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Assessment of Biological and Environmental Factors Influence on Fire Hazard in Pine Forests: A Case Study in Central Forest-Steppe of the East European Plain

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Abstract: Vast forest areas are spreaded in Russia and perform environment-forming, nature-protective and climate-regulating functions, including carbon sequestration. At the same time, increasing of destructive forest fires scale in recent decades has led to depletion of forest resources. To combat forest fires, it is necessary to develop preventive measures to reduce the number and severity of forest fires and establish reliable evaluation criteria for fire hazard assessment in forestry. However, indices of fire hazard assessment that exist in Russia are not always allowed to determine the degree of fire hazard reliably. The studies were performed in pine forests on the territory of the Central Forest-Steppe. The key forestry factors influencing the fire hazard situation in pine stands are identified: the presence and amount of combustible materials, the state of the stand, as well as the age structure of tree stand. According to burning indices, the highest fire hazard was common for young and middle-aged pine stands, while for ripening, mature and old-growth forests, fire hazard increasing was not observed. A set of parameters that characterize soil moisture and ground cover peculiarities have also a significant impact. Forest growth conditions were shown to be an important indicator for assessment of fire hazard class. Identified factors that have a key impact on the fire hazard in forests will make it possible to improve methodological approach for monitoring and preservation of forests.

Keywords: biological and environmental factors; forestry; tree age; forest fires; taxation; burning; forest growth conditions; pine stands; loss of landscape-ecological balance; conservation of forest resources; Central Forest-Steppe

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1. Introduction

Fire is a dominant disturbance in temperate and boreal biomes, and increasing burnt areas may substantially alter forests [1,2]. According to the estimates of the Federal Agency for Forestry [3], total annual damage from forest fires is about 20 billion rubles, while from 3 to 7 billion is a direct economic damage to Russian forestry due to wood loss. Another loss are the costs of firefighting and subsequent clearing of burnt areas, animal deaths, atmosphere pollution by combustion products, greenhouse gases emissions, and costs of reforestation.

Hence, among the many important issues of forest protection and reproduction one of the most urgent is the fight against forest fires. Therefore, development of a system for comprehensive assessment of forest fire hazards taking into account factors of forest typology and forest structure that determine flammability is of particular relevance. Obviously, an operational system for assessing and forecasting fire danger should consider wide range of forest characteristics, vegetation state and reflect the significance of the main taxation characteristics.

These problems were studied by many researchers [4–6]. M.A. Sofronov and A.V. Volokitina [7] developed a method for assessing the distribution of real fire hazard over the territory based on the medium-scale maps of forest combustible materials. N.P. Kurbatsky, G.A. Dorrera, B.I. Dorogova [8], M.Z. Musina [9], E.N. Valendik [10], M. Fosberg and M. Schroeder [11], P. Labenski [12] used wide spectrum of possible fire sources in their forest fire forecasting systems.

E.N. Valendik and G.A. Ivanova [13] established that various types of forests have its own "fire regime" characterized by a certain type and intensity of fire, recurrence intervals, and degree of damage to plant resources. N.S. Ivanova suggested biogeocenotic and genetic approaches in forest typology [14].

Some researchers found that degree of stability of plantings depends on taxation indicators [15–17]. The dependence of the stability of pine plantations against fire was established experimentally, depending on forest site [18], stand age [19,20], average stand height.

Chumachenko [21] investigated natural fire hazard in mixed forest stands [22] and found the admixture of hardwoods in all age classes and in all tiers of coniferous forests reduce fire hazards. Increased flammability of pine plantations is determined by a number of biological features of Scots pine. First of all, high transparency of the tree canopy ofmature pine forests accelerates drying of living ground cover and litter. Also, pine deadwood contains high amount of resinous substances, which inhibit its decomposition rate. Particularly it is inherent to dry group of forest types, where deadwood decomposition is delayed for many years.

To reduce the risk of forest fires systems for regular assessment of forest combustible material stock as well as systems for assessing the fire development (modeling, ground monitoring, satellite data, airborne infrared detection) were used [22,23].

Notably, there are no low-cost methods for significantly reducing the level of fire hazard in forests now. Developing a preventive system that effectively combines data from different remote sensing methods of fire danger as well as implementation of new technologies providing a prompt assess of fire hazards in forests are essential.

The aim of the study was to determine the key factors influencing the flammability in forests for preventive reducing of fire occurrence.

Our stages of work were divided into: preparatory, field, cameral (final).

2. Materials and Methods

2.1. Study Sites

Study sites are located on the territory of Suburban Forestry in the Central Chernozem Region (the northern part of Voronezh Region, Russia) and represented natural and artificial forest stands of various tree species inherent to Central Forest-Steppe (Figure 1A) Geographical location of study sites in the Suburban Forestry; B, C, D) Placement of trees in the study areas within the polygon.

Forest fire hazard is known to vary greatly depending on tree age, the proportion of conifers in the composition, anthropogenic factors, terrain, forest structure, forestry activities, etc. However, despite the diversity of forest vegetation and its combinations different tree stands can be combined into groups with similar occurrence conditions and peculiarities of development of forest fires there.

2.2. Field Studies

Thirteen sample plots were established in different forest types and types of forest growth conditions and investigated during forest inventory of Suburb Forestry in 2022. Also, forest stands in established sample plots belonged to different fire hazard classes [24], which is reflected in Table 1.

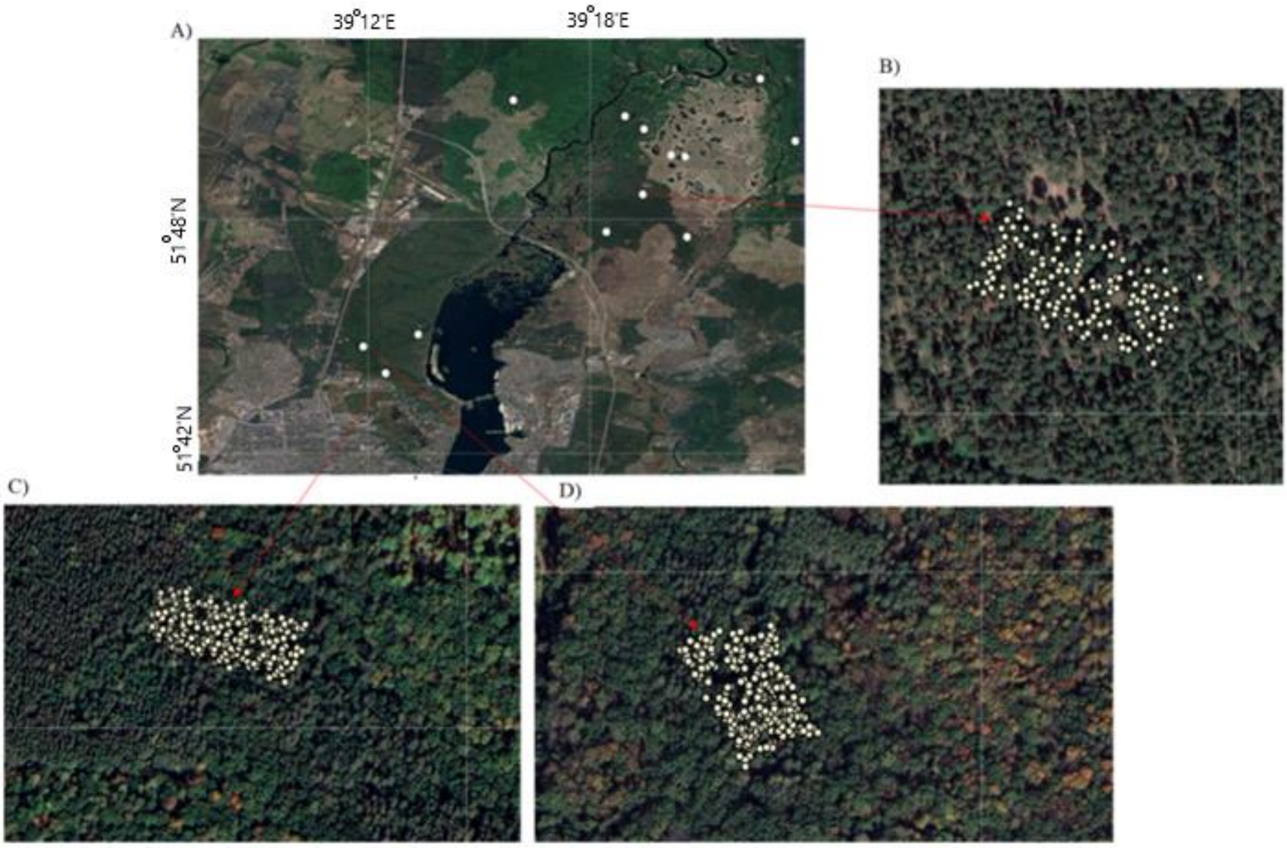

Figure 1. (**A**) Geographical location of study sites in the Suburban Forestry; (**B**–**D**) Placement of trees in the study areas within the polygon.

All taxation and deciphering trial plots are laid в in the forest sites with different growth conditions were studed. For determining the forest growth conditions useds to classifications scheme of P.S. Pogrebnyak [25]. This classification is based on the division of forest areas according to moisture and soil fertility. The trophic groups differ from each other in nutrient contents in the soil: A—pine forest (sandy soils), B—pine-oak forest (sandy loam soils), C—composite forest (loamy soils), D—oak grove (clay soils). Each gigrophic groups divided into: xerophilous (very dry)—0; mesoxerophilous (dry)—1; mesophilous (fresh)—2; mesohygrophilous (moisty)—3; hygrophilous (moist)—4; ultrahygrophilous (wet)—5.

V.N. Sukachev gives the following definition of a forest type [26]: a site of forest is an association of forest parcels (i.e., forest ecosystems), homogeneous in composition of tree species, other vegetation levels, fauna, the relationship between plants and the environment, forest reproduction processes, and corresponding stages of succession and therefore requires uniform forest management practices under the same economic conditions. A type of forest under these conditions can therefore be considered as a type of forest biogeocenosis [24,27,28].

Studied plantings of different ages growing in the forest site: pine site of forest with a predominance in the ground cover the following species: grasses (Szl) (*Festuca glauca* L., *Hieracium pilosella* L.), lichens (Slh) (*Cladonia* L.), green mosses (Szm) (*Dicranum scoparium* Hedw., *Pleurozium schreberi* Brid.), small grasses (Str) (*Bryidae*, *Veronica officinalis* L.), mossy (Smsh) (*Polýtrichum commúne* L., *Lysimachia vulgaris* L.), reed grasses (Srzl) (*Calamagrostis epigejos* L., *Dianthus deltoides* L.), brooms and grasses (Srtzl) (*Phleum phleoides* L., *Festuca ovina* L.), medium grasses (Ssrt) (*Convallaria majalis* L., *Polygonátum odoratum* L.), molinium (Smln) (*Molinia caerulea* L., *Maianthemum bifolium* L.), mixed herbs (Srt) (*Pulmonaria obscura* Dum., *Origanum vulgáre* L.), large herbs (Sdsn) (*Pyrola elliptica* Nutt., *Rubus saxatilis* L.) and ferns (Sdkrt) (*Pteridium aquilinum* L., *Athyrium spinulosum* L.).

Table 1. Studied forest stand characteristics and their fire hazard classes.

Location	Composition of Tree Species, %	Age Groups of Tree Stands	Age, Years	dbh (cm)	h (m)	f	Standing Volume, m^3/ha	Deadwood, m^3/ha	Fire Hazard Class	Forest Site	FGC
Quarter 108; site 8	100% Scots pine + European birch	Young	35	15	9	0.6	60	2	1	Szl	A_1
Quarter 108; site 10	100% Scots pine	Middle aged	55	24	18	0.6	160	14	2	Slh	A_1
Quarter 33; site 12	100% Scots pine	Young	12	5	3.7	0.8	10	-	1	Str	A_2
Quarter 74; site 9	100% Scots pine	Ripening	120	30	27	0.7	370	30	2	Szm	A_2
Quarter 77; site 1	100% Scots pine	Middle aged	50	19	16	0.4	120	11	2	Str	A_2
Quarter 51; site 44	100% Scots pine	Middle aged	70	23	21.5	0.9	320	18	3	Smsh	A_3
Quarter 79; site 14	90% Scots pine 10% European birch	Mature and old-growth	150	48	29	0.7	310	35	2	Srzl	B_1
Quarter 33; site 8	100% Scots pine	Unclosed forest cultures	7	-	2.2	1.0	-	-	1	Ssrt	B_2
Quarter 60; site 11	100% Scots pine	Ripening	140	44	27.5	0.6	290	32	2	Srtzl	B_2
Quarter 78; site 14	70% Scots pine 30% European birch	Middle aged	55	24	21	0.9	350	15	2	Srt	B_2
Quarter 72; site 18	50% Scots pine 50% European birch	Middle aged	45	16	12	0.7	180	10	3	Smln	B_3
Quarter 44; site 26	50% Scots pine 50% English oak	Ripening	90	33	24.5	0.6	260	25	3	Sdsn	C_2
Quarter 7; site 37	50% Scots pine 40% English oak 10% Linden	Ripening	90	36	26.5	0.7	310	28	3	Sdkrt	C_3

Note: h—mean height; dbh—mean diameter on breast height; f—density of tree placement (corresponds to the canopy density); FGC—forest growth conditions.

Complete enumeration was carried out at each sample plot with determination of tree species and coordinates of each tree, stem diameter, tree height and beginning height of the living crown part, crown diameter and forest cluttering. The ground cover, undergrowth, understory and the degree of clutter were also investigated. The height of the tree and the beginning height of living crown were measured with an accuracy of 0.5 m using a Vertex Laser Geo altimeter (Haglöf, Sweden). The stem diameter was measured with a DP II Caliper (Haglöf, Sweden) at a height of 1.3 m, with an accuracy of 1 cm. The crown diameter was measured with a laser rangefinder along the crown projection in two opposite directions (NS/WE). Measurement accuracy was not less than 0.5 m.

We used the approved scale according to the classes of natural fire hazard, where class I (natural fire hazard—very high), class II (natural fire hazard—high), class III (natural fire hazard—medium), class IV (natural fire hazard—weak), V class (natural fire hazard—absent) [29].

Tree health category was determined visually according to 5-point scale [30]: 1—without signs of weakening; 2—weakened; 3—strongly weakened; 4—drying out; 5—dead wood.

The methodology for conducting the State Forest Inventory (SFI) was taken as the basis for determining the main forestry indicators [31] which has been upgraded to detail the work. Deadwood counting in the trial plots was performed with reference to trees; if deadwood was in open spaced areas, its location was fixed relative to the nearest tree. Deadwood was considered as dead trees at an angle of less than 45% from the ground level. Moreover, tree species, length and diameter at $\frac{1}{2}$ of the length were determined for each deadwood on the trial plot.

Undergrowth and understory within the crown of measured tree were assessed by their density and size according to 3-point scales (for undergrowth: 1—up to 0.5 m; 2—0.5–2 m; 3—more than 2 m; for understory: 1—up to 1 m; 2—1–2 m; 3—more than 2 m) with indication of species and viability (alive/dead). Also based on the recommendations for conducting a SFI the viability of the undergrowth (live/dead wood) is indicated. The ground cover was determined on a three-point scale: 3—contributing to combustion; 2—supporting combustion; 1—flame retardant.

2.3. Fire Hazard and Statistical Analysis

The analysis of forest burning was carried out on the territory of Suburban Forestry from 2002 to 2022 according to the scale developed by G.A. Mokeeva [32].

Some indicators were used for analysis of forest fires: the number of fires in forestry; forest area covered by fires; average area of one fire; fire frequency; causes of fire occurrence. Evaluation of fire frequency in Suburban Forestry was provided according to the scale developed by Sofronov M.A. [7] Burning index (γ, %) was calculated as follows:

$$\gamma = \frac{S_f}{S_a} \times 100\% \quad (1)$$

where S_f—forest area covered by fires, ha; S_a—total forest area in the region, ha.

Statistical analysis was provided with STATISTICA 13 [33] a statistical sequential analysis was carried out based on the recommendations of B.A. Dospekhova [34]. Correlation and regression analysis, which allows to assess the closeness of the relationship between various indicators that affect the process and find the relationship between the studied indicators, as well as analysis of variance, which allows to determine the strength of the influence of the acting factor on the effective feature.

3. Results

3.1. Fire Hazard Analysis

There were 689 forest fires recorded from 2002 to 2022 with total area of 4001 ha in Suburban Forestry (Table 2). The average area of one fire was 5.8 ha. The most fire hazardous years were 2010 and 2021.

Table 2. Distribution by age groups of forest areas covered by fires.

Age Groups of Tree Stands	Part in Total Number of Fires, %	Area Covered by Fires, ha	Total Area of Tree Stands, ha	Part in Total Area, %	Area of One Fire, ha
Young	15.3	615.5	4054.2	34.1	12.5
Middle aged	21.9	878.4	1516.4	12.9	6.1
Ripening	55.7	2230.4	2401.9	20.8	2.9
Mature and old-growth	7.1	276.7	3798.7	32.2	1.8
Total	100	4001	11,904.9	100	5.8

The data in Table 2 indicate that the maximum area covered by forest fires was in ripening forests. Over a 20-year period 55.7% of the total area covered by fire was in ripening forest stands, most of them burned down during a severe wildfire in 2010. The fire was largely due to climatic conditions: the air temperature during the fire season was significantly higher than the long-term average for the region and there was too low precipitation.

Accordingly, the highest burning index for the study period was observed in 2010 and amounted to 0.9%. According to Mokeeva's scale it is evaluated as strong flammability. The highest frequency of fires was noted in 2021 (0.7 fires per 100 000 ha). According to Sofronov's scale it is characterized as moderate frequency. The lowest burning index was noted in 2022 (0.002%). The lowest frequency of fires was also observed in 2022 and evaluated as low (0.01 fires per 100,000 ha).

Depending on the nature of the fire and forest composition forest fires are divided into ground fires, crown fires and soil fires. Depending on intensity they are divided into weak, medium and severe. The intensity of burning depends on state and quantity of combustible materials, relief and wind strength. The area covered by fires of different intensity in the study area is shown in Table 3.

Table 3. Distribution by age groups of forest areas covered by fires of various intensity.

Age Groups of Tree Stands	Area Covered by Ground Fire, ha					Area Covered by Crown Fire, ha				
	Weak	Medium	Severe	Total ha	Total %	Weak	Medium	Severe	Total ha	Total %
Young	21.2	30.8	81.8	133.8	6	35.6	91.5	254.6	481.7	25
Middle aged	41.5	158.5	10.8	210.8	10	218	324.7	124.9	667.6	35
Ripening	678.5	498.6	317.3	1494.4	72	34.6	112.4	589.4	736.4	38
Mature and old-growth	14.9	17.8	198.5	231.2	12	9.1	22.1	10.3	41.5	2
Total	856.1	705.7	708.4	2070.2	100	397.3	550.7	979.2	1930.8	100

According to the data in Table 3 ground fire with different intensity was distributed evenly over the study area. The post-fire mortality in forest stands after stable ground fires is significantly greater than under the influence of runaway fires. This is due to runaway ground fires are characterized by fire spreading over the upper layer of ground combustible materials. Areas covered by ground fire vary significantly in intensity depending on age groups: from 14.9 ha to 678.5 ha (weak), from 17.8 ha to 498.5 ha (medium) and from 10.8 ha up to 317.3 ha (severe).

There is no direct relationship between the area of forest fires and their number. Therefore, the burning index can be considered as more informative indicator of fire hazard. Distribution of areas covered by fires in forest stands of different age groups and values of burning indices depending on forest growth conditions are shown in Table 4.

Table 4. Distribution by age groups of forest areas covered by fires depending on forest growth conditions (ha)/burning index (%).

Age Groups of Tree Stands	Forest Growth Conditions A_1	A_2	A_3	B_1	B_2	B_3	C_2	C_3	Total
Young	135.5/ 0.23	211.9/ 0.35	-	80.5/ 0.14	187.6/ 0.28	-	-	-	615.5
Middle aged	97.9/ 0.17	132.1/ 0.25	-	300.4/ 0.43	250/ 0.5	-	79.4/ 0.33	20/ 0.2	878.4
Ripening	1056.4/ 0.88	547.8/ 0.43	23/ 0.74	300.9/ 0.44	125.1/ 0.25	21.3/ 0.74	155.9/ 0.64	-	2230.4
Mature and old-growth	28.9/ 0.02	27.8/ 0.02	-	89.9/ 0.13	123.4/ 0.25	-	6.7/ 0.03	-	276.7
Total	1318.7	919.6	23	771.7	686.1	21.3	242	20	4001

It is obvious that burning index of tree stands increases in dry and fresh forest growth conditions (A_1, A_2, B_1, B_2). This pattern is associated not only with the limit of soil moisture, but also with an increase in content combustible materials and, consequently, increasing of combustion intensity. Contrary, flammability index decreases and fires are often isolated in more humid soil conditions of the studied area (A_3, B_3, C_3). It should be noted that the wildfire in 2010 reached catastrophic scale. Ripening forest stands located at the epicenter of fire were the most harmed. Therefore, tree stands of this age group are out of the general pattern.

Distribution by age groups of forest areas covered by fires depending on forest types are shown in Table 5.

Lichen and grass pine forests grow in forest ecotopes on dry sandy soils. These forests are characterized by a high fire hazard and frequent fires recurrence. Mortality after ground fires of weak and medium intensity the in mature stands confined to these conditions is 20% of the stock, and after severe ground fires—up to 50%.

Table 5. Distribution by age groups of forest areas covered by fires depending on forest types (ha)/burning index (%).

Age Groups of Tree Stands	Forest Site Szl	Slh	Szm	Str	Smsh	Srzl	Srtzl	Ssrt	Smln	Srt	Sdsn	Sdkrt	Total
Young	35/ 0.16	100.5/ 0.36	67/ 0.1	144.9/ 0.3	-	80.5/ 0.14	101.2/ 0.17	59/ 0.1	-	27.4/ 0.05	-	-	615.5
Middle aged	28.9/ 0.03	59.8/ 0.15	64.7/ 0.01	67.4/ 0.01	8.2/ 0.26	300.4/ 0.43	32.5/ 0.21	181.7/ 0.61	-	35.8/ 0.72	79.4/ 0.33	20/ 0.35	878.4
Ripening	760.6/ 0.9	295.8/ 0.8	405.4/ 0.6	142.4/ 0.2	23/ 0.7	300.9/ 0.44	100/ 0.66	15.8/ 0.05	21.3/ 0.25	9.3/ 0.18	155.9/ 0.64	-	2230.4
Mature and old-growth	18.9/ 0.03	10/ 0.03	7.7/ 0.1	20.1/ 0.03	-	89.9/ 0.13	20/ 0.13	98.6/ 0.34	-	4.8/ 0.1	6.7/ 0.03	-	276.7
Total	843.4	466.1	544.8	374.8	31.2	771.7	253.7	355.1	21.3	161	242	20	4001

The consequences of fires in green moss and grass forest types are the most diverse due to their wide area. The state of forest stands after the impact of ground fires in the types of forest growth conditions (A_2, B_2 and C_2) depends on the fire strength and its form, which determines the time of fire exposure. However, the consequences of runaway ground fires of weak and medium strength are more negative in comparison with the consequences of fires of the same strength in dry conditions. This pattern is associated with a longer exposure to fire in these forest types.

Regression analysis was performed to establish the relationship between the burning indices and forest growth conditions/forest types. The results of the initial data alignment are shown in Figure 2.

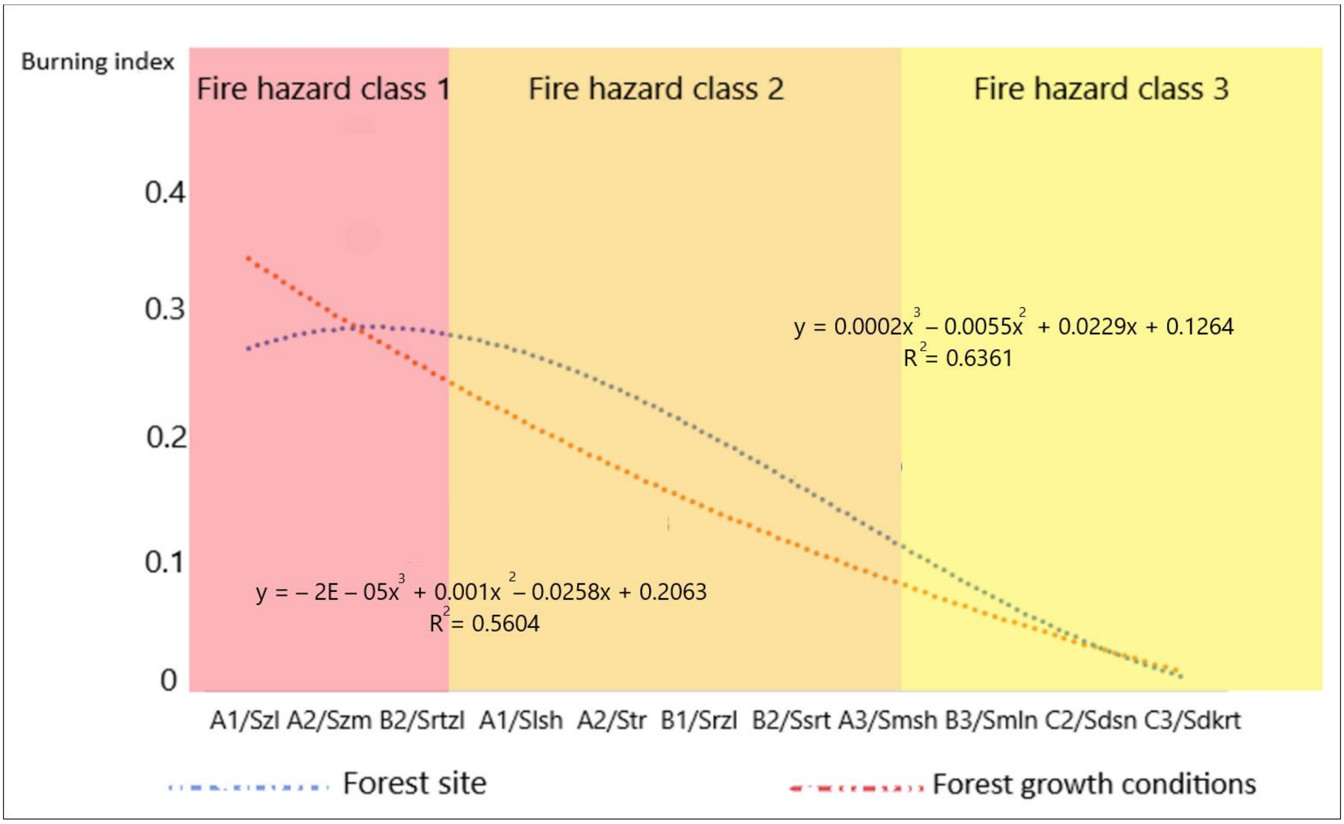

Figure 2. Aligned values of burning indices by forest site (blue) and forest growth conditions (red).

3.2. Influence of Forest Stand Characteristics on Burning Index

Forest stand characteristics (data from sample plots, Table 1) and values of burning indexes (areas covered by forest fires on the territory of Suburban Forestry) were compared for approbation of the obtained results. Sites were selected in similar types of forests, types of forest growth conditions and age groups.

Obviously, burning indices in certain types of forest growth conditions differ significantly from the forest types corresponding to these conditions. Differences are especially significant in forest stands with fire hazard classes 1 and 2. To assess reliability of differences between the average values of burning indices in forest stands growing under different conditions ANOVA was performed. The results of the analysis are summarized in the Table 6.

Table 6. Reliability of differences between the average values of burning indices in different forest site and forest growth conditions. Statistical differences ($p < 0.05$) are marked by bold font.

Forest Growth Conditions	**Forest Site**											
	Szl	**Slh**	**Szm**	**Str**	**Smsh**	**Srzl**	**Srtzl**	**Ssrt**	**Smln**	**Srt**	**Sdsn**	**Sdkrt**
A_1	0.55	1.48	0.08	-	-	-	-	-	-	-	-	-
A_2	-	**2.05**	**2.17**	**2.22**	-	-	-	-	-	-	-	-
A_3	-	-	0.42	1.91	**3.05**	-	-	-	-	-	-	-
B_1	**2.42**	-	-	0.38	-	**3.18**	**4.52**	-	-	-	-	-
B_2	-	-	0.15	**3.23**	-	-	**3.17**	**3.55**	-	1.87	-	-
B_3	-	-	-	-	**2.88**	-	-	-	**3.58**	-	-	-
C_2	-		-	**4.05**	-	-	-	**4.35**	-	**3.15**	**3.41**	1.91
C_3	-	-	0.23	-	**2.13**	-	-	-	**2.97**	-	**3.74**	**4.24**

Significant differences were revealed between individual values of burning indices of tree stands in forest growth conditions B_2 and A_2 as well as three stands growing in the corresponding primary forest site—Str., Ssrt. Tree stands in these conditions have a high degree of fire danger and require the most accurate assessment of probability of fire. Therefore, it is advisable to use of forest growth conditions as an additional clarifying indicator for the fire hazard class determination.

Variability of burning indexes in pine forests of different ages in diverse forest growth conditions is shown in Figure 3.

Regardless of the type of forest growth conditions young forests have the highest burning index. Mature stands are characterized by the highest resistance to fires in dry and fresh types of forest growth conditions. This pattern was previously noted by many authors [34]. At the same time, pine stands do not reduce their fire resistance up to 200 years of age. According to B.P. Tikhomirov [35], growth is often observed not only in diameter, but also in height of pine trees 300 years old in Central Siberia and Transbaikalia. It was established that burning index is approximately the same in all age groups (except for young tree stands) in moisty forest growth conditions (A_3, B_3, C_3).

Statistical analysis showed close correlation between the burning index and the ground cover as well as the coarse debris content (accumulation of combustible materials) (Table 7). The strength of the influence of the factor is given in Table 8.

One-way ANOVA was used to identify the influence of individual factors. Results of analysis shows studied forest stand characteristics has no any key influence on the fire occurrence (Table 8). Therefore, a set of features should be considered for establishment of significance levels, which were calculated according to the Fisher criterion Figure 4.

The key factors influencing the burning index of pine stands are the following: coarse debris content, tree stand state and age group. Moreover, a set of parameters determined by the of forest growth conditions (primarily soil moisture and ground cover) have a significant influence.

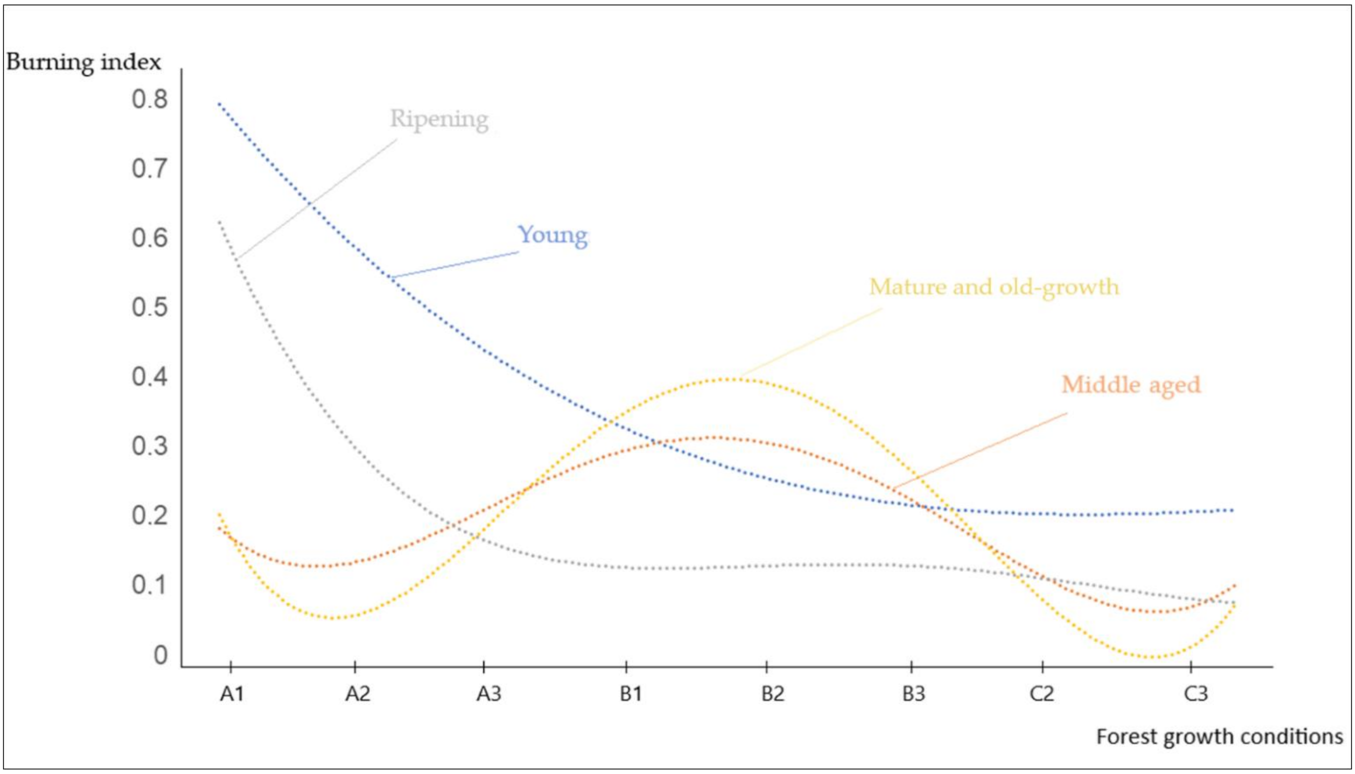

Figure 3. Burning indices of pine forests of different ages in various forest growth conditions.

Table 7. Correlation matrix of forest stand characteristics in different forest growth conditions.

Forest stand Characteristics	Burning Index	Age, Years	Height, m	Dbh, cm	Crown Diameter, m	Beginning Height of Living Crown, m	Categories of Sanitary Condition	Coarse Debris Content	Ground Cover
Burning index	1	0.55	0.17	0.11	0.09	0.28	0.42	0.59	0.61
Age, years	0.55	1	0.66	0.65	0.38	0.53	0.33	0.18	0.04
Height, m	0.17	0.66	1	0.67	0.36	0.52	0.71	0.11	0.02
Dbh, cm	0.11	0.65	0.67	1	0.62	0.23	0.12	0.09	0.03
Crown diameter, m	0.09	0.38	0.36	0.62	1	0.17	0.68	0.12	0.07
Beginning height of living crown, m	0.28	0.53	0.52	0.23	0.17	1	0.32	0.11	0.03
Categories of sanitary condition	0.42	0.33	0.71	0.12	0.68	0.32	1	0.49	0.04
Coarse debris content	0.59	0.18	0.11	0.09	0.12	0.11	0.49	1	0.09
Ground cover	0.61	0.04	0.02	0.03	0.07	0.03	0.04	0.09	1

Tree height, diameter of stem, crown diameter and crown length weakly (or very weakly) correlate with the values of burning indexes.

Table 8. Influence of forest stand characteristics on burning index.

Forest Stand Characteristics	Power of Influence ($\eta^2 \pm$ m)	Fisher Criterion Actual (F f)	Fisher's Criterion Standard (F st)
Age, years	0.22 ± 0.011	15.9	3.1
Height, m	0.21 ± 0.011	16.4	3.1
Mean diameter on breast height	0.14 ± 0.006	16.5	3.1
Crown diameter, m	0.09 ± 0.004	15.5	3.1
Crown length, m	0.17 ± 0.007	15.7	3.1
Categories of sanitary condition	0.25 ± 0.012	15.2	3.1
Coarse debris content	0.35 ± 0.022	15.9	3.1
Ground cover	0.23 ± 0.012	15.4	3.1

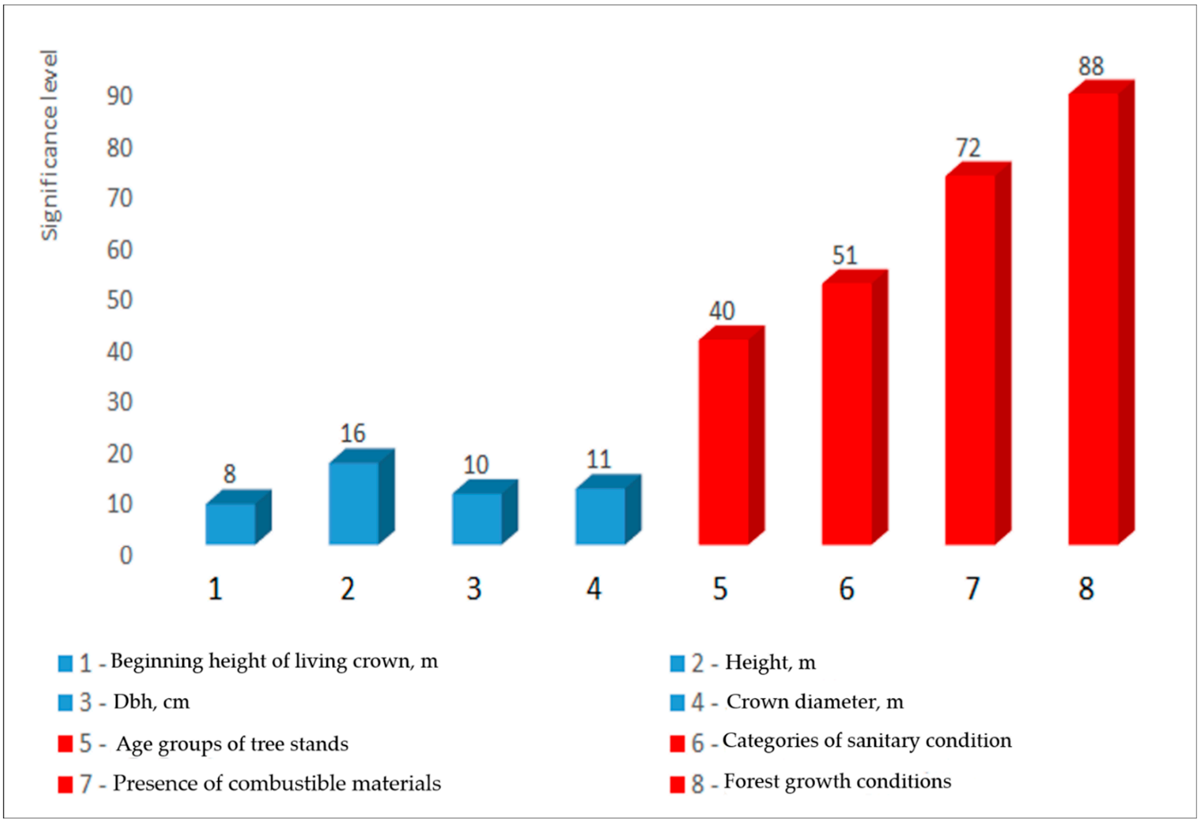

Figure 4. Significance levels of the main taxation characteristics relative to burning index.

Figure 5 shows burning indices change depending on the age of the stand. Approximation of the data was provided by second-degree polynomial function with a high value of determination coefficient.

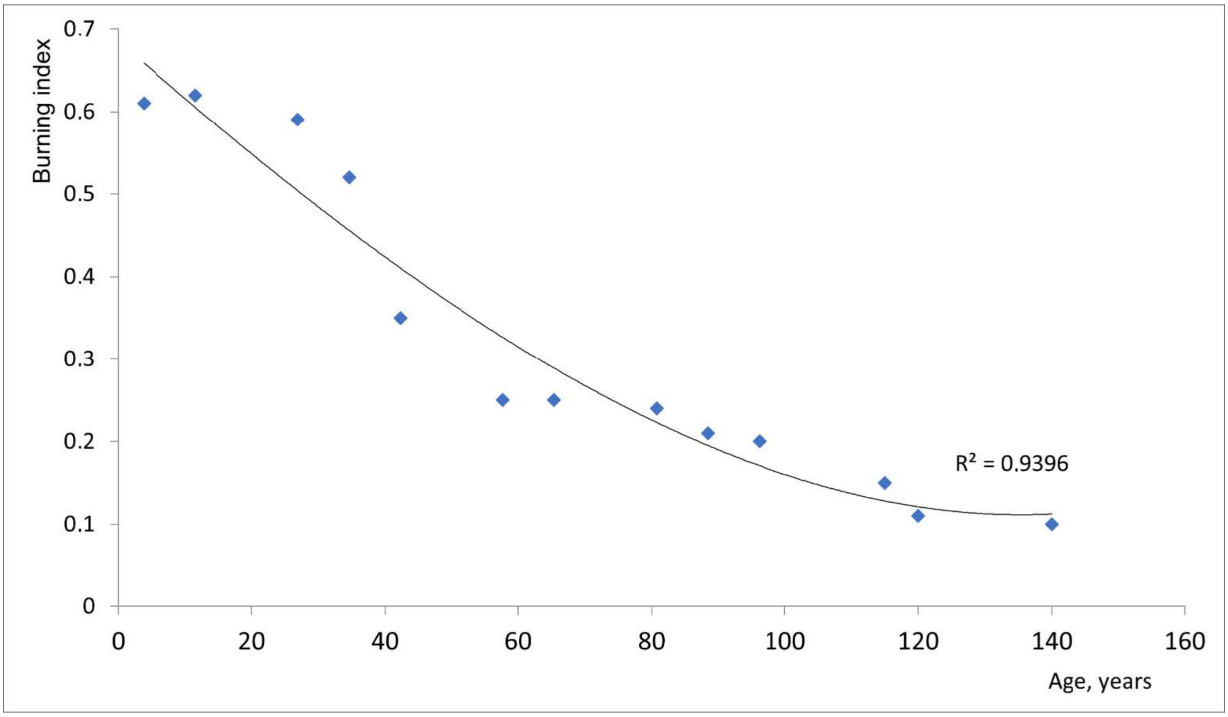

Figure 5. The dependence of burning indices on tree stand ages.

According to the Figure 5, decreasing of fire hazards in forest stands with increasing of their age was revealed. Young tree stands have the highest potential fire hazard. Then, there is a "smoothing" of burning indices values starting from the second class of medium-aged pine stands (more than 60 years).

4. Discussion

Fire management programs typically include prevention measures to reduce the number fires that occur, systems to find fires and fire management systems [36–40]. Improved information about how fire-induced changes to forests may feedback to affect subsequent burning at regional scales could inform forest management and climate-mitigation strategies [41–43]. Therefore, the development of preventive measures to reduce the number of fires and the establishment of reliable forestry evaluation criteria for the diagnosis of fire danger are extremely urgent tasks. Forest typology is closely connected not only with the geography of the ranges of tree species, but also with soil biochemistry [44–47], structure and properties of biogeocenoses [48], dynamics of the carbon balance [49], and is also the basis for monitoring forest biodiversity [50]. The formation of the structure and state of ecosystems based on forest-forming tree species largely depends on their bioecological features [50–55] at specific age stages of development.

Also, consideration of environmental factors is of great importance in understanding the state, stability, and ecological role of forest stands [56–63]. It is especially important for protection and restoration of forest ecosystems [64–66] as well as in their management [67–69]. Accounting for the data obtained on the bioecological features of forest stands and environmental conditions are of paramount importance in managing the resource qualities of forest ecosystems, their stability and protection in forest-steppe and other landscapes. This can be implemented in different areas in natural and artificial ecosystems (in parks, squares, recreational and protective forest plantations) based on *Pinus sylvestris* L.

In the context of abiotic [70–74] and phytocenotic conditions [75–78], it is just expedient to consider the ecological state, landscape functions of pine forests and the possibility of protecting them from fires. Maksimova, Abakumov [79] found the average fire interval is more than 2 times shorter in lichen and grass pine forests on sandy and sandy loamy soils than in grass and green moss pine forests in the Central Forest-Steppe. The same peculiarities are typical for other forests in dry conditions. In our study this trend was confirmed. Maximum burning index was revealed in dry of forest growth conditions (A_1, B_1). However, burning index in fresh forest growth conditions (A_2, B_2) is comparable to the drier ones, and the frequency of fires decreases. There is a clear trend towards decreasing of part of the area covered by fires with an increase in soil moisture. Our studies are in consistence with the M.A. Sofronov's opinion [7] about the relationship between tree stand resistance to fire impact and forest growth conditions.

D. Moya et al. [79] note that post-fire mortality increases with increasing fire intensity. In our studies the pattern of increasing mortality depending on tree stand age was noticed: post-fire mortality was greater in mature or old-growth forests than in medium-aged tree stands. At the same time, mature forest stands were the most resistant to fires and young tree stands are damaged to a greater extent.

The indices of fire hazard assessment that exist in Russia do not always make it possible to determine the degree of fire hazard reliably. Protecting forests from fires is a global problem. Vast forest areas are concentrated on the territory of Russia, which perform environment-forming, nature-protective and climate-regulating functions, including carbon storage. The identified factors that have a key impact on the fire hazard in forests will make it possible to improve methodological approach for monitoring and preservation of forests.

5. Conclusions

The main conclusions from the results of our study are given below.

1. Tree stand age has a significant factorial influence on burning index in young and middle aged Scots pine stands. At the same time, there is no significant change of

burning index in ripening, mature and old-growth pine forests. Additionally, fire hazard decreases with increasing age of middle aged pine tree stands. The tightness of relationship between burning index and tree stand age in young forests is 0.56, and in mature and old-growth is much lower (0.17).

2. The key factors influencing the index of burning of pine stands are the following: the presence and amount of combustible materials, the state of the stand, age groups. In addition, a complex of parameters characterizing soil moisture and the nature of the ground cover have a significant impact.
3. The frequency of fires and the values of the fire index reach high values in dry types growth conditions due to presence of lichens in the ground cover. Under optimal humid conditions the frequency of fires is reduced but the flammability index can remain high in the presence of a significant amount of combustible materials.
4. We have proved (with mathematical confirmation of the reliability of differences) that forest growth conditions are an important indicator that can be used in determining the fire hazard class.

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References

1. Kumar, G.; Kumar, A.; Saikia, P.; Roy, P.S.; Khan, M.L. Ecological impacts of forest fire on composition and structure of tropical deciduous forests of central India. *Phys. Chem. Earth* **2022**, *128*, 103240. [CrossRef]
2. Winslow, D.; Hansen, M.A.; Krawchuk, A.; Trugman, T.; Park Williams, A. The Dynamic Temperate and Boreal Fire and Forest-Ecosystem Simulator (DYNAFFOREST): Development and evaluation. *Environ. Model. Softw.* **2022**, *156*, 105473. [CrossRef]
3. Annual Report on the State and Use of Forests in the Russian Federation in 2022. Forests and Forest Resources of the Russian Federation [Electronic Resource]. Available online: http://www.rosleshoz.gov.ru (accessed on 3 October 2022).
4. Volodkin, A.A.; Larionov, M.V.; Sharunov, O.A. Changes in the Structure of Forest Communities in Penza Region under the Influence of Natural Factors. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *808*, 012064. [CrossRef]
5. Abaimov, A.P.; Zyryanova, O.A.; Prokushkin, S.G.; Koike, T.; Matsuura, Y. Forest Ecosystems of the Cryolithic Zone of Siberia. *Eurasian J. For. Res.* **2000**, *1*, 1–10.
6. Kukavskaya, E.A.; Soja, A.J.; Petkov, A.P.; Ponomarev, E.I.; Ivanova, G.A.; Conard, S.G. Fire emissions estimates in Siberia: Evaluation of uncertainties in area burned, land cover, and fuel consumption. *Can. J. For. Res.* **2013**, *43*, 493–506. [CrossRef]
7. Sofronov, M.A.; Volokitina, A.V. Maps of Combustible Forest Materials. *Mapp. Sci. Remote Sens.* **1988**, *25*, 169–177. [CrossRef]
8. Kurbatsky, N.P.; Dorogov, B.I.; Dorrer, G.A. Forecasting forest fires with the help of a computer. *Forestry* **2007**, *7*, 51–55.
9. Musin, M.Z. Determination of the daily fire hazard of forest areas. *Forestry* **2018**, *7*, 78–80.
10. Valendik, E.N.; Vekshin, V.N.; Lasko, R. *Fundamentals of Fire Management in the Boreal Forests of Eurasia. Management of Forest Fires at the Ecoregional Level*; Alex: Moscow, Russia, 2004; 208p.
11. Fosberg, M.A. Fine herbaceous fuels in Fire Danger Rating. In *USDA Forest Service Research Notes RM-185*; Rocky Mountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture: Fort Collins, CO, USA, 2017; 7p.

12. Labenski, P.; Ewald, M.; Schmidtlein, S.; Ewald Fassnacht, F. Classifying surface fuel types based on forest stand photographs and satellite time series using deep learning. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *109*, 102799. [CrossRef]
13. Valendik, E.N.; Ivanova, G.A. Fire regimes in the forests of Siberia and the Far East. *Forestry* **2001**, *4*, 69–79.
14. Tepley, A.J.; Thomann, E.; Veblen, T.T.; Perry, G.L.W.; Holz, A.; Paritsis, J.; Kitzberger, T.; Anderson-Teixeira, K.J. Influences of fire-vegetation feedbacks and post-fire recovery rates on forest landscape vulnerability to altered fire regimes. *J. Ecol.* **2018**, *106*, 1925–1940. [CrossRef]
15. Prichard, S.J.; Stevens-Rumann, C.S.; Hessburg, P.F. Tamm review: Shifting global fire regimes: Lessons from reburns and research needs. *For. Ecol. Manag.* **2017**, *396*, 217–233. [CrossRef]
16. Valendik, E.N.; Bychkov, V.A.; Kisilyakhov, E.K.; Verkhovets, S.V. Forest fires in rural forests. *Forestry* **2002**, *1*, 46–48.
17. Barbati, A.; Marchetti, M.; Chirici, G.; Corona, P. European forest types and forest Europe SFM indicators: Tools for monitoring progress on forest biodiversity conservation. *For. Ecol. Manage.* **2014**, *321*, 145–157. [CrossRef]
18. Johnstone, J.F.; Allen, C.D.; Franklin, J.F.; Frelich, L.E.; Harvey, B.J.; Higuera, P.E.; Mack, M.C.; Meentemeyer, R.K.; Metz, M.R.; Perry, G.L.; et al. Changing disturbance regimes, ecological memory, and forest resilience. *Front. Ecol. Environ.* **2016**, *14*, 369–378. [CrossRef]
19. Keeley, J.E.; Syphard, A.D. Different historical fire–climate patterns in California. *Int. J. Wildland Fire.* **2017**, *26*, 253–268. [CrossRef]
20. Savage, M.; Nystrom, M.J. How resilient are southwestern ponderosa pine forests after crown fires? *Can. J. For. Res.* **2005**, *35*, 967–977. [CrossRef]
21. Chumachenko, S.I. Natural fire hazard of mixed forest plantations. Model approach. *For. Bull.* **2013**, *7*, 72–74. Available online: https://cyberleninka.ru/article/n/prirodnaya-pozharnaya-opasnost-smeshannyh-lesnyh-nasazhdeniy-modelnyy-podhod (accessed on 3 October 2022).
22. Veblen, T.T.; Kitzberger, T.; Donnegan, J. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado front range. *Ecol. Appl.* **2000**, *10*, 1178–1195. [CrossRef]
23. Baćmaga, M.; Wyszkowska, J.; Borowik, A.; Kucharski, J.; Paprocki, Ł. Role of forest site type in determining bacterial and biochemical properties of soil. *Ecol. Indic.* **2022**, *135*, 108557. [CrossRef]
24. Kuplevatsky, S.V.; Zakharova, I.S.; Shabalina, N.N. Burning of forests on the territory of the Ural Federal district and legal aspects of improving their protection from fires. *For. Russ. Econ.* **2021**, *2*, 16–24. [CrossRef]
25. Khanina, L.G. Classification of forest sites by the Vorobjev-Pogrebnyak's species indicator tables: Database and experience of analysis of forest inventory data. *For. Sci. Issues* **2019**, *2*, 1–30. [CrossRef]
26. Lukina, N.V.; Tikhonova, E.V.; Danilova, M.A.; Bakhmet, O.N.; Kryshen, A.M.; Tebenkova, D.N.; Kuznetsova, A.I.; Smirnov, V.E.; Braslavskaya, T.Y.; Gornov, A.V.; et al. Associations between forest vegetation and the fertility of soil organic horizons in northwestern Russia. *For. Ecosyst.* **2019**, *6*, 34. [CrossRef]
27. Ivanova, N.; Fomin, V.; Kusbach, A. Experience of Forest Ecological Classification in Assessment of Vegetation Dynamics. *Sustainability* **2022**, *14*, 3384. [CrossRef]
28. Migunova, E.S. Forest typology G.F. Morozov—A.A. Krudener—P.S. Pogrebnyak—the theoretical basis of forestry. *For. Bull.* **2017**, *5*, 52–63. [CrossRef]
29. Order of the Federal Forestry Agency. On Approval of the Classification of Natural Fire Hazard of Forests and the Classification of Fire Hazard in Forests Depending on Weather Conditions. Available online: https://docs.cntd.ru/ (accessed on 5 July 2011). (In Russian)
30. Rules of Sanitary Safety in Forests: Decree of the Government of the Russian Federation of 9 December 2020 No. 2047. On the Rules of Sanitary Safety in Forests//Collection of Legislation. 2020. Available online: http://docs.cntd.ru/document/436736467 (accessed on 9 December 2022). (In Russian).
31. Order of the Federal Forestry Agency. On Approval of Guidelines for the State Forest Inventory. 10 November 2011. Available online: http://docs.cntd.ru/document/436736785 (accessed on 15 March 2018). (In Russian)
32. Tsvetkov, P.A. Essay on the history of domestic forest pyrology. *Sib. For. J.* **2015**, *3*, 3–25. [CrossRef]
33. *STATISTICA Version 13.0*; StatSoft: Hamburg, Germany, 2021.
34. Dospekhov, B.A. *Methods of Field Experience with the Basics of Statistical Processing*; Kolos: Moscow, Russia, 2011; 547p, Available online: https://www.elibrary.ru/item.asp?id=19517484 (accessed on 3 October 2022).
35. Tikhomirov, B.P. Burns and their influence on the natural fodder vegetation of the DVK. *Proc. Far East. Branch Russ. Acad. Sci.* **2019**, 102–112.
36. David, L.M. Forest Fires. *Behav. Ecol. Eff.* **2001**, 527–583. [CrossRef]
37. Ding, X.; Liu, G.; Fu, S.; Chen, H.Y.H. Tree species composition and nutrient availability affect soil microbial diversity and composition across forest types in subtropical China. *CATENA* **2021**, *201*, 105224. [CrossRef]
38. Abatzoglou, J.T.; Battisti, D.S.; Williams, A.P.; Hansen, W.D.; Harvey, B.J.; Kolden, C.A. Projected increases in western US forest fire despite growing fuel constraints. *Commun. Earth Environ.* **2021**, *2*, 1–8. [CrossRef]
39. Albrich, K.; Rammer, W.; Turner, M.G.; Ratajczak, Z.; Braziunas, K.H.; Hansen, W.D.; Seidl, R. Simulating forest resilience: A review. *Glob. Ecol. Biogeogr.* **2020**, *29*, 2082–2096. [CrossRef]
40. Hantson, S.; Kelley, D.I.; Arneth, A.; Harrison, S.P.; Archibald, S.; Bachelet, D.; Forrest, M.; Hickler, T.; Lasslop, G.; Li, F.; et al. Quantitative assessment of fire and vegetation properties in simulations with fire-enabled vegetation models from the Fire Model Intercomparison Project. *Geosci. Model Dev. (GMD)* **2020**, *13*, 3299–3318. [CrossRef]

41. Juang, C.S.; Williams, A.P.; Abatzoglou, J.T.; Balch, J.K.; Hurteau, M.D.; Moritz, M.A. Rapid growth of large forest fires drives the exponential response of annual forest-fire area to aridity in the western United States. *Geophys. Res. Lett.* **2022**, *49*, e2021GL097131. [CrossRef]
42. Serra-Diaz, J.M.; Maxwell, C.; Lucash, M.S.; Scheller, R.M.; Laflower, D.M.; Miller, A.D.; Tepley, A.J.; Epstein, H.E.; Anderson-Teixeira, K.J.; Thompson, J.R. Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century. *Sci. Rep.* **2018**, *8*, 6749. [CrossRef]
43. Cheng, X.; Yu, M.; Wang, G.G. Effects of Thinning on Soil Organic Carbon Fractions and Soil Properties in Cunninghamia lanceolata Stands in Eastern China. *Forests* **2017**, *8*, 198. [CrossRef]
44. Buotte, P.C.; Levis, S.; Law, B.E.; Hudiburg, T.W.; Rupp, D.E.; Kent, J.J. Nearfuture forest vulnerability to drought and fire varies across the western United States. *Glob. Chang. Biol.* **2018**, *25*, 290–303. [CrossRef]
45. Cochrane, M.A.; Bowman, D.M.J.S. Manage fire regimes, not fires. *Nat. Geosci.* **2021**, *14*, 455–457. [CrossRef]
46. Coop, J.D.; Parks, S.A.; Stevens-Rumann, C.S.; Crausbay, S.D.; Higuera, P.E.; Hurteau, M.D.; Tepley, A.; Whitman, E.; Assal, T.; Collins, B.M.; et al. Wildfire-driven forest conversion in western North American landscapes. *Bioscience* **2020**, *70*, 659–673. [CrossRef]
47. Hagmann, R.K.; Hessburg, P.F.; Prichard, S.J.; Povak, N.A.; Brown, P.M.; Fulé, P.Z.; Keane, R.E.; Knapp, E.E.; Lydersen, J.M.; Metlen, K.L.; et al. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecol. Appl.* **2021**, *31*, e02431. [CrossRef]
48. Fomin, V.V.; Zalesov, S.V.; Popov, A.S.; Mikhailovich, A.P. Historical avenues of research in Russian forest typology: Ecological, phytocoenotic, genetic, and dynamic classifications. *Can. J. For. Res.* **2017**, *47*, 1–12. [CrossRef]
49. Keyser, A.R.; Westerling, A.L. Predicting increasing high severity area burned for three forested regions in the western United States using extreme value theory. *For. Ecol. Manag.* **2019**, *432*, 694–706. [CrossRef]
50. Parks, S.A.; Abatzoglou, J.T. Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophys. Res. Lett.* **2020**, *47*, e2020GL089858. [CrossRef]
51. Bonari, G.; Fernández-González, F.; Coban, S.; Monteiro-Henriques, T.; Bergmeier, E.; Didukh, Y.; Xystrakis, F.; Angiolini, C.; Chytrý, K.; Acosta, A.T.R.; et al. Classification of the Mediterranean lowland to submontane pine forest vegetation. *Appl. Veg. Sci.* **2021**, *24*, e12544. [CrossRef]
52. Larionov, M.V.; Volodkin, A.A. Parameters of the state and biological stability of woody plants from native flora in conditions of artificial and natural phytocenoses. *Nat. Tech. Sci.* **2021**, *1*, 13–16. [CrossRef]
53. Germaine, H.L.; McPherson, G.R. Effects of biotic factors on emergence and survival of *Quercus emoryi* at lower treeline, Arizona, USA. *Ecoscience* **1999**, *6*, 92–99. [CrossRef]
54. Gibadulina, I.I.; Larionov, M.V.; Maslennikova, N.N. Anatomical and morphological features of the leaves of *Tilia cordata* Mill. as an indicator of the adaptive capabilities of the species to the conditions of the urban environment. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *988*, 032082. [CrossRef]
55. Larionov, M.V.; Larionov, N.V.; Gromova, T.S. Expediency of biological improvement of urban and rural settlements in the Chernozem region and the Volga region. *Nat. Tech. Sci.* **2020**, *6*, 70–72. [CrossRef]
56. Billings, R.; Clarke, S.R.; Mendoza, V.E.; Cabrera, P.C.; Figueroa, B.M.; Campos, J.R.; Baeza, G. Bark beetle outbreaks and fire: A devastating combination for central America's pine forests. *For. Chem. Rev.* **2014**, *124*, 10–15.
57. Gromova, T.S.; Siraeva, I.S.; Ermolenko, A.S.; Larionov, N.V.; Larionov, M.V. Vitality of woody plants as the aggregate basis of the ecological condition of urban and suburban ecosystems of the Khopyor River Region. *Mod. Sci. Actual Probl. Theory Pract. Ser. Nat. Tech. Sci.* **2020**, *7*, 20–27. [CrossRef]
58. Ding, J.; Travers, S.K.; Eldridge, D.J. Grow wider canopies or thicker stems: Variable response of woody plants to increasing dryness. *Glob. Ecol. Biogeogr.* **2020**, *30*, 183–195. [CrossRef]
59. Larionov, M.V.; Tarakin, A.V.; Minakova, I.V. Creation of artificial phytocenoses with controlled properties as a tool for managing cultural ecosystems and landscapes. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *848*, 012127. [CrossRef]
60. Lemaire, J.; Vennetier, M.; Prévosto, B.; Cailleret, M. Interactive effects of abiotic factors and biotic agents on Scots pine dieback: A multivariate modeling approach in southeast France. *For. Ecol. Manag.* **2022**, *526*, 120543. [CrossRef]
61. Han, X.; Zhao, Y.; Chen, Y.; Xu, J.; Jiang, C.; Wang, X.; Renying, Z.; Lu, M.-Z.; Zhang, J. Lignin biosynthesis and accumulation in response to abiotic stresses in woody plants. *For. Res.* **2022**, *2*, 9. [CrossRef]
62. Tetemke, B.A.; Birhane, E.; Rannestad, M.M.; Eid, T. Species diversity and stand structural diversity of woody plants predominantly determine aboveground carbon stock of a dry Afromontane forest in Northern Ethiopia. *For. Ecol. Manag.* **2021**, *500*, 119634. [CrossRef]
63. Van Auken, O.W. Causes and consequences of woody plant encroachment into Western North American grasslands. *J. Environ. Manag.* **2009**, *90*, 2931–2942. [CrossRef]
64. Liu, M.; Zhang, Z.; Liu, X.; Li, M.; Shi, L. Trend Analysis of Coverage Variation in Pinus yunnanensis Franch. Forests under the Influence of Pests and Abiotic Factors. *Forests* **2022**, *13*, 412. [CrossRef]
65. Vedernikov, K.E.; Bukharina, I.L.; Udalov, D.N.; Pashkova, A.S.; Larionov, M.V.; Mazina, S.E.; Galieva, A.R. The State of Dark Coniferous Forests on the East European Plain Due to Climate Change. *Life* **2022**, *12*, 1874. [CrossRef]
66. Volodkin, A.A.; Volodkina, O.A.; Larionov, M.V. Dynamics of reproduction of forest plantations in the forest-steppe zone of the Middle Volga Region. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *979*, 012101. [CrossRef]

67. Royal, E.J.; Greene, D.U.; Miller, D.A.; Willson, J. Influence of landscape and vegetation characteristics on herpetofaunal assemblages in Gulf Coastal Plain pine forests. *J. Wildl. Manag.* **2022**, *86*, e22199. [CrossRef]
68. Thapa, U.K.; George, S.S. Detecting the influence of climate and humans on pine forests across the dry valleys of eastern Nepal's Koshi River basin. *For. Ecol. Manag.* **2019**, *440*, 12–20. [CrossRef]
69. Zheng, S.; Webber, B.L.; Didham, R.K.; Chen, C.; Yu, M. Disentangling biotic and abiotic drivers of intraspecific trait variation in woody plant seedlings at forest edges. *Ecol. Evol.* **2021**, *11*, 9728–9740. [CrossRef] [PubMed]
70. Chavardès, R.D.; Danneyrolles, V.; Portier, J.; Girardin, M.P.; Gaboriau, D.M.; Gauthier, S.; Drobyshev, I.; Cyr, D.; Wallenius, T.; Bergeron, Y. Converging and diverging burn rates in North American boreal forests from the Little Ice Age to the present. *Int. J. Wildland Fire* **2022**, *31*, 1184–1193. [CrossRef]
71. Connor, S.; Araújo, J.; Boski, T.; Gomes, A.; Gomes, S.D.; Leira, M.; da Conceição Freitas, M.; Andrade, C.; Morales-Molino, C.; Franco-Múgica, F.; et al. Drought, fire and grazing precursors to large-scale pine forest decline. *Divers. Distrib.* **2021**, *27*, 1138–1151. [CrossRef]
72. Şahan, E.A.; Köse, N.; Güner, T.; Trouet, V.; Tavşanoğlu, Ç.; Akkemik, Ü.; Dalfes, N. Multi-century spatiotemporal patterns of fire history in black pine forests, Turkey. *For. Ecol. Manag.* **2022**, *518*, 120296. [CrossRef]
73. Sánchez-Cámara, A.E.S. Dynamics of mediterranean pine forests reforested after fires. *J. For. Res.* **2022**. [CrossRef]
74. Wu, T.; Kim, Y.-S. Pricing ecosystem resilience in frequent-fire ponderosa pine forests. *For. Policy Econ.* **2013**, *27*, 8–12. [CrossRef]
75. Matusick, G.; Hudson, S.J.; Garrett, C.Z.; Samuelson, L.J.; Kent, J.D.; Addington, R.N.; Parker, J.M. Frequently burned loblolly–shortleaf pine forest in the southeastern United States lacks the stability of longleaf pine forest. *Ecosphere* **2020**, *11*, e03055. [CrossRef]
76. Merschel, A.; Beedlow, P.; Shaw, D.C.; Woodruff, D.R.; Lee, E.H.; Steve, C.; Comeleo, R.; Hagmann, K.; Reilly, M.J. An Ecological Perspective on Living with Fire in Ponderosa Pine Forests of Oregon and Washington: Resistance, Gone but not Forgotten. *Trees For. People* **2021**, *4*, 100074. [CrossRef]
77. Sandström, J.; Edman, M.; Jonsson, B.G. Rocky pine forests in the High Coast Region in Sweden: Structure, dynamics and history. *Nat. Conserv.* **2020**, *38*, 101–130. [CrossRef]
78. Swann, D.E.B.; Bellingham, P.J.; Martin, P.H. Resilience of a tropical montane pine forest to fire and severe droughts. *J. Ecol.* **2022**, *111*, 90–109. [CrossRef]
79. Maksimova, E.; Abakumov, E. Micromorphological characteristics of sandy forest soils recently impacted by wildfires in Russia. *Solid Earth* **2017**, *8*, 553–560. [CrossRef]