. | Negative | 10.84 |
| | $X_2$ | Coefficient of Variation | The coefficient of variation reflects the degree of dispersion of the mass of deadfall per unit area. | Positive | 9.22 |
| | $X_3$ | Bias Angle | The bias angle describes the symmetry of the data distribution pattern. | Positive | 8.03 |
| | $X_4$ | Kurtosis | Kurtosis describes how steep the data distribution pattern is. | Positive | 7.17 |
| Spatial Structure Attributes | $X_5$ | Range | Range size can reflect the scale of aggregation of surface litter. | Negative | 12.58 |
| | $X_6$ | Fractal Dimension | The number of subdimensions reflects the degree of spatial heterogeneity of surface litter. | Positive | 11.71 |

**Table 3.** *Cont.*

| Classification of Indicators | Serial Number | Indicator Name | Interpretation of Indicator | Standardized Treatment | Weighting (%) |
|---|---|---|---|---|---|
| Combustion properties | $X_7$ | Calorific Value | The calorific value of combustion is the amount of heat released during the complete combustion of a unit mass of surface litter. | Negative | 8.69 |
| | $X_8$ | Burning Time | The combustion temperature change is the temperature difference between the water tank outside the calorimeter before and after combustion, which reflects the thermal conductivity of the surface litter. | Negative | 11.16 |
| | $X_9$ | Temperature Variation | The combustion temperature change is the temperature difference between the water tank outside the calorimeter before and after combustion, which reflects the thermal conductivity of the surface litter. | Negative | 10.23 |
| | $X_{10}$ | Poor Combustion Index | The incomplete combustion index is the mass ratio of the residue after combustion to the original combustible material. | Positive | 10.36 |

#### 3.2.1. Data Normalization

Using the correlation between indicators positively and negatively influencing community fire resistance, Equation (6) was employed to establish a standard for the indications defining positive community fire resistance, while Equation (7) was employed to standardize the indicators negatively correlated with community fire resistance.

$$x_j = \frac{x_{max} - x_i}{x_{max} - x_{min}} \tag{6}$$

$$x_j = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{7}$$

where $x_j$ represents the value obtained after data normalization, while $x_i$ represents the original value. $x_{max}$ and $x_{min}$ represent the maximum and minimum values of the original data set, respectively.

#### 3.2.2. Determination of Indicator Weights

The weights of the indicators determined using the CRITIC weighting approach in the SPSS platform for community-related data are presented in Table 3.

The fire resistance of quality characteristics ($Y_1$) contributes just 24.09%. However, this is attributed to the limited number of indications in this category, resulting in a relatively low overall weight. On an individual indicator basis, the range holds the most substantial weightage at 12.58%, followed by the fractal dimension with a weightage of 11.71%, ranking second. Both the range and fractal dimension directly impact the potential spread area and the likelihood of surface fires. The spatial structure attributes are crucial in determining the plant community's ability to withstand flames.

A comprehensive assessment system for the fire resistance of plant communities based on surface litter can be established using the following equations:

$$Y_1 = 0.1084X_1 + 0.0922X_2 + 0.0803X_3 + 0.0717X_4 \tag{8}$$

$$Y_2 = 0.1258X_5 + 0.1171X_6 \tag{9}$$

$$Y_3 = 0.0869X_7 + 0.1116X_8 + 0.1023X_9 + 0.1036X_{10} \tag{10}$$

$$Y = Y_1 + Y_2 + Y_3 \tag{11}$$

The variable "Y" represents a plant community's overall score for fire resistance. "$Y_1$", "$Y_2$", and "$Y_3$" represent the fire resistance of quality characteristics, spatial structure attributes, and combustion properties, respectively. "$X_1$" to "$X_{10}$" represent the average value of surface litter mass per unit area, the quality coefficient of variation, the bias angle, kurtosis, range, the fractal dimension, the calorific value, the burning time, temperature variation, and the poor combustion index, respectively.

The fire resistance of the study communities was evaluated using Equations (8)–(11), and the corresponding scores and rankings are presented in Table 4.

**Table 4.** Ranking table of fire resistance evaluation system based on surface litter.

| Plant Community (Latin Name) | Comprehensive Scoring | Scheduling |
|---|---|---|
| ***Liquidambar formosana + Pterocarya stenoptera*** | 0.493 | 6 |
| *Celtis sinensis*-A | 0.481 | 8 |
| *Acer buergerianum* | 0.397 | 15 |
| ***Firmiana simplex + Ligustrum lucidum*** | 0.571 | 1 |
| ***Sapindus saponaria*-B** | 0.545 | 2 |
| ***Koelreuteria bipinnata + Ligustrum lucidum*** | 0.537 | 3 |
| ***Sapindus saponaria*-A** | 0.518 | 4 |
| ***Camphora officinarum*** | 0.499 | 5 |
| *Elaeocarpus decipiens + Liriodendron chinense* | 0.492 | 7 |
| *Ginkgo biloba* | 0.479 | 9 |
| *Ginkgo biloba + Camphora officinarum + Ligustrum lucidum* | 0.474 | 10 |
| *Distylium racemosum + Populus euramericana* 'I-214' | 0.468 | 11 |
| *Koelreuteria bipinnata* | 0.454 | 12 |
| *Ligustrum lucidum + Sapindus saponaria* | 0.413 | 13 |
| *Zelkova serrata* | 0.405 | 14 |
| *Osmanthus fragrans*-A | 0.343 | 16 |
| *Ligustrum lucidum* | 0.338 | 17 |

Note: the plant communities listed in bold font in the table have demonstrated exceptional fire resistance.

### 3.3. Prediction Model of Community Fire Resistance Based on Spatial Structure

Separate scatter plots were generated for the stem component ($F_1$), the crown component ($F_2$), the density component ($F_3$), and the composite scores of the resistant community (Figure S1). Outliers were excluded to facilitate subsequent correlation analysis and the development of a regression model. Notably, the *Taxodium distichum* var. *imbricatum* community, *Celtis sinensis* B community, *Osmanthus fragrans* B community, and *Taxodium distichum* community were excluded from the scoring range. Therefore, after excluding these four communities, 17 experimental communities were chosen for further correlation analysis and the construction of a predictive model.

#### 3.3.1. Correlation Studies: Relationship between Spatial Structure of Plant Communities and Comprehensive Evaluation of Community Fire Resistance

Correlation studies were undertaken to explore the relationship between the spatial structure factors of plant communities—specifically the stem component, the crown component, and the density component (represented by Equations (4)–(6), respectively) and the community fire resistance score based on surface litter as a dependent variable. Both variables are continuous. The results of this analysis are presented in Figure 5. The fire resistance of quality characteristics ($Y_1$), spatial structure attributes ($Y_2$), and combustion properties ($Y_3$) were determined using Equations (9)–(11), respectively.

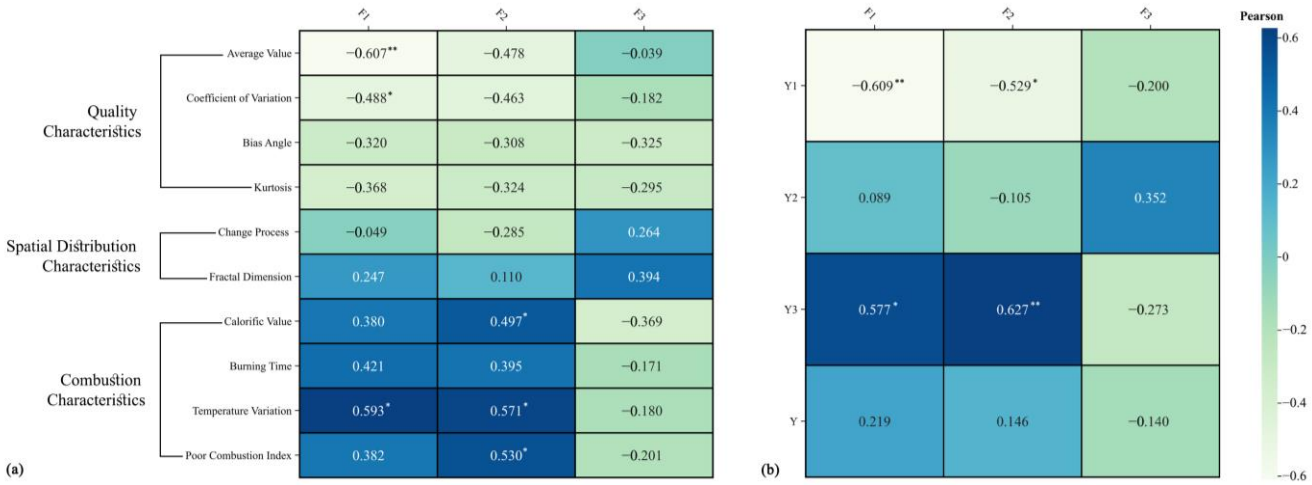



**Figure 5.** The visualization of (**a**) The correlation between community spatial structure and fire resistance indexes. and (**b**) The correlation between community spatial structure and comprehensive evaluation of fire resistance. All values followed by * are significantly different at $p \leq 0.05$, and values followed by ** are significantly different at $p \leq 0.01$.

A robust and statistically significant negative correlation emerged between the stem component ($F_1$) and the fire resistance of quality characteristics ($Y_1$) ($p$ = 0.009, r = −0.609, Figure 5a). Furthermore, this negative correlation extended to all four factors comprising $Y_1$ (Figure 5b). In contrast, the stem component showed a strong and positive correlation with the fire resistance of combustion properties ($Y_3$) ($p$ = 0.015, r = 0.577, Figure 5a), along with positive correlations observed with each of the four characterization elements of $Y_3$ (Figure 5b). Notably, the stem component demonstrated negligible impact on the fire resistance of spatial structure attributes ($Y_2$), as indicated by correlation coefficients with absolute values below 0.2 (Figure 5).

The crown component ($F_2$) exhibited a robust and statistically significant negative correlation with the fire resistance of quality characteristics ($Y_1$) ($p$ = 0.029, r = −0.529, Figure 5a). Furthermore, this negative correlation extended to all four variables comprising $Y_1$ (Figure 5b). Conversely, the crown component demonstrated a strong positive correlation with the fire resistance of combustion properties ($Y_3$) ($p$ = 0.007, r = 0.627, Figure 4), with positive associations observed with all four elements of $Y_3$ to varying extents (Figure 5b). Importantly, there was no significant correlation between the crown component and the fire resistance of spatial structure attributes ($Y_2$), with all absolute correlation coefficients falling below 0.3 (Figure 5).

The density component ($F_3$) exhibited a positive correlation with the fire resistance of spatial structure attributes ($Y_2$). However, this correlation was not statistically significant ($p$ = 0.166, Figure 5a). Furthermore, the density component showed no noteworthy impact on the fire resistance of quality characteristics ($Y_1$) and the fire resistance of combustion properties ($Y_3$), as shown in Figure 5.

#### 3.3.2. Developing a Predictive Model for Community Fire Resistance Based on Spatial Structure

(1) Predictive modeling of the fire resistance of mass characteristics

A linear mathematical model was formulated through stepwise regression analysis to investigate the relationship between the fire resistance of quality characteristics ($Y_1$) and the stem component ($F_1$), the crown component ($F_2$), and the density component ($F_3$).

Based on the data presented in Tables S3 and S4, the most effective model for elucidating the correlation between the spatial structure factor and the fire resistance of quality characteristics ($Y_1$) is a single-variable linear equation, with the stem component ($F_1$) as the independent variable. The adjusted $R^2$ value of 0.329 indicates a moderate level of explained variation in the dependent variable $Y_1$, representing the fire resistance of quality

characteristics. The F statistic of 8.855 and the associated *p*-value of 0.009, which is below the significance level of 0.05, suggest a statistically significant linear correlation between $Y_1$ and the independent variable $F_1$, which represents the stem component. This implies that the stem component ($F_1$) is the only variable capable of explaining the fire resistance of quality characteristics ($Y_1$). A comparative analysis with Pearson's correlation results reveals that the stem component $F_1$ holds the highest significance level as a spatial structural factor associated with the quality feature of fire resistance $Y_1$.

The mathematical representation of the prediction model was deduced based on the information provided in Table S5.

$$Y_1 = 0.206 - 0.065 \times F_1 \quad (12)$$

where $Y_1$ represents the fire resistance of quality characteristics, while $F_1$ represents the stem component of the plant community.

(2) Predictive modeling of the fire resistance of spatial structures

Based on the fitting results presented in Tables S6 and S7, it becomes apparent that the intricate factors influencing the spatial arrangement of surface litter are numerous and cannot be accurately predicted solely based on spatial structure factors. These factors emerge from the complex interplay between plant communities and various living and non-living elements. For a precise prediction model, it is necessary to incorporate additional variables and conduct controlled experiments to thoroughly investigate the impact patterns of plant species, environmental factors, meteorological factors, and more.

A prediction model for the fire resistance of spatial structures was developed based on the data provided in Table S8. The stem component ($F_1$), crown component ($F_2$), and density component ($F_3$) had VIF values of 4.938, 5.062, and 1.077, respectively, indicating weak multicollinearity. Furthermore, these factors were found to be independent of each other. The given mathematical expression was as follows:

$$Y_2 = 0.130 + 0.122 \times F_1 - 0.129 \times F_2 + 0.068 \times F_3 \quad (13)$$

where $Y_2$ denotes the fire resistance of a spatial structure, while $F_1$, the crown component by $F_2$, and the density component by $F_3$ represent the stem component.

The stem component ($F_1$) and the density component ($F_3$) exhibited positive effects on fire resistance, signifying that as these factors increased, the fire resistance also heightened. Additionally, an increased basal cover of trees enhanced the barrier effect against surface fires. Conversely, the crown component had a negative impact; as it increased, there was a stronger tendency for surface litter to be evenly distributed.

(3) Predictive modeling of fire resistance and combustion properties

A linear mathematical model was created using stepwise regression analysis to scrutinize the correlation between the fire resistance of combustion properties ($Y_3$) and the stem component ($F_1$), crown component ($F_2$), and density component ($F_3$). As outlined in Tables S9 and S10, two models were constructed to enhance the understanding of the relationship between the fire resistance of combustion properties and spatial structure factors. Model 1 comprises a one-variable equation with the crown component ($F_2$) as the independent variable, yielding an adjusted $R^2$ of 0.353, an F-statistic of 9.735, and a *p*-value of 0.007 ($p < 0.05$). Model 2, also a one-variable equation, incorporates the crown component ($F_2$) and the density component ($F_3$) as independent variables. With a modified $R^2$ value of 0.542, indicating that the model can explain 54.2% of the variation in the data, an F-statistic of 10.469, and a *p*-value of 0.002 ($p < 0.05$), this model outperforms Model 1. Hence, Model 2, inclusive of the independent variables crown component ($F_2$) and density component ($F_1$), provides a more accurate prediction of fire resistance and combustion properties compared to Model 1.

According to Table S11, the VIF values for the crown component ($F_2$) and the density component ($F_3$) were both $1.074 < 5$, indicating weak multicollinearity between these two

variables and their independence. The mathematical expression for predicting the fire resistance of combustion properties is as follows:

$$Y_3 = 0.131 + 0.096 \times F_2 - 0.078 \times F_3 \quad (14)$$

In the context of the presented formulas, $Y_3$ represents the fire resistance of combustion properties, $F_2$ stands for the crown component, and $F_3$ denotes the density component.

The Pearson correlation analysis did not show a significant correlation between the density component ($F_3$) and the fire resistance of combustion properties ($Y_3$). However, the predictive model indicated an intricate interaction between the density component and the crown component ($F_2$). This interaction exerted both positive and negative influences on the fire resistance of combustion properties ($Y_3$). Specifically, an increase in the crown component ($F_2$) led to an increase in the fire resistance of combustion properties ($Y_3$), while increasing the density component ($F_3$) led to a decrease in the fire resistance of combustion properties ($Y_3$). The model suggests that a community characterized by lower population density, a wider average crown breadth, and a higher proportion of crown length is likely to exhibit superior fire resistance and combustion properties ($Y_3$).

(4) Predictive modeling of the fire resistance of spatial structures

In the context of the overall fire resistance (Y), which is determined by the fire resistance of quality characteristics ($Y_1$), the fire resistance of spatial structure attributes ($Y_2$), and the fire resistance of combustion properties ($Y_3$), the mathematical expression for the combined fire resistance of the spatial structure can be derived using Equations (12)–(15):

$$Y = 0.467 + 0.057 \times F_1 - 0.033 \times F_2 - 0.010 \times F_3 \quad (15)$$

where Y is the comprehensive score of fire resistance. $F_1$ is the stem component, $F_2$ is the crown component, and $F_3$ is the density component.

### 3.4. Assessment of Plant Community Fire Resistance Based on the Prediction Model

The data collected from the field survey were used in predictive modeling to calculate and rank the fire resistance of spatial structures. The results are presented in Table 5. Among the communities studied, the *Celtis sinensis* community, *Sapindus saponaria* community, *Osmanthus fragrans* community, *Koelreuteria paniculata* community, and *Distylium racemosum* + *Populus euramericana* 'I-214' community exhibited a notably high level of fire resistance. On the other hand, the *Koelreuteria paniculate* + *Ligustrum lucidum* community, *Ginkgo biloba* + *Camphora officinarum* + *Ligustrum lucidum* community, and *Ligustrum lucidum* + *Sapindus saponaria* community displayed lower scores, indicating lower fire resistance rankings.

**Table 5.** Scheduling table of community fire resistance based on surface litter and spatial structure.

| Plant Community (Latin Name) | Comprehensive Scoring | Scheduling |
|---|---|---|
| *Liquidambar formosana* + *Pterocarya stenoptera* | 0.462 | 8 |
| ***Celtis sinensis*-A** | 0.470 | 1 |
| *Acer buergerianum* | 0.454 | 14 |
| *Firmiana simplex* + *Ligustrum lucidum* | 0.459 | 11 |
| *Sapindus saponaria*-B | 0.469 | 2 |
| *Koelreuteria bipinnata* + *Ligustrum lucidum* | 0.453 | 15 |
| ***Sapindus saponaria*-A** | 0.459 | 12 |
| *Camphora officinarum* | 0.462 | 9 |
| ***Elaeocarpus decipiens* + *Liriodendron chinense*** | 0.463 | 6 |
| *Ginkgo biloba* | 0.462 | 10 |
| *Ginkgo biloba* + *Camphora officinarum* + *Ligustrum lucidum* | 0.453 | 16 |

**Table 5.** *Cont.*

| Plant Community (Latin Name) | Comprehensive Scoring | Scheduling |
|---|---|---|
| ***Distylium racemosum* + *Populus euramericana* 'I-214'** | 0.465 | 5 |
| ***Koelreuteria bipinnata*** | 0.466 | 4 |
| *Ligustrum lucidum* + *Sapindus saponaria* | 0.452 | 17 |
| *Zelkova serrata* | 0.463 | 7 |
| ***Osmanthus fragrans*-A** | 0.468 | 3 |
| *Ligustrum lucidum* | 0.455 | 13 |

Note: the plant communities listed in bold font in the table have demonstrated exceptional fire resistance.

## 4. Discussion

### *4.1. Investigating the Relationship between Spatial Organization and Fire Resistance*

The results of the Pearson correlation analysis indicate a substantial negative correlation between the stem component ($F_1$) ($p$ = 0.009, r = −0.609), the crown component ($F_2$) ($p$ = 0.029, r = −0.529), and the fire resistance of quality characteristics ($Y_1$) within the plant community. These findings are consistent with prior research. For instance, Ai [39] identified a positive correlation between the quality of surface litter and depression and a significant correlation with average tree height. Similarly, Guo [40] found a positive correlation between the quality of surface litter and the mean DBH and average tree height of the community. Shan [41] developed a linear regression model using the average DBH and the average tree height to predict the quality of surface litter in major forest types in the Greater Khingan Mountains. They observed that surface litter increased with an increase in the average DBH. The observed negative correlation implies that communities with taller trees and greater stem dimensions exhibit lower fire resistance in terms of surface litter quality. This suggests that the structural attributes of individual trees, such as stem size and crown dimensions, play a crucial role in influencing the potential flammability of the surface litter within a plant community.

In our study, we observed a non-significant association between the density component ($F_3$) and the fire resistance of quality characteristics ($Y_1$). Notably, the highest coefficient seen in the density component ($F_3$) was associated with tree density. This finding contrasts with some of the existing literature that proposes a direct proportional relationship between the quality of surface litter and its density [39,41]. Several factors may contribute to these results. Firstly, the majority of the communities under investigation exhibited a density exceeding 0.1 plants per square meter, a crown density surpassing 80%, and canopy projection overlap after crop closure. Additionally, as trees grow beyond a certain threshold, there might be a decrease in leaf weight, potentially influencing surface litter quality. Furthermore, the density component ($F_3$) values estimated for each community exhibited minimal variation, thus indicating a lack of association in the outcomes of the statistical studies.

Strong positive correlations were observed between the stem component ($F_1$), the crown component ($F_2$), and the fire resistance of combustion properties ($Y_3$). The species' structure manifests its ability to adapt to environmental changes [42]. The community's spatial structure, representing the overall structure of the species, can provide insights into its fire resistance performance, either directly or indirectly. Jamie [43] developed a structural equation modeling (SEM) using leaf properties to forecast the combustion properties of the forest surface fuel layer. Li [44] determined the fire resistance ranking of broadleaf evergreen plants by analyzing their functional shape and conducting combustion experiments, resulting in a similarity score of 0.8. Zhang [45] assessed the fire resistance of tree species by examining their combustion properties and morphological features, discovering that the fire resistance rankings obtained from the two evaluation methods were somewhat similar.

The density component ($F_3$) showed a positive correlation with the fire resistance of spatial structure attributes ($Y_2$) and the fractal dimension of the distribution fragmentation

degree of litter. The primary factors influencing the density component ($F_3$) were tree density, basal coverage, and crown density. In Wang's study conducted in 2016 [28], which focused on six primary coniferous forests in southwest Sichuan, China, a positive correlation was found between the community crown density level and the uneven distribution of surface fuel quality. These findings align somewhat with the results of the present study. According to our current survey, the bases of trees in the community acted as barriers, hindering the uninterrupted spread of surface litter. Furthermore, as the density and coverage of tree bases increased, the distribution of surface litter became more fragmented.

There is no statistically significant correlation between variable Y and the stem component ($F_1$), the crown component ($F_2$), and the density component ($F_3$) ($p > 0.3$). This lack of correlation can be attributed to multiple factors influencing the overall assessment of fire resistance in the plant community. There may be intricate interactions among these factors. The impact of a single spatial structure element on the comprehensive evaluation is limited and biased, making it challenging to analyze using the Pearson correlation model [46].

### 4.2. Integrated Fire Resistance Prediction Model of Plant Community Based on Spatial Structure

The fire resistance score of plant communities is determined by analyzing the quality characteristics, spatial structure attributes, and combustion properties of surface litter. This score accurately reflects the actual fire resistance performance of plant communities [47,48]. The study communities' relevant data were incorporated into the fire resistance evaluation system, utilizing surface litter and an integrated fire resistance prediction model based on spatial structure. This allowed for the calculation and ranking of the communities resulting in a similarity degree between the two ranking results of 0.7. This indicates that the fire resistance prediction model based on spatial structure is reasonably reliable for comparing and assessing the fire resistance performance of different plant communities.

In certain communities, such as the *Firmiana simplex* + *Ligustrum lucidum* community and *Koelreuteria paniculate* + *Ligustrum lucidum* community, the model calculation yielded a fire-resistance ranking lower than the observed ranking. This discrepancy can likely be attributed to the heterogeneous spatial structure of trees in these communities, which includes aggregation groups (Figure S2). These groups further impact the fragmentation of surface litter distribution, resulting in a larger fractal dimension of the representation index. Hence, the fire resistance rating derived from surface litter is elevated, leading to a higher grade.

The model's ranking of fire resistance for specific communities, such as the *Osmanthus fragrans* A and *Koelreuteria paniculata* community, was notably higher than the observed fire resistance rating. This is due to the localized and centralized distribution of surface litter in these areas. When a surface fire ignites, it can rapidly propagate within the designated area, posing a significant danger by increasing the likelihood of the fire spreading to adjacent flammable units, exacerbating the overall fire situation. Consequently, the fire resistance rating for this scenario is deemed low [47]. Furthermore, the model's creation relies on the mean value of each community's spatial structure index, leading to the sacrifice of certain information and resulting in significant disparities in the ranking of specific communities.

### 4.3. Limitations of This Study

Plants and habitats outside the quadrats' range can inevitably impact the interior of the quadrat. For instance, wind can carry surface litter from nearby trees and end up inside the quadrat. Animal activities may also disrupt the distribution of surface litter, introducing systematic inaccuracies in data collection. The fire resistance of a community is influenced by several factors, including climate, topography, wind, and the presence of plants and their litter as the primary flammable materials. This study is centered in Shanghai, situated in the flat and low alluvial plain of the Yangtze River Delta. The terrain and landform in this area are relatively uniform, with minimal fluctuations in slope. Therefore, the selected study sites do not exhibit noticeable variations in slope. Nevertheless, it is imperative

to thoroughly examine the role of topography in influencing surface litter dispersion in future research.

### 4.4. Suggestions on the Management of Strengthening the Fire Resistance of WUI Greening

A plant community exhibiting strong fire resistance should incorporate three essential components. Firstly, the plant community should feature a well-defined vertical structure based on elevation, with variations in the DBH, height, and crown breadth of trees. Each stratum should have a high density, resulting in a limited area for tree development. Secondly, the plant community should exhibit a compact and meticulously organized spatial arrangement. The neighborhood should have a moderate population density, with various groups clustered around large canopy trees. Finally, the tree species in the community should demonstrate robust fire resistance. It is advisable to combine flammable species with fire-resistant tree species to enhance overall resistance.

In the low-intensity greening management within WUI areas, it is essential to carefully plan and design the horizontal spatial layout of the community to avoid uniformity in plant specifications and a single distribution form. Additionally, densely planting the chosen plant species is recommended. To maintain the overall ecological stability of the mechanically laid-out community, consideration should be given to the growth status of the community's dominant individuals. If any individuals exhibit poor growth, it is advisable to remove them.

The density of the plant community should be carefully managed throughout its succession. During the initial phase of community development, it is crucial to consider both the DBH and crown breadth of tree species. It is recommended to establish an initial threshold for plant placement to ensure sufficient space for the growth of tree crowns. As the community develops, dynamic density regulation should be implemented to monitor for intense competition among the trees or the ingress of wild species and young seedlings into the community. Thinning can then be performed reasonably based on the growth status of the trees.

## 5. Conclusions

This study aimed to investigate the relationship between the spatial arrangement of plant communities and their resistance to fire, with a specific focus on surface litter. Additionally, a predictive model was developed to predict fire resistance based on spatial structures. The model facilitates accurate forecasts of fire resistance in plant communities, making it practical for the maintenance and administration of urban green areas.

The correlation study revealed the significant impact of the community's spatial organization on fire resistance. The quality characteristics' fire resistance was notably influenced by both the stem and crown components. Communities with more extensive and denser trees exhibited a more consistent surface litter level, increasing the likelihood of fire propagation. Similarly, the combustion property's fire resistance was significantly influenced by both the stem and crown components, where larger trees contributed to reduced heat radiation, shorter burning times, and decreased fire spread probabilities. The density component played a crucial role in influencing the fire resistance of spatial structure attributes, contributing to a more scattered surface litter distribution, and reducing the risk of fire spread. A comprehensive fire resistance prediction model was established using multiple linear regression incorporating three independent variables: the stem component, the crown component, and the density component. The model allows for the rapid assessment of fire resistance using easily measurable tree morphological markers such as the diameter at breast height (DBH), the diameter at ground level DGL), the crown breadth, the tree height, and the branch height. This technique eliminates the need for laborious sequential measurements and combustion studies on surface litter, enabling efficient assessments on a large scale. A direct correlation was observed between fire resistance and the stem component, indicating that increased stem component values enhance community fire resistance. The community's fire resistance declined as the crown

and density components increased. The triad of stem, crown, and density components collectively influenced the fire resistance of plant communities, with the stem component emerging as the most impactful element. Given the escalating threats of fires in green belts at the Wildland–Urban Interface (WUI) due to climate change, urban heat islands, and human activities, incorporating the characteristics of plant communities and fostering ecological resilience in the planning, design, and management stages becomes a crucial strategy to enhance greening's capacity to withstand extreme climatic conditions. Thus, maintaining a focus on climate change and developing landscape plant communities with ecological resilience stands out as an effective approach for sustainable development.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15071266/s1, Figure S1: Scatter plot of community spatial structure factors and fire resistance evaluation. Where F1 is the stem shape factor, F2 is the crown cover factor, F3 is the density factor, Y1 is the mass characteristic fire resistance, Y2 is the spatial distribution fire resistance, and Y3 combustion fire resistance; Figure S2: Plan of a community with aggregated groups of trees; Table S1: KMO and Bartlett's Test; Table S2: Total variance interpretation table of community spatial structure factors; Table S3: Quality fire resistance prediction model explanatory degree; Table S4: Quality fire resistance prediction model variance explanation; Table S5: Quality fire resistance prediction model coefficient; Table S6: Spatial distribution fire resistance prediction model explanatory degree; Table S7: Spatial distribution fire resistance prediction model variance explanation; Table S8: Spatial distribution fire resistance prediction model coefficient; Table S9: Combustion fire resistance prediction model explanatory degree; Table S10: Combustion fire resistance prediction model variance explanation; Table S11: Combustion fire resistance prediction model coefficient.

**Author Contributions:** Conceptualization, M.Y., D.Z. and Z.Z.; methodology, M.Y., D.Z., R.Z. and Z.Z.; software, M.Y. and R.Z.; validation, M.Y. and M.E.; formal analysis, M.Y., Z.Z. and R.Z.; resources, R.Z.; data curation, R.Z.; writing—original draft preparation, M.Y. and R.Z.; writing—review and editing, M.Y., D.Z., and M.E.; visualization, M.Y. and R.Z.; supervision, D.Z.; project administration, D.Z.; funding acquisition, D.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China grant number 32071824 The project is overseen by Deshun Zhang.

**Data Availability Statement:** The original contributions presented in the study are included in the article and Supplementary Material, further inquiries can be directed to the corresponding authors.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Shakeel, M.; Ali, Z. Integration of Exponential Weighted Moving Average Chart in Ensemble of Precipitation of Multiple Global Climate Models (GCMs). *Water Resour. Manag.* **2024**, *38*, 935–949. [CrossRef]
2. Bastin, J.F.; Clark, E.; Elliott, T.; Hart, S.P.; van den Hoogen, J.; Hordijk, I.; Ma, H.; Majumder, S.; Manoli, G.; Maschler, J.; et al. Understanding climate change from a global analysis of city analogues. *PLoS ONE* **2019**, *14*, e0217592.
3. Manzello, S.L.; Suzuki, S. The importance of combustion science to unravel complex processes for informal settlement fires, urban fires, and wildland-urban interface (WUI) fires. *Fuel* **2022**, *314*, 122805. [CrossRef]
4. Ryu, S.R.; Choi, H.T.; Lim, J.H.; Lee, I.K.; Ahn, Y.-S. Post-fire restoration plan for sustainable forest management in South Korea. *Forests* **2017**, *8*, 188. [CrossRef]
5. Price, O.; Bradstock, R. Countervailing effects of urbanization and vegetation extent on fire frequency on the Wildland Urban Interface: Disentangling fuel and ignition effects. *Landsc. Urban Plan.* **2014**, *130*, 81–88. [CrossRef]
6. Zhang, W.H.; Shen, R.F. The summary, logical limitations and countermeasures of urban fire risk cognition. *Syst. Eng. Theory Pract.* **2019**, *39*, 387–396.
7. Enrico, R.; Steven, M.G.; Guillermo, R.; Intini, P.; Wadhwani, P.R. An open multi-physics framework for modelling Wildland-Urban Interface fire evacuations. *Saf. Sci.* **2019**, *118*, 868–880. [CrossRef]
8. Li, H.Q.; Zhang, D.S. Research on fireproof landscape plants: Progress and prospects. *J. Chin. Urban For.* **2022**, *20*, 133–139.
9. Zheng, W.X.; Guo, X.B.; Guo, L.F.; Ma, Y.F.; Guo, F.T. Overview of fire management in the Wildland-Urban Interface of the United States and its enlightenment to China. *Chin. J. Ecol.* **2020**, *39*, 300–307.
10. Li, B.X. Application of aviation fire-fighting capability in urban forest fire fighting—A case study of Xichang "3·30" fire site. *For. Fire Prev.* **2020**, *3*, 37–40.

11. Chui, X.L. Research on the social characteristics of fires and governance in mega cities—Shanghai as an Example. *J. Wuhan Univ. (Philos. Soc. Sci.)* **2016**, *69*, 32–45.
12. Bond, W.J.; Keeley, J.E. Fire as a global 'herbivore': The ecology and evolution of flammable ecosystems. *Trends Ecol. Evol.* **2005**, *20*, 387–394. [CrossRef] [PubMed]
13. Tian, X.R.; Shu, L.F. The application and research of fire break forest belts. *World For. Res.* **2000**, *1*, 20–26.
14. Whelan, R.J. *The Ecology of Fire*; Cambridge University Press: New York, NY, USA, 1995.
15. Debano, L.F.; Neary, D.G.; Folliott, P.F. *Fire's Effects on Ecosystems*; John Wiley & Sons Inc.: New York, NY, USA, 1998.
16. Quintiere, J.G. *Principles of Fire Behavior*; Delmar Publishers: New York, NY, USA, 1998.
17. Zylstra, P.J. Flammability dynamics in the Australian Alps. *Austral Ecol.* **2018**, *43*, 578–591. [CrossRef]
18. Polinova, M.; Wittenberg, L.; Kutiel, H.; Brook, A. Reconstructing pre-fire vegetation condition in the wildland urban interface (WUI) using artificial neural network. *J. Environ. Manag.* **2019**, *238*, 224–234. [CrossRef] [PubMed]
19. Knapp, E.E.; Valachovic, Y.S.; Quarles, S.L.; Johnson, N.G. Housing arrangement and vegetation factors associated with single-family home survival in the 2018 Camp Fire, California. *Fire Ecol.* **2021**, *17*, 25. [CrossRef]
20. Chen, L.; Chen, F.; Niu, S.K.; Li, L.Q.; Tao, C.S. Correlation analysis between the spatial characteristics of landscape pattern and risk of forest fire in Jiufeng Forest Park of Beijing. *J. Beijing For. Univ.* **2021**, *43*, 41–49.
21. Winkler, J.; Malovcová, M.; Adamcovám, D.; Ogrodnik, P.; Pasternak, G.; Zumr, D.; Kosmala, M.; Koda, E.; Vaverková, M.D. Significance of urban vegetation on lawns regarding the risk of fire. *Sustainability* **2021**, *13*, 11027. [CrossRef]
22. Bradstock, R.A.; Cary, G.J.; Davies, I.; Lindenmayer, D.B.; Price, O.F.; Williams, R.J. Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: Insights from landscape-scale simulation. *J. Environ. Manag.* **2012**, *105*, 66–75. [CrossRef]
23. Schwilk, D.W.; Caprio, A.C. Scaling from leaf traits to fire behavior: Community composition predicts fire severity in a temperate forest. *J. Ecol.* **2011**, *99*, 970–980. [CrossRef]
24. Mcpherson, E.G. Accounting for benefits and costs of urban greenspace. *Landsc. Urban Plan.* **1992**, *22*, 41–51. [CrossRef]
25. Busing, R.T.; Mailly, D. Advances in spatial, individual-based modelling of forest dynamics. *J. Veg. Sci.* **2004**, *15*, 831–842. [CrossRef]
26. Fensham, R.J.; Fairfax, R.J.; Butler, D.W.; Bowman, D.M.J.S. Effects of fire and drought in a tropical eucalypt savanna colonized by rain forest. *J. Biogeogr.* **2003**, *30*, 1405–1414. [CrossRef]
27. Schwilk, D.W.; Keeley, J.E.; Knapp, E.E.; McIver, J.; Bailey, J.D.; Fettig, C.J.; Fiedler, C.E.; Harrod, R.J.; Moghaddas, J.J.; Outcalt, K.W.; et al. The national fire and fire surrogate study: Effects of fuel reduction methods on forest vegetation structure and fuels. *Ecol. Appl.* **2009**, *19*, 285–304. [CrossRef] [PubMed]
28. Wang, C. *Fuel Spatial Structure and Potential Fire Behavior of Major Coniferous Forests in Southwest Sichuan, China*; Beijing Forestry University: Beijing, China, 2016.
29. Fujioka, F.M.; Weise, D.R.; Chen, S.C.; Kin, S.H.; Kafatos, M.C. Reaction intensity partitioning: A new perspective of the National Fire Danger Rating System Energy Release Component. *Int. J. Wildland Fire* **2021**, *30*, 351–364. [CrossRef]
30. Viedma, O.; Quesada, J.; Torres, I.; Santis, A.D.; Moreno, J.M. Fire severity in a large fire in a *Pinus pinaster* forest is highly predictable from burning conditions, stand structure, and topography. *Ecosystems* **2015**, *18*, 237–250. [CrossRef]
31. Li, L.Q.; Niu, S.K.; Tao, C.S.; Chen, L.; Chen, F. Correlations between stand structure and surface potential fire behavior of *Pinus tabuliformis* forests in Miaofeng Mountain of Beijing. *J. Beijing For. Univ.* **2019**, *41*, 73–81.
32. Pais, C.; Miranda, A.; Carrasco, J.; Shen, M. Deep fire topology: Understanding the role of landscape spatial patterns in wildfire occurrence using artificial intelligence. *Environ. Model. Softw.* **2021**, *143*, 105122. [CrossRef]
33. Li, Y.; Liu, C.J.; Wang, Y.; Zhou, P.S.; Wu, X.C. Establishment and management of forest greenbelts in urban forest—With Shanghai's forest greenbelt as a case study. *J. Shanghai Jiaotong Univ. (Agric. Sci.)* **2008**, *2*, 168–171.
34. Da, L.J.; Yang, Y.C.; Chen, M. The method of ecological greening and its application in the construction of the approaching nature plant community in Shanghai. *J. Chin. Landsc. Archit.* **2004**, *3*, 41–43.
35. Zhang, K.X. *Study on Community Ecology of Shanghai Green Belt and Ecological Benefits and Aesthetics Assessment of Its Plant Communities*; East China Normal University: Shanghai, China, 2010.
36. Shlens, J. A Tutorial on Principal Component Analysis. *Int. J. Remote Sens.* **2014**, *51*, 1–12.
37. Mishra, P.S.; Muhuri, S. Value assessment of existing architectural heritage for future generation using criteria importance through inter-criteria correlation and grey relational analysis method: A case of Odisha temple architecture in India. *Curr. Sci.* **2021**, *121*, 823–833. [CrossRef]
38. Hayes, A. Introduction to mediation, moderation, and conditional process analysis. *J. Educ. Meas.* **2013**, *51*, 335–337.
39. Ai, Y.B.; Cun, Y.D.; Fan, Y.Q.; Cheng, R.Y.; Yan, H. Factors affecting surface fuel load of *Pinus tabuliformis* forest in Songshan, Beijing. *Chin. J. Ecol.* **2018**, *37*, 2559–2565.
40. Guo, L.F. *Research on Artificial Pinus tabulaeformis Forest Combustibility of Badaling Forest Center in Beijing*; Beijing Forestry University: Beijing, China, 2007.
41. Shan, Y.L.; Shu, L.F.; Li, C.J. A relation between forest combustible parameters and stand characteristics. *J. Nat. Disasters* **2004**, *6*, 70–75.
42. Poorter, L.; Bongers, F.; Sterck, F.J.; Woll, H. Architecture of 53 rain forest tree species differing in adult stature and shade tolerance. *Ecology* **2003**, *84*, 602–608. [CrossRef]

43. Jamie, E.B.; Jane, G.C.; Alex, F.I.; Trent, D.P. Leaf traits predict global patterns in the structure and flammability of forest litter beds. *J. Ecol.* **2021**, *109*, 1344–1355.
44. Li, X.P.; Yang, X.D.; Yu, S.Q.; Yan, E.; Zhang, J.H. Functional trait-based evaluation of plant fireproofing capability for subtropical evergreen broad-leaved woody plants. *Acta Ecol. Sin.* **2013**, *33*, 6604–6613.
45. Zhang, D.S.; Wu, X.; Chen, L.Q.-Y.; Hu, L.H.; Li, K.K.; Zhan, Y.; Yao, C.Y. Combustibility evaluation of 26 landscape tree species in Shanghai. *J. Tongji Univ. (Nat. Sci.)* **2021**, *49*, 1399–1406.
46. Liang, Y.; Li, J.M.; Zhao, F.J.; Kong, T.T.; Nurgul, M. Surface fuel loads of Tianshan spruce forests in the central Tianshan mountains and the impact factors. *Sci. Silvae Sin.* **2017**, *53*, 153–160.
47. Zhu, R.L. *Assessment of Fire Resistance of Plant Community Based on Spatial Structure about Fire Spread: A Case of Shanghai Green Belt*; Tongji University: Shanghai, China, 2023.
48. Zheng, H.N.; Chen, H.H.; Liu, Q.Z. The classification of flammability of forest lands. *Sci. Silvae Sin.* **1988**, *24*, 94–100.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.