Analysis of post-fire effects in pine stands in various landscape conditions of the boreal zone

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Abstract. The study analyzes the pyrogenic effect on the condition of pine trees in two landscapes of the Leningrad region. The polynomial regression method in the description of the process tree attrition depending on the scorch height on the trunk allowed determining the trend of the thinning process for pine trees in different vitality conditions. The post-fire attrition of trees follows different scenarios in the studied landscapes of the Luga Upland and Putilov Plateau. The correlation analysis showed that the inverse relationship between the thickness of the remaining forest ground cover and the scorch height on trunks, i.e., the intensity of the past fire, is stronger in the landscape of the Putilov Plateau than in the Luga landscape. The studied landscapes created a different environment for the emergence and spread of fires of both natural and anthropogenic origin.

1. Introduction

Fires have always been a part of the factors acting in the formation of light-needle coniferous stands, for example, pine stands, and for many centuries the fires retain their particular importance in forest forming [1, 2]. In the boreal zone, pine forests of natural origin have been developing and continue doing so under the influence of fires, which is the dominant factor that determines their composition and structure [3-5]. Fires also act as a driving selection factor, contributing to the survival of fire-resistant forest-forming species. Post-fire pine forests are characterized by a non-catastrophic thinning of the stands, as well as the dying-off of individual trees, and these processes have a positive effect on natural forest regeneration, increasing light permeability that ultimately favors the emergence of a new generation of pine. Surface fires generally damage underdeveloped and weakened trees. In each individual geographical area, in turn, the degree of damage to stands by surface forest fires is determined by the characteristics of the fires, fire type, model, strength, and frequency of fire exposure. In areas where pine stands grow on sandy and sandy loam-loamy soils, surface fires of up to moderate force do not cause significant damage, which is a manifestation of natural adaptation for self-preservation [6-9]. Our study in the territory of the Leningrad Oblast (region) is driven by the fact that the effects of surface fires in coniferous forests on the areas of the Northwest district of Russia have not been studied sufficiently.
2. Methods and Materials

2.1. Objects of study
To study the impact of the surface fires, were created two experimental sites in 2 landscape research areas of the Leningrad Oblast. The landscape of the Luga Upland is characterized by two types of landforms: 1 landform is sandy and sandy loam kame hills with a relative height of 25–40 m (up to 75 m) with lichen, heather, and lingonberry pine forests and surface- or slightly podzolic soils. In depressions between the hills, the soils are slightly podzolic ferruginous and swampy, or alternatively there might be small lakes. 2 landform - a hilly-moraine complex with non-carbonate red-brown light and medium boulder loam hills with weakly or moderately podzolic soils and native southern taiga spruce green-moss forests replaced by birch and aspen and gray alder forests [10].

This landscape area is exposed to fire in the first place, which is associated with its soil and hydrological conditions, as well as the greatest anthropogenic load compared to the rest of the Luga administrative region of the Leningrad Oblast.

Putilov Plateau is the eastern part of the Ordovician Upland with absolute heights of 50-90 m. The upper layer of bedrock is composed by Ordovician calcareous deposits. Quaternary sediments overlap limestones with a thin cover of moraine loam and boulders on the surface. The soils are represented by varved clay, loam, sandy loam, very-fine, fine, medium-coarse sands, and locally gravel-pebble soils. Kames are composed mainly of sand of various grain size with interbeds of sandy loam and loam [10]. The thickness of kame massifs is up to 15.00–25.00 m. Fluvio-glacial deposits are localized and lay on the surface and under glaciolacustrine deposits, on glacial deposits. They are represented by sands of different grain size with an average gravel and pebble content up to 10%, in some cases reaching 30–40%. Sands that compose eskers and kames have a well-defined stratification, different directions, thicknesses from 0.30 m to 4.00-6.00 m, sometimes reaching 10.00 m. Sod-carbonate-podzolized soils are widely spread under the same conditions; they are characterized by a fairly well-developed sod horizon and signs of weak podzolization. At the northern end of the Plateau, covered by weakly weathered boulder sands and sandy loams with a large amount of very coarse material, sod-cryptopodzolic soils are widespread. In general, this landscape has more humid soils than the Luga Upland landscape [10].

The taxation characteristics of the stands exposed to surface fires differ between the studied areas. In the Luga landscape, these are mostly pure stands or stands that can be considered pure, with a share of spruce or birch 1-2 specimens in Vaccinium myrtillus and Vaccinium vitis-idaea forest types (table 1). In the Putilov Plateau landscape, forest stands exposed to fire have a greater share of spruce in their composition. These stands also differ by their growth class — the Luga landscape has mainly III class stands, whereas the Putilov Plateau - the II growth class stands. The taxation data indicate that the stands of the experimental plots differ from each other, the relative density of the stands at the experimental plots (PP) and the control plots (CPP) varies from 0.4 (PP-3) to 0.8 (CPP-17). The research was based on the experimental plot method. The dimensions and description of the plots is given above, in table 1. Were selected forest plots with the area ranging from 0.01 ha to 0.3 ha and exposed to surface fires of different intensities. All experimental plots were created and treated according to the generally adopted methods of forest management. Taxation of stands was done instrumentally. The complete enumeration of trees on the experimental plots was done adopting a 4 cm step for diameter classes, divided into five classes of sanitary state [11, 12]. The trees were measured with a tree caliper at a height of 1.3 meters from the root collar. The sum of the cross-sectional areas per 1 ha was derived from the tables of the sums of cross-sectional areas per number of trees and the cross-sectional area of an average tree; the average diameter was determined. Plot density was measured using an angle gauge. The average height of the stand was determined by selecting 3-5 trees with a subsequent measurement using the Blume-Leiss device. The age was determined using an increment borer. The vitality condition of pine trees was determined using the methodology described in the guide for sanitary measures.
The trees were divided into the following categories: 1 - healthy (without the signs of weakening), 2 - weakened, 3 - considerably weakened, 4 - drying out, 5 - deadwood. The level of damage to the stand was calculated from the share of trees of different vitality categories. For that, the index of stands condition (weighted average category of sanitary condition - CSC) was used. It is is calculated as the weighted average of the condition categories of trees, given as:

$$C_{av} = \frac{P_i \times C_{i1} + P_2 \times C_{i2} + P_3 \times C_{i3} + P_4 \times C_{i4} + P_5 \times C_{i5}}{\sum P_i}$$

(1)

where, $C_{av}$ is the weighted average condition of the species; $P_i$ is the percentage of each condition category, $C_i$ is the index of the tree condition category [12]. The intensity of the fire was determined by the height of the scorch on the trunks [12]. The height of the scorch on tree trunks was measured by a measuring tape; the collected data were processed in the office to obtain the average scorch heights in the studied area.

To describe the relationship between the attrition of trees and the height of scorch on the trunk, i.e., the intensity of the fire, we used a polynomial regression model [13, 14]. The coefficients of lower degree polynomials can be interpreted specifically depending on the content of the time series. In our case, they can be interpreted as an increase in the attrition of trees ($a_1$), an acceleration of this process ($a_2$), a change in acceleration ($a_3$), the initial level of the series at $t = 0$ ($a_0$). Usually, the maximal order of polynomials used in environmental studies is third-degree polynomials. Using higher degree polynomials to determine the trend is not justified since in this case, the obtained approximation functions will reflect random deviations, which contradicts the objective of the trend.
A second degree polynomial is applicable when there is a uniform acceleration in the process development (i.e., the increase or decrease of levels is uniformly accelerated). If the coefficient $a^2 > 0$, then the branches of the parabola are directed upward; if $a^2 < 0$, then they are directed downward. Coefficients $a_0$ and $a_1$ do not affect the shape of the parabola, they only define its location. A third-degree polynomial is defined as:

$$y_t = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

(2)

This polynomial can change the sign of the ordinates increase once or twice. A distinctive feature of polynomials is that the increment is not explicitly dependent on ordinate values ($y_t$). We used the analysis of variance of the obtained data to detect the influence of a number of individual factors on the experimental results [14].

2.2. Experimental part

The studied areas affected by fire present the traces of tree damage: burnt bark, yellowing needles, etc. After fires, the number of drying out trees varies from 2 to 11%, the amount of deadwood is from 2 to 6%. This indicates a thinning of the stands. The highest thinning indicator was recorded three years after the fire on the plot (PP-13). It is presented by deadwood (8%) and drying out trees (9%). The largest projective cover of the territory by undergrowth that emerged after the fire was also recorded on the same experimental plot. These data indicate that after the surface fires the stands are thinned, which should be considered a favorable factor for subsequent abundant reforestation.

Figures 1-4 present the relationships between the attrition of trees and the height of scorch on the trunks. Each experimental plot had its own distinguishing feature: a projective undergrowth cover and thickness of forest ground cover that in turn had a significant effect on the height of scorch on the trunks, and, consequently, on the vitality of trees. Deadwood was registered on the experimental plots 3 and 5, comprising 7% and 6%, respectively. The greatest amount of drying out trees was observed on the experimental plots 6 and 7, and was 8% and 11%, respectively. This attrition rate of the trees is determined by the scorch height on the trunks, leading, in its turn, to thinning of the stands. The height of the scorch on these experimental plots was between 0.9 and 1 m, i.e., the damage to the trees at this height can cause weakening and attrition of the trees. There were also stands minimally damaged by the surface fires. At these experimental plots, the observed damage is not significant, indicating an individual resistance of the trees to the surface fires: thick bark at the base of the trunk, absence of outward protruding roots.

To describe the dependence of the attrition of trees on the scorch height on the trunk, i.e., the intensity of the fire, we used a polynomial regression. The obtained graphical data can be interpreted as follows: for the Luga Forestry, the obtained relationships reflect a high degree of correlation between the scorch height on the trunks and the attrition of trees (figure 5-8). With an increase in the height of scorch on the trunks, depending on the vitality category of the trees: weakened, considerably weakened, and drying out, the attrition rate of trees also increases. The correlation coefficient also increases: for a weakened category it is $R = 0.52$, for considerably weakened $R = 0.69$, and for drying out trees it is $R = 0.71$. Burning of the root collar area up to a height of 0.4 m determines the percentage of trunk attrition for these categories of trees. However, if for these categories with an increase in the scorch height the trunk attrition rate decreases, then for deadwood the opposite is noted, with a high correlation coefficient $R = 0.73$. Apparently, this can be explained by the fact that these trees have already lost their physical and mechanical resistance, and the higher the fire damage to the trunk, the more trees transform to waste.

Comparing the coefficients in the equations, with a certain degree of probability they can be interpreted as follows: the indicator of the tree attrition increment ($a_1$) has the highest values of 17.57-22 in the categories of weakened, considerably weakened, and drying out trees. In the category of deadwood this coefficient is not high - 6. The acceleration of the trunk attrition process indicated by the coefficient ($a_2$) is higher among considerably weakened and drying out trees: 61-65, which is logical, as these categories of trees lose their vitality. In the category of weakened trees, this process is
not so acute, therefore the coefficient \( (a_2) \) is lower – 23. The change in acceleration \( (a_3) \) is positive only in the category of weakened trees; it indicates the increase of the trees attrition rate. In the categories of considerably weakened and drying out trees, the coefficients have the greatest absolute values - 42 and 33 - with a negative sign, i.e., the attrition acceleration rate decreases. This coefficient is minimal in the deadwood category, i.e., similar to the previous cases, the acceleration of the attrition rate almost doesn't change.

![Figure 1](image1.png)  
**Figure 1.** The relationship between the attrition of weakened trees and the scorch height (Luga landscape).

![Figure 2](image2.png)  
**Figure 2.** The relationship between the attrition of considerably weakened trees and the scorch height (Luga landscape).

![Figure 3](image3.png)  
**Figure 3.** The relationship between the attrition of drying out trees and the scorch height (Luga landscape).

![Figure 4](image4.png)  
**Figure 4.** The relationship between the attrition of deadwood and the scorch height (Luga landscape).

Figures 5-8 show the relationships between the attrition of trees and the height of scorch on the lower part of trunks for the Putilov Plateau landscape. At the maximal scorch height of 1.3 m on PP 13 the attrition reached (9%). In the Putilov Plateau landscape, the attrition of trees depending of their vitality categories is different from the Luga landscape. The attrition rate of weakened trees increases as the scorch height increases, and the correlation coefficient is \( R=0.63 \), whereas for considerably weakened trees this relationship is not as strong, \( R=0.52 \). For drying out trees and deadwood the relationship between trees attrition rate and the scorch height is very strong, \( R=0.85-0.87 \), and the trend line demonstrates an increase.
Figure 5. The relationship between the attrition of weakened trees and the scorch height (Putilov Plateau landscape).

Figure 6. The relationship between the attrition of considerably weakened trees and the scorch height (Putilov Plateau landscape).

Figure 7. The relationship between the attrition of drying out trees and the scorch height (Putilov Plateau landscape).

Figure 8. The relationship between the attrition of deadwood and the scorch height (Putilov Plateau landscape).

For the Putilov Plateau landscape and the Luga landscape, were obtained different equations and coefficients describing the relationship between the attrition rate and the scorch height depending on the vitality categories of the trees on the experimental plots. Comparing the coefficients of the equations, with a certain degree of probability the obtained data can be interpreted as follows: the coefficient of the tree attrition increment \( a_1 \) is positive for all vitality categories of trees and has the greatest value in the category of weakened trees, 11.5; in other categories, this coefficient is rather low. The coefficient of the trunk attrition acceleration is low for all categories of trees and lies within 2 and 8. The change in acceleration \( a_3 \) of the trees attrition has the opposite direction for the categories of drying out trees and deadwood. In the category of weakened and drying out trees the coefficient is rather low, less than one.

3. Results and Discussion
We have found a relationship between the attrition of the trees and the height of scorch: the higher were the flames during the fire, the greater was the damage to the trees. On the experimental plots of the Luga landscape, the damaged stands were represented by deadwood (1.9%) and drying out trees (3.5%) of the total amount of examined stands. On the experimental plots of the Putilov Plateau landscape, the damaged stands were represented by deadwood (2.3%) and drying out trees (3.7%) of the total amount of examined stands. It should be underlined that in the Putilov Plateau landscape, the
percent of drying out trees is higher than on the similar experimental plots of the Luga landscape; this is caused by the presence of trees of a smaller diameter comparing to other trees. The most part of the stands was not damaged that was visually verified; this, after all, will not cause large-scale attrition of the trees and will not pose the risk of insect pest outbreak.

In the pine stands on the experimental plots, the height of the scorch is generally 0.7-0.8 m (figure 9), the thickness of the forest ground cover is 2.1 cm. This favorably affects the heating of the soil and its mineralization in the post-fire period and, most importantly, it stimulates the germination of pine seeds. The greatest scorch height of 1.3 m and the smallest remaining thickness of forest ground cover of 1.2 cm were registered at the CPP-13. We have found a direct relationship between the remaining forest ground cover after the fire and the height of the scorch on the trunks. The lowest scorch height and the thickest remaining forest ground cover of 1.2 cm were registered at the CPP-9. This is obviously an obstacle to quality natural regeneration in this area.

![Figure 9. The relationship between the thickness of the remaining forest ground cover and the scorch height in the Luga landscape (a) and the Putilov Plateau landscape (b).](image)

Differences in the relief, soils, and vegetation of these landscapes determine the possibilities and rationale of their use by human and define the nature of anthropogenic impact. The correlation analysis showed that the inverse relationship between the thickness of the remaining forest ground cover and the scorch height on trunks, i.e., the intensity of the past fire, is stronger in the landscape of the Putilov Plateau, R=-0.92, than in the Luga landscape, R=-0.72.

The analysis of variance revealed statistically significant differences in the thickness of the remaining forest ground cover after the fire in these landscapes (table 2). This indicates that in the habitats of one type of forest there are created different conditions for the emergence and spread of fires of both natural and anthropogenic origin.

**Table 2.** The analysis of variance of the thickness of the remaining forest ground cover after the fire in the studied landscapes.

| Variance          | Sum of squares | Graduates of freedom | Mean square | Effective F-value | Theoretical F-value F_{tab}=5% | The probability of accepting the null hypothesis |
|-------------------|----------------|----------------------|-------------|-------------------|------------------------------|--------------------------------------------------|
| Total             | 6.357778       | 17                   |             | 3.21              | 3.0                          | 0.06                                              |
| Variants          | 4.947778       | 9                    | 0.549753    |                   |                              |                                                   |
| Unexplained       | 1.41           | 8                    | 0.17625     |                   |                              |                                                   |

4. Conclusion
The results of the study allow concluding that:
The post-fire attrition of trees follows different scenarios in the studied landscapes.
We have found a relationship between the attrition of the trees and the height of scorch, i.e., the higher were the flames during the fire, the greater was the damage to the trees.
The subsequent correlation between the condition of trees and fire impact has different strength depending on landscape conditions.
We have found a direct relationship between the remaining forest ground cover after the fire and the height of the scorch on the trunks.
The analysis of variance revealed statistically significant differences in the thickness of the remaining forest ground cover after the fire in the studied landscapes.
These landscapes created a different environment for the emergence and spread of fires of both natural and anthropogenic origin.

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