Timberline and treeline dynamics: *Pinus sibirica* trees move

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Abstract. In the context of climate change, one of the important issues in assessing the state of mountain forest ecosystems is the study of the upward movement of the tree line (tree line) and forest line (timberline). To determine the potential of a particular species when moving up the slope, the functional characteristics of the needles are of great importance. This paper considers changes in the pigment composition of needles and the depth of winter dormancy of two coniferous species *Pinus sibirica* and *Abies sibirica* growing in the area of the Ergaki Ridge of the Western Sayan.

1 Introduction

In connection with climate change, the problem of assessing the resistance of plants to adverse environmental factors becomes very relevant. In many species of coniferous trees, which are the main forest-forming forests of the temperate zone, there are shifts in both latitudinal and altitudinal boundaries of the range. As a result of a faster movement of the southern (or, in the case of altitudinal zonality, lower) boundary due to a decrease in humidity and a slower movement of the northern (or upper) boundary, associated with an increase in temperature and the development of new territories by undergrowth, the range area may decrease. In turn, this reduces the carbon capacity of the area and can lead to an increase in the greenhouse effect.

Tree growth in northern boreal webs is mainly limited by summer temperature due to the short and cool growing season prevailing in the subarctic [1]. However, climate change in temperate latitudes is accompanied by winter-spring thaws, which were previously uncharacteristic for these regions [2]. The release of conifers from the state of winter dormancy in response to early thaws makes plants sensitive to low negative temperatures. As a result, drying of needles, weakening of trees and their death is observed. It is generally recognized that further studies of plant response to winter thaws caused by climate change are needed [3, 4].

Downslope shifting of the forest boundary appears to be closely related to centuries of cold spells or changes in rainfall in dry regions. However, the reverse upslope movement of the tree line may not automatically follow climate warming because this movement

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depends on the survival of undergrowth outside the forest canopy, where they are exposed to frost and extreme light intensity [5, 6].

Therefore, one of the important issues in assessing the state of mountain forest ecosystems is the study of the upward movement of the tree line and the timberline.

According to some data, an increase in temperature, for example, in the Kuznetsk Alatau mountains, has a stimulating effect on the advancement of the tree line along the height gradient, an increase in the radial growth of trees and the density of the forest stand. At the same time, the rate of advance of the line of advanced trees / tree line is somewhat lower than the rate of movement of the upper forest boundary and is approximately 0.2-0.3 m/year; timberline ~ 0.5 m/year [7].

Among the possible risks, one of the most important, perhaps, is the process of leaving the state of winter dormancy during short-term winter-spring thaws. A temporary increase in temperature under conditions of high insolation can cause a resumption of photosynthetic activity, accompanied by a resumption of gas exchange. This, in turn, under conditions of negative soil temperature, leads to water deficiency, desiccation and death of needles.

To determine the potential of a particular species when moving up the slope, the functional characteristics of the needles are of great importance. In this paper, changes in the pigment composition of the needles and the depth of winter dormancy of two coniferous species, Siberian pine (*Pinus sibirica* Du Tour) and Siberian fir (*Abies sibirica* Ledeb.), growing in the region of the Ergaki Ridge of the Western Sayan, are considered.

2 Materials and methods

In February 2023, shoots of Siberian pine and Siberian fir were collected along the transect laid in the Western Sayan mountains at the intersection of the upper forest boundary, at an altitude of 1455 to 1636 m above sea level. It should be noted that Siberian fir trees were noted only on the lower trial plot.

The characteristics of the trial plots are given in Table 1. Photos in the infrared and visible range were obtained using a Flir thermal imager.

The cut shoots were delivered to the laboratory within one day, where they were placed with their lower parts in vessels with water and brought out of winter dormancy at a temperature of +24°C and fluorescent lighting for 10 days.

To characterize the readiness of the photosynthetic apparatus to exit the state of winter dormancy, the amount of chlorophylls and carotenoids was determined. The content of chlorophylls and carotenoids was quantified in an ethanol extract on a SPEKOL 1300 Analytik Jenna AG spectrophotometer (Germany) [8].

The dormancy depth of trees was determined by recording heat-induced changes of chlorophyll fluorescence (HICCF) [9].

The chlorophyll fluorescence temperature curve was recorded with needle segments using the pulse-shaped modulated chlorophyll fluorimeter Junior-PAM (Walz, Germany). The needles were linearly heated from 25 to 75° C at the rate of 2.5° C using a computer-controlled heating device (Figure 1).

Depth of winter dormancy was interpreted through the ratio (R2) between amplitudes of low temperature (ca. 50°C) and high temperature (ca. 70°C) peaks of zero chlorophyll fluorescence levels. The assumption was that $R2<1$ is typical for plants having entered winter dormancy, while $R2>1$ indicates that plants are active [10]. The results were processed using the WinControl full-featured software.

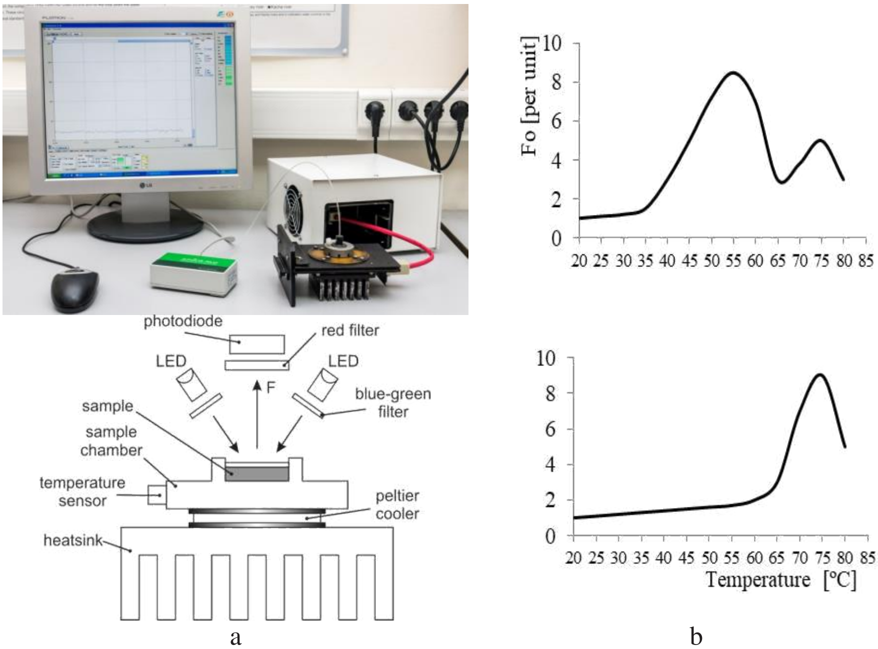


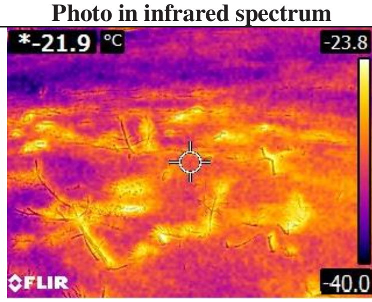
Fig. 1. Appearance of the "Junior-PAM" fluorometer, diagram of a heating device controlled from a computer (a) and typical curves of thermally induced changes in the zero level of needle chlorophyll fluorescence (b).

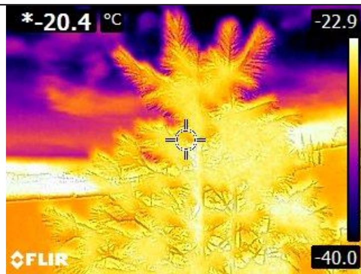
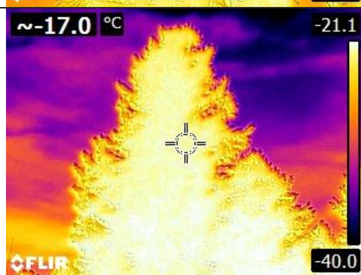
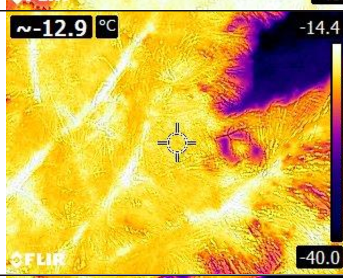
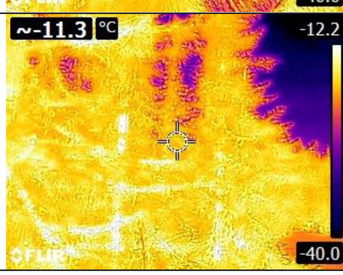
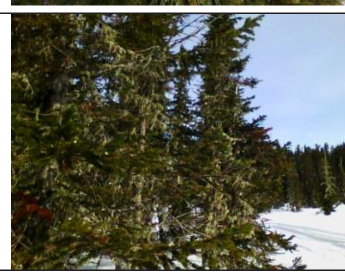
3 Results

Despite the cloudiness and low air temperature (-23-25º C) on the day of sampling, the temperature of the needles was somewhat higher. The difference ranged from three degrees at the top of the slope to twelve degrees at its foot. In these photographs, the "warm spot" mode was selected during shooting, which corresponds to the location of the needles.

As evidenced by the data presented in Figure 2, tree shoots from the lower part of the slope (SP3 and, especially, SP4) come out of dormancy much faster (R2>1), compared to samples from the upper plots (SP1 and SP2). Thus, it can be assumed that only those specimens of Pinus sibirica survive in the upper part of the slope, which have a greater depth of rest, and it is they who have the potential ability to move the treeline up.

Table 1. Coordinates of trial plots and needle temperature indicators.

Trial area	Photo in infrared spectrum	Photo in the visible spectrum
PP1 *Pinus sibirica* 1636 m num N 52º50'40.4" E 093º16'24.2"		

PP2 *Pinus sibirica* 1558 m num N 52º50’26.3” E 093º16’26.9”		
PP3 *Pinus sibirica* 1605 m num N 52º50’17.2” E 093º16’21.0”		
PP4 *Pinus sibirica* 1455 m num N 52º50’14.6” E 093º15’28.4”		
PP4 *Abies sibirica* 1455 m num N 52º50’14.6” E 093º15’28.5”		

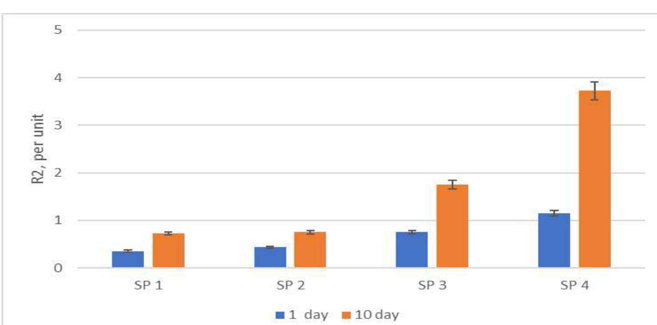
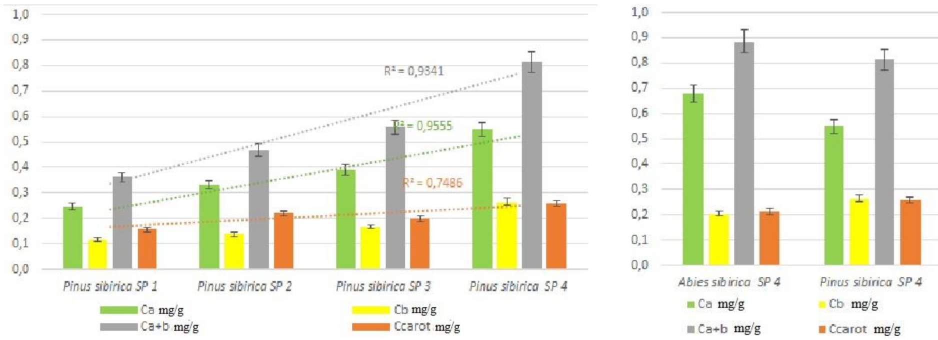


Fig. 2. The values of the coefficient R2 of the needles of Pinus sibirica trees on the first day after collection and after 10 days of dormancy in the laboratory.

Of no small importance in the study of the state of vegetation is the study of the plasticity of the photosynthetic apparatus, its ability to adapt to changing external conditions. One of the informative and most common parameters characterizing the photosynthetic apparatus is its pigment composition. It is known that one of the biochemical indicators of the reaction of plants to changes in environmental factors, the degree of their adaptation to new environmental conditions is the content of chlorophylls, the main photoreceptors of a photosynthetic cell. The most significant indicators are the ratio of chlorophylls a and b, and the sum of chlorophylls to carotenoids. Analyzing the content of photosynthetic pigments (Figure 3) in the needles of the studied *Pinus sibirica* trees, one can see a significant increase in chlorophylls as the height above sea level decreases. The approximation value for the linear trend line was 0.93 for the sum of chlorophyll a and b, 0.96 for chlorophyll a. Significant differences ($P<0.05$) for chlorophyll concentrations are found for all the samples. According to the content of carotenoids in the needles of Siberian pine, no significant differences were found between the sample plots.



a b

Fig. 3. Chlorophyll and carotenoids (mg/g) in needles of the *Pinus sibirica* in SP1 – SP4 (A) and *Abies sibirica* (B). Error bars correspond to standard deviation (n = 3).

The needles of Abies sibirica contain more chlorophylls, but less carotenoids. This, together with the data of fluorescent analysis, indicates its potential readiness to exit the state of winter dormancy. The ratio of chlorophylls and carotenoids on SP4 in Siberian fir is 3.19, while in Siberian pine it is only 2.12.

The low content of carotenoids, which protect reaction centers from powerful energy flows at high light intensities and stabilize the lipid phase of thylakoid membranes, protecting it from overoxidation, makes fir needles vulnerable to too strong light at low temperatures.

4 Discussion

At the end of winter and the beginning of spring, at the upper limit of tree growth, the critical conditions are a combination of negative soil temperatures, occasional positive air temperatures, and high illumination. In order to avoid drying up the needles during the resumption of photosynthesis and, consequently, gas exchange, the trees must have a sufficiently deep winter dormancy. The exit from this state in winter conditions can be provoked only by a long period of positive temperatures.

In order to predict a possible change in the treeline in the Western Sayan in the context of ongoing climate change, it is necessary to establish the relationship between *Pinus sibirica* and *Abies sibirica*, which co-dominate over most of the range, and anticipate the response of species to long-term regional climate change. The results obtained indicate that, under conditions of possible warming in the mountains of Southern Siberia, *Pinus sibirica* will have an advantage in colonizing the zone above the timberline. Some features of this species, both physiological and biochemical, may provide its wider distribution compared to *Abies sibirica*. The features include a higher content of carotenoids in winter, which is characteristic of light coniferous plants, and a lower rate of restoration of photosynthesis processes even at positive temperatures.

5 Conclusion

Abies sibirica, as a dark coniferous species, needs shading of seedlings and young plants, so it will move above the treeline only under the canopy of other trees. Under the given environmental conditions, this treeline-moving species is probably *Pinus sibirica* due to its physiological and ecological adaptive traits.

Acknowledgement

This research was funded by Russian Science Foundation to the research project: “Intrapopulation variability of ecophysiological features of Siberian pine (*Pinus sibirica* Du Tour) trees under climate change”, grant number 23-24-00251.

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