Influence of high-temperature convective flow on viability of Scots pine needles (*Pinus sylvestris L.*)

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Abstract

During the attack of a forest fire, the vegetative organs of plants are affected by high temperatures, which lead to their stressful state. At the time of burning, it is quite difficult to record temperature changes in the tree crown and the associated reactions in the photosynthetic needle apparatus. This article presents the results of modelling a high-temperature effect simulating a convective flow from a ground fire. Experimental heating at 55° C lasted for 5 and 10 minutes. Evaluation of the response was carried out by the parameters of rapid fluorescence (Fv / Fm, ETR), the state of the pigment complex, the relative water content in the needles. To characterize the degree of heat endurance and short-term effects concerning thermal damage, saplings of Scots pine (Pinus sylvestris L.) in different periods of the vegetation phase were used. The researchers have discovered different levels of heat resistance of the needle assimilation apparatus. Usually heat resistance is rising by the end of the vegetation season. The data obtained in June show that heating of the saplings led to a significant suppression of the photosynthesis rate. In subsequent periods (July, August, September), the photochemical quantum yield (Fv / Fm) was restored to 75% and 60% from the initial level on average, after 5- and 10-minute heating respectively. The values of the electron transport rate (ETR) for saplings selected in September restored to the initial level within 3 days after a short heat exposure. For the study of long-term effects after high-temperature exposure during the vegetation season, the undergrowth of Scots pine was used. Restoration of the photosynthetic activity in needles from model trees was observed only after a short-term (5-minute) impact, but by the end of the studied period the restoration had not reached the control values. A longer heating (during 10 minutes) resulted in an irreversible suppression of photosynthesis and destruction of the photosynthetic apparatus, as evidenced by the decrease in the number of photosynthetic pigments.

Keywords Pinus sylvestris · Heat stress · Chlorophyll · fluorescence · Forest fires

Introduction

The problem of the resistance of plant organisms and forest ecosystems as a whole to changing environmental conditions and to the influence of various stress factors has long been the focus of researchers (Ashraf and Harris 2013; Walter et al. 2013). During the life cycle, plants are affected by changes in the existing environmental regime as a result of human activity, as well as by various biotic and abiotic factors that influence their viability. For forest ecosystems, one of the most important cyclically recurring environmental factors is forest fires. Annually, from 4.5 to 27 thousand forest fires (Ivanova et al. 2014) occur in forest and steppe zones of Siberia, most of them affecting larch (Larix Sibirica) and Scots pine (Pinus Sylvestris L.). Many authors have obtained data on the multifaceted effect of forest fires on various components of forest ecosystems, both through direct exposure to high temperatures during burning, and through subsequent changes in environmental conditions (Bond and Van Wilgen 1996; Michaletz and Johnson 2007; Dayamba et al. 2010; Sudachkova et al. 2016). During the burning of the forest floor, the temperature of the convective flow in the crown and cambial zone of the forest stand may vary depending on the intensity and nature of burning, as well as the age of the stand, which determines the height of the crown and the thickness of the bark (Varner et al. 2009; Yadegarnejad et al. 2015; Michaletz 2018). Young trees are the most vulnerable, as they have thin bark and low crown. The silvicultural and ecological consequences of fires, depending on the intensity of the fire (strength and time of action) and the structure of forest communities, can be both negative and positive (Verkhovets 2000; Renninger et al. 2013; Matthew et al. 2017; Akburak et al. 2018). Such are the changes in growth rates and species composition of forest plantation; transformation of chemical and biological properties of the soil, transformation of the hydrological regime, changes in the availability of nutrients, colonization by pests (Certini 2005; Tarasov et al. 2008; Bogorodskaya et al. 2010; Ivanova et al. 2014; Guo et al. 2015).

The damage to the stand is directly and simultaneously caused by the intensity of burning and the various degrees of heat resilience typical of the species (Bond and Van Wilgen 1996; Yadegarnejad et al. 2015). At the same time, the possibility of repairing injuries got during heat exposure in a fire depends on the degree of impairment of physiological functions in living tissues of the roots, stem and crown (Swezy DM and Agee 1991; Dickinson et al. 2005; Sudachkova et al. 2016).The convective flow of a ground fire has a direct effect on the vegetative organs of plants, which subsequently influences the state of the organism as a whole. Needles, being an assimilating organ of woody plants, are the structural unit of the shoot which is the most sensitive to environmental changes. Under the influence of heat flow on the crown, various changes take place in the structural and functional organization of the leaves, including, among other things, the intensity of photosynthesis (Fleck et. al. 1996; Klimov 2008; Ashraf and Harris 2013). These changes are of particular interest, as they can be indicators of a stressful state.

The study of changes in photosynthetic activity under the influence of thermal effects, on the one hand, can concern the stress response of a tree as a biological system, on the other hand, it may help to determine the degree of a tree weakening during the fire and during the damage repair. The aim of the work was to examine the response of the photosynthetic apparatus of pine needles to high temperatures which simulated the effect of convective flow on the crown during a ground fire.

Materials and methods

Plant material and study site

The experimental site was located outside Krasnoyarsk (56°22′07.48″ N 92°57′17.95″ E). This territory geographically belongs to the Central Siberian Plateau.

To characterize the degree of heat endurance and short-term effects from thermal damage, there were used Scots pine needles at different periods during the vegetation phase (June, August, September). For experiments on modelling heat exposure, saplings of 10 model 20-year old pine trees were chosen as samples. From each tree, the researchers selected 3 branches among the branches of the lower part of the crown (a height of 2.5-3 meters); for measurements the needles of the second year were used. The cut parts in vessels with water were delivered to the laboratory where their condition was monitored during the next four days.

To characterize the long-term effects after high-temperature exposure, which remain throughout the vegetative period, there was used the undergrowth of Scots pine. In the spring, model trees, growing under the same conditions of moisture and lighting, were transplanted into garden plant trays and placed under the canopy of an adult forest stand. The undergrowth trees were about 10 years old, with an average height of 50-70 cm. An experiment of modelling a convective flow was carried out on June 30 by heating a part of the main shoot of the second year (the second whorl). Following this, during the vegetation period, the parameters of fast fluorescence on the needles of the second year were recorded, and after that on the needles of the first year, too.

Convection flow simulation

Finding the temperature of the convective flow in the crown during burning and the correspondent physiological changes is quite a difficult task; therefore, all experiments were carried out on an installation aimed to simulate a stable convective flow of a given temperature (Figure 1). The installation allows the researchers to create a steady convective flow, which imitates the effects of fire on a certain branch and model trees (Valendik et al. 2008). Heating was simulated by heat flow from the flame of a gas burner. The duration of heating was 5 and 10 minutes at a temperature of 55°C.

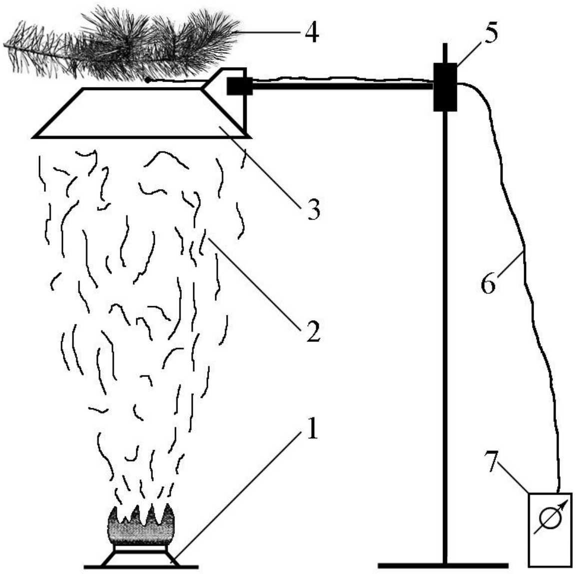


Fig. 1 Convection Heater Installation for Samples:

1 – gas burner, 2 – convective flow, 3 – flow regulator,

4 – sample, 5 – stand with holder, 6 – thermocouple,

7 – temperature sensor

The sample was fastened horizontally on the flow regulator, the thermocouple was fixed directly under the sapling in the centre of the flow, where the temperature corresponded to the temperature set in the experiment. The flow temperature was recorded at intervals of one second by standalone recorders. Measuring tools were chromel-alumel thermocouples of factory production.

Measurements were carried out in 5 biological replications for 10 model trees at each temperature and heating time parameters. The saplings and trees not exposed to high temperature were used as control ones.

Measurement of fast fluorescence parameters

One of the most common methods for studying the activity of photosynthetic processes is PAM-fluorometry, based on pulse amplitude modulation (Goltsev et.al. 2014).

Fast fluorescence parameters were measured by fluorometer Junior-PAM (Walz, Germany) for pulse-amplitude modulated fluorometry. Control values were those obtained on saplings before high temperature exposure and those obtained on the model undergrowth which did not undergo heat treatment. Fluorescence parameters were calculated using WinControl program. The ratio of Fv/Fm was used as an estimate of the maximum quantum yield of photosystem II photochemistry, with *ETR* characterizing the density of electron flow through the electron transport chain of the thylakoid membranes (Maxwell and Johnson 2000).

Estimation of the content of photosynthetic pigments

Various deviations from the optimal for the species environmental conditions influence the quantitative and qualitative characteristics of the pigment stock of plastids, which is an important indicator of the physiological state of the forest stands. The content of photosynthetic pigments was studied on the needles of the second year of life with a SPEKOL1300 Analytik Jena AG spectrophotometer after extraction in 85% acetone (Gavrilenko and Zhigalova 2003). The amount of pigments was measured using three wavelengths: 452.5, 644 and 663 nm. The quantitative content of the sum of *a+b* and *Car* in the needles not exposed to heat was taken as the control value.

Measurement of the relative water content (RWC)

RWC is a parameter which enables characterizing the water regime of a plant in response to various stress factors. To calculate RWC we used samples of 2-year-old needles of Scots pine (experimental saplings). The needles were taken from the middle part of the tree in at least 5 replications for each study period. Raw mass (fresh weights) was figured out before saplings’ exposure to convective flow (these were control values); for experimental samples fresh weights were calculated 30 minutes after heat exposure at 55°C. Mass of completely water-saturated needles (turgid weights) was measured after soaking needles in distilled water in Petri dishes for 16-18 hours, at room temperature, in a laboratory with low light. After soakage the material was blotted quickly and carefully with dry paper tissues. The last weighing (dry weights) was carried out after drying the samples of needles in a drying oven for 72 hours at 70°C. RWC was calculated using the equation by Schonfeld et al. 1988

$$\text{RWC (\%)} = \frac{\text{fresh weight - dry weight}}{\text{turgid weigh - dry weight}} \times 100$$

Results and discussion

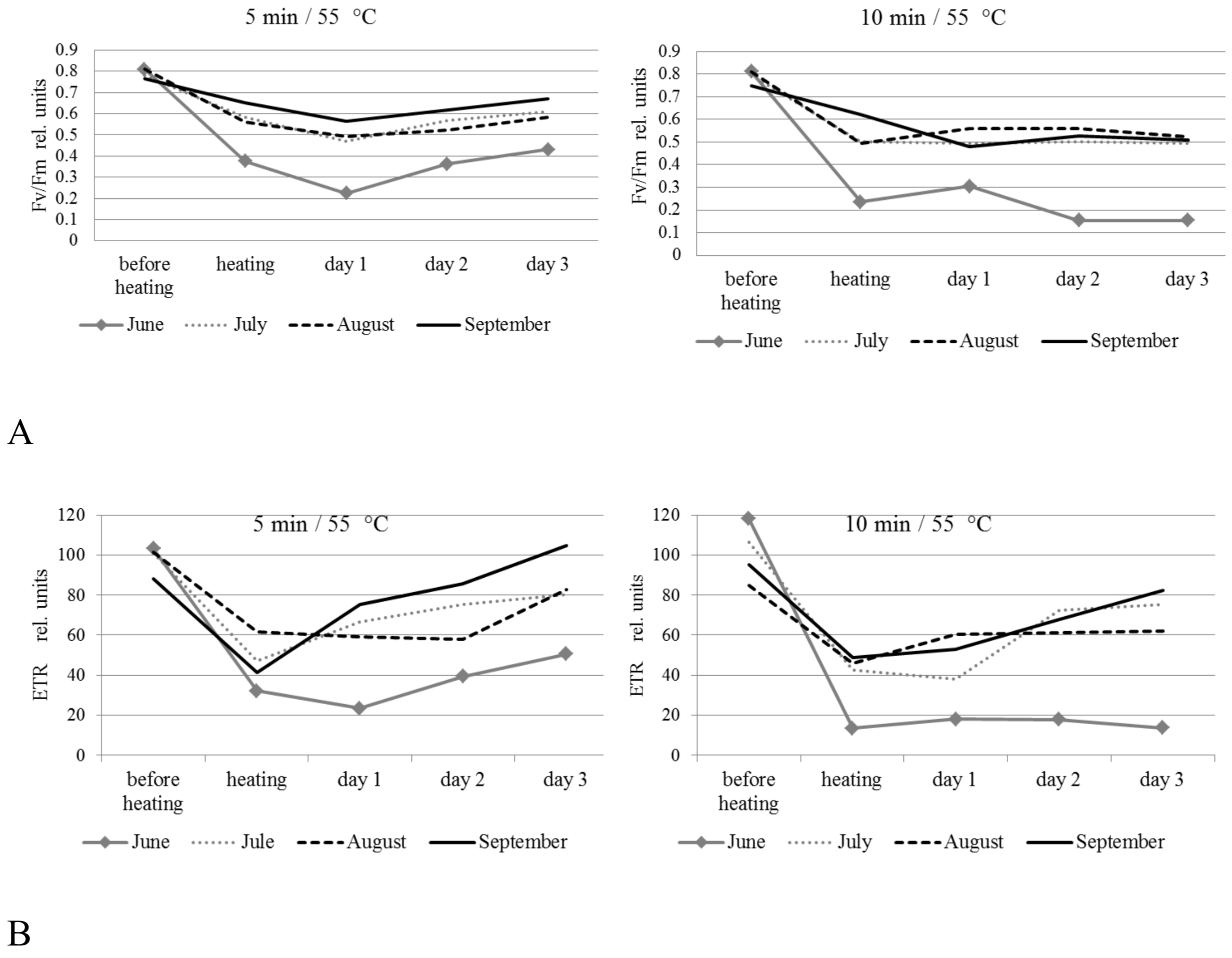
When exposed to a temperature of 55°C for 5 minutes the saplings of Scots pine showed different thermal stability of the needles during various vegetative periods. During the period of saplings' growth (June), the two-year-old needles were damaged and fell off much more intensively than in subsequent periods, and 10-minute heating turned out to be completely detrimental to the saplings with most of the needles turning yellow and falling off on the next day of observation. Resilience of the pine needles to the high temperatures had increased by the end of the growing season. Visual assessment of the saplings condition after 5-minute heating in August and September (three-day exposure in the laboratory) did not provide us with characteristic signs of needle drying, while longer heating led to that about half of the needles went yellow and dried in 3 days on average.

In a high-temperature simulation experiment conducted at the end of June, 5-minute heating affected the state of the assimilation apparatus but to different extent, according to a visual assessment of the state of undergrowth. On the next day after exposure, there was found a slight browning of the tips of the needles (about 10% of the material), and after 2 weeks the number of the needles getting brown increased and reached 30%, at the same time by the end of the observation the whole number of the needles had fallen by more than a half as compared to the control branches. A longer heating (during 10 minutes) resulted in a significant yellowing of the needles in 4 days. A month later, the stressed two-year-old needles fell off almost completely.

The parameters of rapid fluorescence on the needles after the heat stress exposure of the saplings

Chlorophyll fluorescence analysis is a means that is often used to study the effect of various environmental stresses on photosynthesis (Briantais et al. 1996; Chaerle and Van Der Straeten 2000; Lichtenthaler et al. 2007; Guidi and Degl'Innocenti 2011). Fluorescent indicators of the needles reveal the functional state of plants in general (239(Goltsev et al. 2012; Yordanov et al. 2012). Figure 2 shows fast fluorescence indicators recorded on saplings during different study periods.

One of the main characteristics of the photosystems' work is the quantum yield of photochemical energy conversion or photochemical quantum yield (Fv / Fm), which signals the potential efficiency of photosystem II (Björkman and Demmig 1987). The electron transport parameter (ETR) determines the intensity of the electron transport in the plastoquinone carrier chain. Thus, increased electron movement in cells is associated with a higher rate of photosynthesis during vegetation, while its suppression under the action of abiotic stresses accounts for photo-oxidation (Kreslavski et al. 2007, Goltsev et al. 2012).



A – Fv / Fm (maximum photochemical quantum yield of photosystem II); B – ETR (electron transport rate).

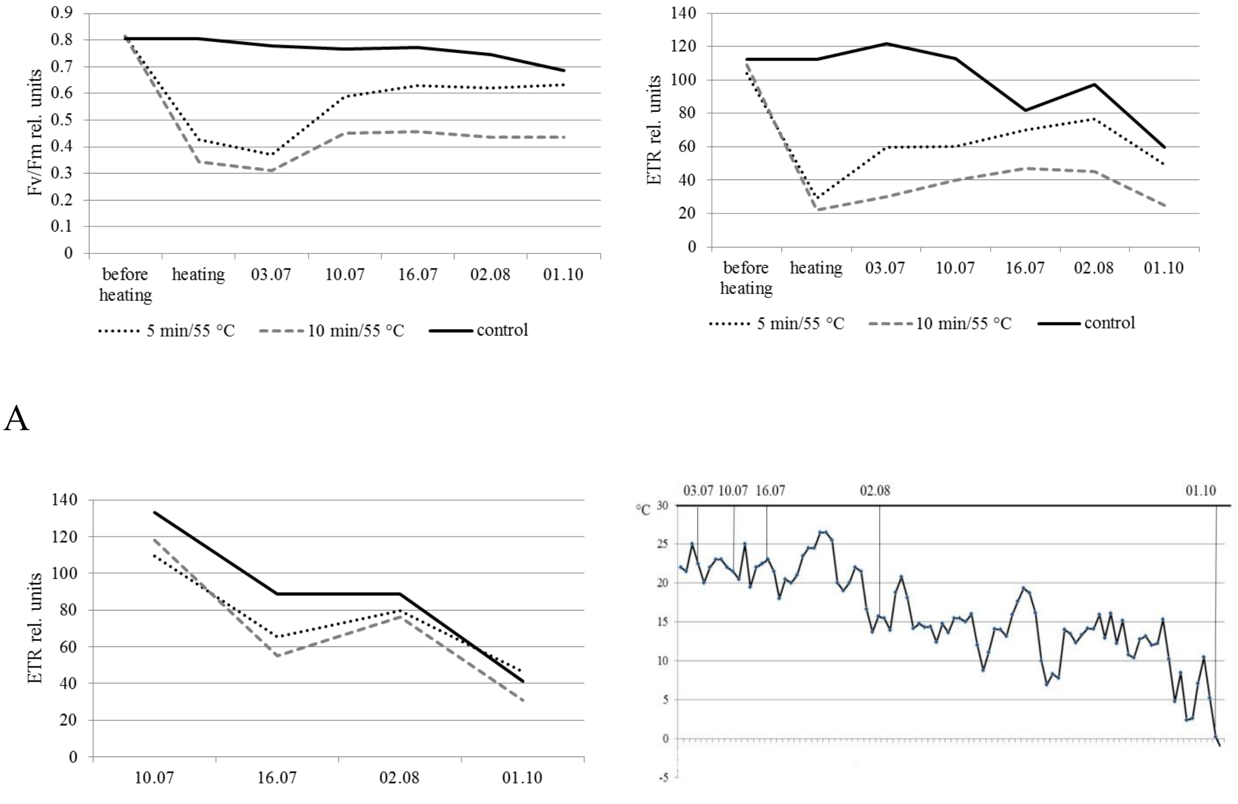
Fig. 2 Changing parameters of the fast fluorescence on the needles after saplings' exposure to the convection flow

In the normal state, the ratio of Fv / Fm and ETR is about 0.80 and 120 relative units in all study periods. After exposure to a convection flow of varying duration a decrease in both parameters was found. Saplings selected in June (Figure 2A, B) are characterized by the lowest heat resilience. Immediately after heat exposure, a sharp decrease in both Fv / Fm and ETR was observed, while during the third day of exposure in the laboratory there was no noteworthy increase in the studied fluorescence parameters after 5-minute heating. An irreversible decrease in the photochemical activity of photosystem II and electron transport rate happened only during prolonged heating (10 minutes), which evidences the profound suppression of photosynthesis.

The subsequent study periods (July, August, September) were characterized by higher damage repair capacity. Meanwhile, the duration of thermal impact became an essential factor. The quantum yield (Fv / Fm) on the third day reduced by 25% and 40% from the relative initial level (on average) after 5- and 10-minute heat treatment. The saplings collected in September showed the restoration of the electron transport value (ETR) to the control level in 3 days after a short exposure. The results prove an increase in the level of heat resistance of vegetative organs during the growing season. This conclusion agrees with the data obtained by other scientists (Girs 1982; Valendik et al. 2006).

Parameters of fast fluorescence on the undergrowth needles after the heat stress influence

The changes in photosynthetic activity during the heat exposure and as the aftereffect of high temperatures confirm the functional stability of the assimilation apparatus. In order to characterize the long-term effects after high-temperature exposure, as well as the ability to repair damage during the recovery period, an experiment was conducted on 10-year-old samples of Scots pine undergrowth (Figure 3). The needles of the main sapling were heated with convective flow on June 30. After this thermal damage, a sharp decrease in photosynthetic activity (exceeding 50%) was detected. Recovery of photosynthetic activity for the model trees happened only on the 4th day after a short-term (during 5 minutes) impact, moreover, it had not reached the control values by the end of the studied period. Prolonged heating (during 10 minutes) appeared to be lethal to the cells. An irreversible decline in photochemical activity and electron transport can be identified with damage to the photosystem II complexes. Therefore, there is an undeniable inconvertible suppression of the photosynthetic process, which is followed by the destruction of the photosynthetic apparatus.



A

B

C

A – 2-year-old needles; B – the needles of the current year, having not been exposed to heat; C – average daily air temperatures on the study site (data from the Pogorelsky Bor weather station), the days of fast fluorescence measurement are marked by lines

Fig. 3 Changes in the fast fluorescence parameters of the needles on the main sapling of the model plants after heat exposure

Figure 3B presents the values of the electron transport rate in one-year-old needles, which had not been exposed to direct high-temperature impact, but formed during the post-stress period. When young needles of the undergrowth were growing in the post-stress period, the ETR values were recorded on the 11th and 17th days of observation as falling below those of the control model plants. This result may substantiate a weakened state of the whole organism. The overall diminishing of the studied parameters at the end of the growing season is connected with a decrease in average daily air temperatures (Figure 3B).

Change in the number of photosynthetic pigments

The quantitative and qualitative characteristics of the pigment stock in plastids have been considered in a number of works as some of the parameters vindicating the physiological changes of the assimilation apparatus in response to various stress factors (Ashraf and Harris 2013).

Table 1 Changes in the chlorophyll a + b and carotenoids content a day after heating of the needles on the certain section of the sapling, mg/g of air-dry weight (control level – the original content of pigments prior to the exposure to high temperatures)

Period	Control	55°C		Control	55°C	
	Chl a+б	5 minutes	10 minutes	*Car*	5 minutes	10 minutes

June	3.01±0.08	2.05±0.15	1.97±0.20	0.31±0.01	0.22±0.03	0.23±0.04
July	2.99±0.03	2.43±0.04	1.99±0.05	0.36±0.01	0.29±0.01	0.25±0.01
August	3.20±0.04	2.34±0.05	2.10±0.04	0.36±0.02	0.27±0.01	0.25±0.02
September	3.01±0.04	2.12±0.08	1.97±0.03	0.46±0.01	0.31±0.01	0.31±0.01

Table 1 gives the results on the quantitative change in the number of pigments in Scots pine needles after heat exposure on the saplings (for different phases of the growing season). On average, a 5-minute high-temperature influence on the saplings leads to a 30% decrease in the amount of Chl a + b and Car as compared to the control level. However, in July, after high-temperature stress, only by a 18% decrease of photosynthetic pigments was registered. This kind of heat resistance could be induced by high daily average temperatures. Longer heating brought about a decrease in the Chl a + b and Car content by an average of 35% and 30%, respectively, as compared to the content values.

Table 2 Changes in the chlorophyll a + b and carotenoids content a day during recovery period after the heating, mg/g of air-dry weight (control level – the original content of pigments wothout exposure to high temperatures)

Period	Control	55°C		Control	55°C	
		5 minutes	10 minutes		5 minutes	10 minutes
01.07	2.75±0.05	2.21±0.02	1.80±0.02	0.88±0.01	0.61±0.01	0.59±0.02
10.07	2.74±0.07	2.12±0.03	1.69±0.04	0.87±0.03	0.70±0.01	0.57±0.01
02.08	3.13±0.1	2.08±0.1	1.44±0.01	0.95±0.01	0.62±0.01	0.50±0.01
01.10	3.12±0.16	1.98±0.02	1.25±0.01	1.05±0.02	0.65±0.02	0.48±0.02

The result of a short response recorded on the following day cannot unmistakably assert the resistance of the pigment apparatus to the damaging effects of high-temperature exposure. To determine the possibility of reparation of the pigment fund, we measured the content of Chl a + b and Car in the needles of the undergrowth in the recovery period under natural conditions below the canopy of the pine forest stand.

Changes in the quantitative content of pigments caused by thermal effects on the undergrowth can be seen in Table 2. The needles of the main sapling (model trees) were heated on June 30. According to the obtained results, on the day following 5- and 10-minute high-temperature exposure, Chla + b decreased by 20% and 35%, respectively, as compared to the control values. In general, negative heat exposure for 10 minutes was extreme for the undergrowth, which introduced the irreversible changes in chloroplasts. So, by the end of the vegetation period, the content of chlorophyll + b and carotenoids in needles had dropped sharply and amounted to 60% and 51% of the control values.

Changes in the relative water content in the needles

The presence of water in the assimilating organs of plants is a vital factor for the normal course of physiological processes. Changes in the water content in the vegetative organs are related to the activity of metabolic processes, which can be used to assess the intensity of stress on the trees' functioning. (Ganji et al. 2012)

Table 3 displays the values of the relative water content (RWC) of the 2-year-old needles of Scots pine from June to September.

The relative water content in the needles characterizes the state and stability of the water balance in plants. As can be seen from the table, the RWC of the control two-year-old pine needles depends on the study period and ranges from 65% to 87%, increasing from the beginning of the growing season to its end.

Table 3 Change in the relative water content in the needles a day after the part of the sapling was heated (control level – RWC in the needles having not been exposed to high temperatures)

Period	Control, Rwc, %	55° Rwc, %	
		5 minutes	10 minutes
June	65.02	37.84	30.11
July	70.93	41.18	35.29
August	75.91	41.65	38.17
September	87.03	68.75	60.51

A number of researchers admit that the natural fluctuations of this indicator are related to the temperature conditions of the environment, the rate of transpiration and the conditions of soil moisture (). In addition, lower RWC values at the beginning of the vegetative phase may be conditioned by the beginning metabolic processes in the new organs of assimilation and the outflow of moisture into them (Repin 2018).

After 5- and 10-minute high-temperature exposure of saplings selected in June-August, the relative water content decreased by 40% and 50% on average, respectively. The water content in the needles is necessary for the main normal physiological processes, including photosynthesis, whose intensity abates with water deficit (), which is consistent with our data on measuring fast fluorescence parameters. In September, there was a less decrease in the relative water content by 22% and 30% as compared to the control level, which characterizes greater resistance of the September needles to high-temperature stress.

Conclusions

Summing it up, the data presented on the assessment of the long-term effect of high-temperature stress indicate a major influence of thermal exposure at a temperature of about +55°C on the Scots pine undergrowth. At the same time, the needles of the current year, having grown after thermal exposure, show the same tendencies of changes in the photosynthetic apparatus activity, as the stressed two-year-old needles, which attests to a systemic response of the whole plant to heat stress.

With a 5-minute heating, characteristic of the spring running ground fire, a faster recovery of the needles was discovered, including the period at the beginning of the growing season. A 10-minute heating at a given temperature, which may happen in a slower and more dangerous summer ground fire, was found to be detrimental in early summer, though the heat resilience of the needles increased in the second half of the growing season.

When comparing the experimental data collected via using cut saplings and whole plants of Scots pine, we can conclude that the obtained indicators are comparable. In this regard, we believe that for studies assessing the short-term effects of damaging factors with the help of fluorescence parameters, there can be used saplings of woody plants, if it is impossible to make measurements in natural conditions.

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