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ORIGINAL ARTICLES

# DISRUPTIONS OF THE AUTUMNAL AGING OF LARCH NEEDLES IN THE KRASNOYARSK CITY AND ITS SURROUNDINGS

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**Abstract.** A disruption of the needle fall in Siberian larch was recorded during the autumn of 2016 in the Krasnoyarsk city, the Krasnoyarsk Pillars National Park, and, according to media reports, in other Siberian cities. To determine the causes of this phenomenon, the chlorophyll *a* content and the quantum yield of photosystem II (PS II) were assessed in Siberian larch trees of the Krasnoyarsk city under natural growing conditions (Mansky District, Krasnoyarsk Territory) during the autumn of 2016 and compared with the data obtained in the autumn of 2017. Data on air temperature and precipitation for September and October in Krasnoyarsk city, the Mansky District, and the Krasnoyarsk Pillars National Park over the entire course of observations were also analysed. Based on the analysis of the weather data, it can be assumed that the main cause of the needle fall disruptions were the abnormally warm average and average minimum air temperatures in September 2016 and the abnormally cold average and average minimum temperatures that followed them in October 2016.

**Keywords:** *Siberian larch, stress, autumnal aging, extreme weather conditions, needle fall disruptions*

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Larch trees, deciduous species of the Pine family, are major components of boreal, montane and subalpine forests of Eurasia and North America. The most common larch species occupy vast areas with a wide range of climatic conditions (Richardson et al., 2018). The larch adaptation complex includes the process of physiological senescence of photosynthetic cells, which affects the metabolism of pigments, proteins, lipids, and other important compounds (Prochazkova and Wilhelmova, 2007; Thomas et al., 2009). Autumn senescence in deciduous plants is controlled by a family of genes (Thomas et al., 2009) responsible for the transformation of chloroplasts into gerontoplasts (Matile, 2000; Hörtensteiner and Feller, 2002) and the appearance of yellow, orange, or red leaf coloration. It is generally accepted that the main signal for the onset of autumn physiological senescence of needles in larch and many other deciduous tree species is a decrease in daylight length, while air temperature also influences the onset and duration of leaf fall (Rosentall and Camm 1997; Frachebund et al., 2009).

The process of autumn leaf senescence also includes recycling (reutilization) of major nutrients by transferring them to storage tissues (Hörtensteiner and Feller, 2002). The importance of nutrient recycling has been demonstrated by studying the growth and reproductive potential of bear oak (*Quercus ilicifolia* Wangenh.) (May, Killingbeck, 1992)

Disturbances of the process of autumn physiological senescense of needles in 2016 were registered in Siberian larch (*Larix sibirica*) everywhere in Krasnoyarsk and in the mid-mountain conditions in the Stolby Nature Reserve (from 2019 — Krasnoyarsk Pillars National Park). The larch needles were on the shoots until the end of November and retained green-yellow coloration. On the contrary, in the low-mountain conditions in the Reserve, larch leafing ended on October 28, 2016, which corresponds to the phenological norm (Goncharova, 2015, 2016, 2017).

Another location of Siberian larch trees, where autumn senescence in 2016 was completed by leaffall, was the village of Verkhnyaya Yesaulovka in Mansky District, Krasnoyarsk Territory. According to our own observations and media reports, in 2016, the disruption of tree leafing occurred in Abakan (Republic of Khakassia) (own observations), Kemerovo Oblast (Kemerovo biologists..., 2016), Novosibirsk (Green Leaves..., 2016.), and Barnaul (Altai Republic) (Barnaul botanists..., 2016.)

The aim of the work was to identify the main causes of disturbance of Siberian larch conifers in the fall of 2016.

## OBJECTS AND METHODOLOGY

Geographical location of Siberian larch: Krasnoyarsk — 56° 02´ N, 92° 43´ E, 276 m above level; Stolby Nature Reserve — 55° 54´ N, 92° 43´ E, 200—531 m above sea level; Verkhnyaya Esaulovka village — 55° 40´ 29 N, 93° 47´ 22 E, 378 m above sea level. Photos of trees that retained needles on 19.11.2016 in Krasnoyarsk, as well as trees in the phase of leaf fall (03.10.2016) and after its completion (15.11.2016.) in Verkhnyaya Yesaulovka village are presented in Fig. 1.

Weather indicators (air temperature, precipitation) in the above Siberian larch growing areas were obtained from the meteorological sites of Krasnoyarsk Experimental Field weather station (56°01'31 "N, 92°42'13 "E277 m a. s. l., located 8 km west of Krasnoyarsk, in the forest-steppe zone), Shalinskoye weather station (55° 43´ N, 93° 44´ E, 399 m a. s. l., located in the Mansky District of Krasnoyarsk Krai, 5 km from the village of Verkhnyaya Yesaulovka), the meteorological station Stolby (Goncharova 2016, 2017) (located in the middle-mountain altitude-belt complex (ABC) of the Reserve), the meteorological station Laletino (located in the low-mountain ABC). The climatic norm for September and October was determined as a monthly average for 15 years, in the period from 2001 to 2015.

Chlorophyll *a* content was determined in brachyblasts of second-year shoots by spectrophotometric method in four young trees (30—35 years old) in artificial stands (Krasnoyarsk) and in six different-aged trees in natural stands (Verkhnyaya Yesaulovka v.), two replicates per tree. Freshly collected needles (40—60 mg) were ground in 6 ml of 96% ethyl alcohol with crushed glass and $CaCO_3$. The suspension was filtered through a Schott glass filter. The optical density of the extract was determined on a spectrophotometer (Spekol 1300, Analytik Jena, Germany). The concentration of chlorophyll *a* μg×ml$^{-1)}$ was calculated according to H. K. Lichtenthaler (1987): $C_{chl\ a} = 13.36\ _{D(665)}$-$5.19´\ _{D(649)}$ and expressed per g$^{-1}$ crude weight (s. m.)

The functional state of the photosynthetic apparatus of needles was determined by the maximum quantum yield of PS II (ETR), which was recorded using a portable pulse fluorimeter (model PAM-Junior, WALZ, Germany). The time of dark adaptation was 30 min. The maximum quantum yield of PS2 [$Y(II)_{(m)}$] was calculated from zero $F_0$ and maximum $F_m$ levels (Kitajima and Butler, 1975):

$$Y(\mathbf{II})_m = (F_m - F_0)/F_m.$$

Statistical processing of data was performed using Microsoft Excel 2016 program. The table and figures show the mean values of parameters and standard errors of the mean.

## RESULTS AND DISCUSSION

The content of chlorophyll *a* in the samples of needles collected on 19.11.2016 in Krasnoyarsk from trees from different locations ranged from 1049 to 388 μg×g$^{-1}$ s. m. with an average content of 770±197 μg×g$^{-1}$ s. m. Photosynthetic activity of needles, determined by the maximum quantum yield of PS II, was completely absent (Fig. 2).

Active yellowing of needles in Krasnoyarsk in 2017 began after September 22 and ended on October 14—20 simultaneously with intensive leaf fall. The content of chlorophyll *a* during this period (Fig. 2) decreased from 1595±61 μg×g$^{-1}$s.m. (22.09.17) to 71±45 μg×g$^{(-1)}$ s. m. (14.10.17) and to 23±6 μg×g$^{-1}$ s. m. (23.10.17). The rate of change in the amount of chlorophyll *a* was 69 μg×g$^{-1}$ s. m.×day$^{(-1)}$ between

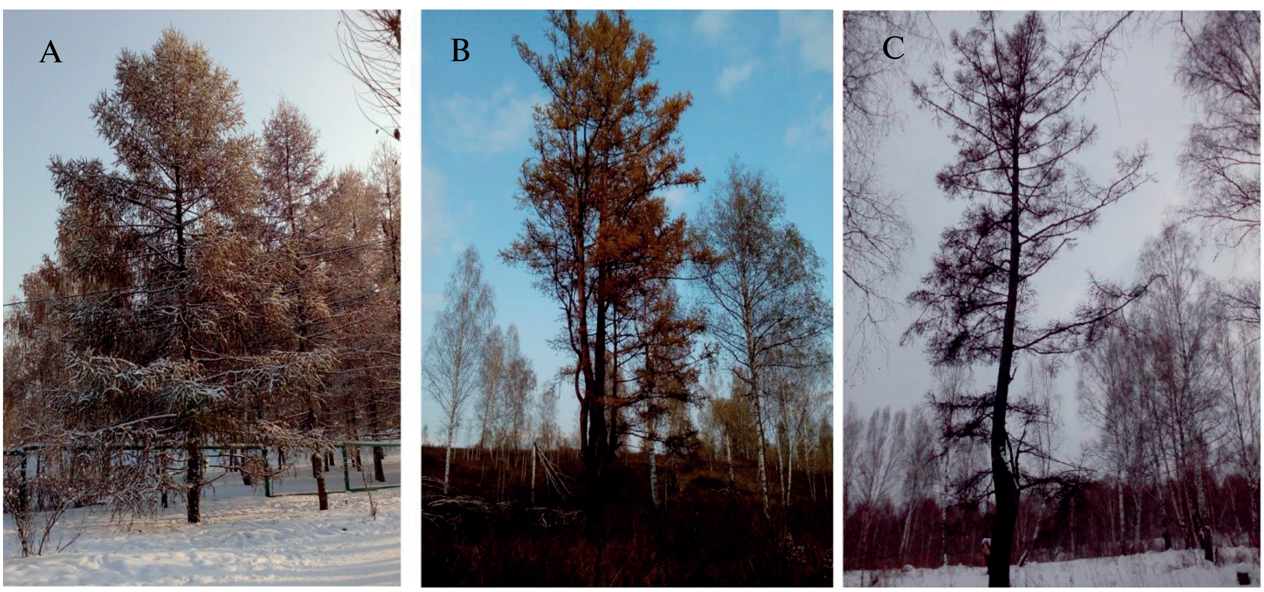


**Fig. 1.** Condition of Siberian larch trees in the fall of 2016. A — November 19, Krasnoyarsk (coniferfall is not completed at this time); B — October 3, v. Verkhnyaya Esaulovka (on the eve of strong frosts in early October); C — November 15, v. Verkhnyaya Esaulovka (completed coniferfall is observed) (photo by N. S. Pomytkin).

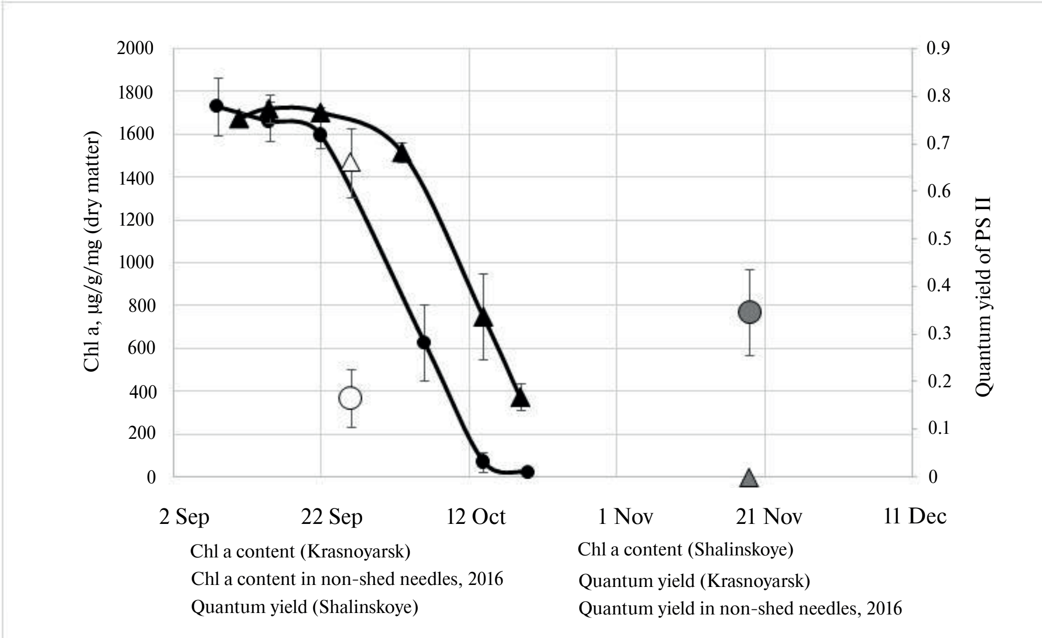


**Fig. 2.** Chlorophyll *a* content and maximum quantum yield of PS II in the raw mass of Siberian larch needles in Krasnoyarsk in 2017 and residual chlorophyll *a* content in unstored needles in 2016. Arithmetic mean ±SE.

20.09—14.10.2017. The maximum quantum yield of PS II in larch needles was 0.77±0.04 at the beginning of conifer fall and decreased to 0.17±0.05 when the needles visually turned yellow. The content of chlorophyll *a* in the needles of trees near the village of Verkhnyaya Esaulovka was 547± 65 µg×g$^{-1}$ s. m. (24.06.17), 1158±40 µg×g$^{(-1)}$ s. m. (19.07.17), 368±92 µg×g$^{-1}$ s. m. (26.09.17).

We studied the dynamics of mean daily and minimum air temperatures in Krasnoyarsk, in the middle mountains of the Stolby Reserve and in the village of Verkhnyaya Yesaulovka in September-October 2016—2020. Dynamics of the above weather indicators in 2016 and 2017 are shown in Fig. 3. Data of average daily ($T_{s.s.}$) and minimum ($T_{min}$) air temperatures were considered as the most significantly affecting the autumn phenology of trees (Galvagno et al., 2013)

The peculiarity of 2016 in the Stolby Nature Reserve, located near Krasnoyarsk, was the absence of the last phenological phase (complete die-off and leaf fall) of larch in the mid-mountain conditions. In 2015, this phenophase was observed on October 2, in 2017 — September 19. Complete die-off in the previous years 2013 and 2014 was recorded on October 1 and September 20, respectively.

On the second and fourth October 2016, there was a significant decrease of air temperature from –1.0—2.0 °C to –9.0 °C in Krasnoyarsk, to –8.0 °C in the middle mountains of the Stolby Reserve and to –11.0 °C in Verkhnyaya Yesaulovka village (Fig. 3, B). Such values of $T_{min}$ at the beginning of October were not observed in the following 2017—2020. In addition, the time interval of air $T_{min}$ decrease from +5 °C to 0 °C in the Stolby Nature Reserve 2016 was

A

B

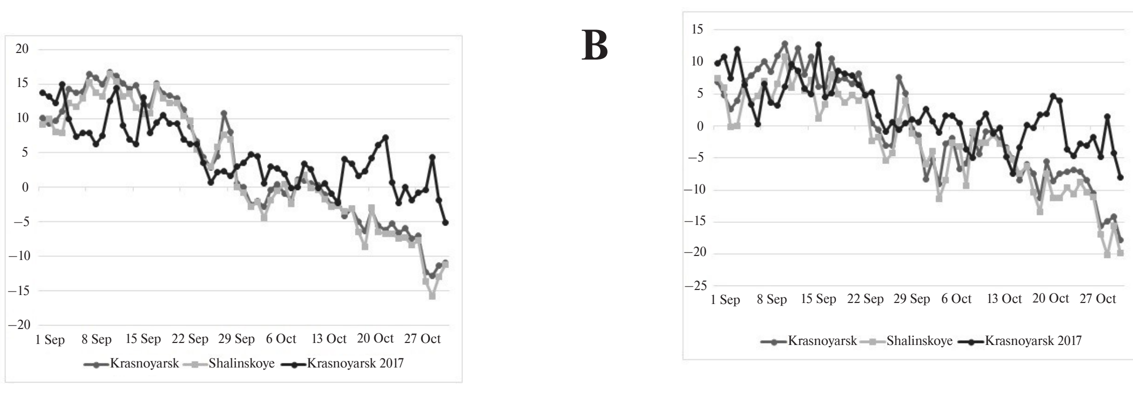


**Fig. 3.** Dynamics of mean daily and minimum temperatures in September and October 2016 and 2017 in Krasnoyarsk and v. Verkhnyaya Esaulovka (meteorological station Shalinskoye). A — dynamics of mean daily temperatures in September and October 2016. B — dynamics of minimum temperatures in September and October 2016

**Table.** Mean, mean minimum air temperatures °C and their difference in September and October 2016—2020 in Krasnoyarsk, middle mountains of the Stolby Reserve and v. Verkhnyaya Esaulovka

| Year | Month / Parameter / Location | September | | October | | Difference | |
|---|---|---|---|---|---|---|---|
| | | Medium | Minimum | Medium | Minimum | Medium | Minimum |
| 2016 | Krasnoyarsk | 11.5 | 6.0 | -4.0 | -7.2 | 15.5 | 13.2 |
| | Pillars | 10.7 | 6.5 | -4.7 | -7.1 | 15.4 | 13.6 |
| | Verkhnyaya Esaulovka | 10.2 | 3.4 | -4.8 | -8.6 | 15.0 | 12 |
| | Laletino | 10.6 | 5.4 | -4.0 | -7.4 | 14.6 | 12.8 |
| 2017 | Krasnoyarsk | 8.3 | 5.4 | 1.6 | -1.2 | 6.7 | 6.6 |
| | Pillars | 6.5 | 3.8 | 0.0 | -2.2 | 6.5 | 6 |
| | Verkhnyaya Esaulovka | 7.6 | 4.5 | -0.9 | -2.1 | 8.5 | 6.6 |

7 days, and in 2010—2015.— on average 24 days. The transition of $T_{min}$ of air through 0 °C in 2016 was 13 days ahead of the transition of maximum temperatures through this boundary and was much shorter than in the previous five years (Goncharova, 2015, 2016, 2017). At the site in Verkhnyaya Esaulovka v., the transition of $T_{min}$ through 0 °C coincided with the transition in the Stolby Nature Reserve. In Krasnoyarsk, this transition took less than a day (Experimental Field Weather Archive, 2022).

Comparison of chlorophyll *a* content (Fig. 2) in larch needles in 2016, at the moment of cessation of the aging process, with the chlorophyll *a* content in 2017 showed that the average values of chlorophyll *a* content recorded in the un-aged larch needles on November 19, 2016 (770±197 μg×$g^{-1}$ s. m.) can be correlated with the chlorophyll *a* content at the moment of cessation of autumn aging of needles in the first days of October 2016 (628±179 μg×$g^{-1}$ s. m.). The absence of a reliable difference suggests that the process of chlorophyll *a* loss in 2016 may, as in 2017, have ended in the second decade of October. The quantum yield of FS II in early October 2017 was at a high level (0.68) with chlorophyll *a* content of 628±179 μg×$g^{-1}$ s. m. Also, the photosynthetic apparatus of needles in the v. Verkhnyaya Esaulovka on 26.09.2017 had a high level of quantum yield (0.66) at chlorophyll *a* content of 368±134 μg×$g^{-1}$ s. m. (Fig. 2).

The process of physiological aging of needles in 2016 may have been delayed by high temperature and precipitation in September (Estrella and Menzel, 2006). The amount of precipitation in September in 2016.— 37 mm, which amounted to 76% of the norm (49 mm) (Weather in Krasnoyarsk, 2022). Insufficient moisture content of the territory, however, did not lead to accelerated yellowing of needles. Thus, the precipitation factor can be excluded from the regulation of leaf fall in larch in 2016, and temperature can be considered as the main factor. High average temperatures in September 2016 could slow down the processes of needle yellowing (chlorophyll degradation) (Galvagno et al., 2013; Xie et al., 2018) and preparation for low negative temperatures (hardening) (Tumanov and Krasavtsev, 1959).

Interruption of the process of autumn needle senescence in larch in 2016 in Krasnoyarsk and in the Stolby Nature Reserve could probably be caused by strong frosts to –7.5 °C, –8 °C, recorded on October 2 and 4, respectively (Fig. 3, B). The decrease in $T_{min}$ to –3—4 °C at the end of September 2016 can be excluded from the possible cause of stopping the process of needle senescence, since even plants unprepared for frosts can withstand –2 to –6 °C (Tumanov and Krasavtsev, 1959; Öquist, 1983). A slight warming until October 13, when $T_{s.c.}$ rose above zero for 5 days, to a maximum of 1.1 °C, was insufficient for complete completion of the coniferous period. After 13 October, $T_{s.d.}$ finally passed above zero, and $T_{min}$ never rose above 0 °C during the whole October

It is difficult to say when irreversible consequences occurred. For example, a frost of –9 °C on October 12, 2020 (Weather Archive of the Experimental Field, 2022) did not lead to interruption of the senescence process, despite the fact that the needles were green. Probably, strong frosts in the first half of October 2016 delayed the senescence process, and irreversible consequences occurred in late frosts, when $T_{min}$ dropped to – 17 °C

September in Krasnoyarsk 2016 was the warmest month for the last 100 years in terms of average monthly temperature, while October following it was the coldest month for the same period (Weather in Krasnoyarsk, 2022), September 2016 in Siberia was the warmest in the history of meteorological observations. Air $T_{s.c.}$ repeatedly reached extreme maximums in the first two decades of the month, and the mean decadal temperatures were 4—8 °C above the multiyear average. At the same time October in 2016 was anomalously cold. Record daily minimums were registered in Altai and Kemerovo Oblast. In Krasnoyarsk Krai and Irkutsk Oblast, night temperatures reached –30 °C.

The difference between $T_{s.\,d.\,m.}$ of September and October was a record for 120 years and comprised 15.5 °C. During these years, the $T_{s.d.}$ of air in September in Krasnoyarsk rose above +11 °C9 times. $T_{s.c.}$ = +11.5 °C in September 2016, according to the Weather and Climate website, is in 4th place, behind the values of +12.8 °C (1966),+ 12.5 °C (1900) and +12.0 °C (1953). Mean monthly October temperatures have fallen below –3.0 °C8 times during the same period. The average monthly October temperature in 2016 was –4.0 °C and was only higher than $T_{s.c.}$= –5.5 °C in 1912. Only 2016 made both lists. The difference in monthly mean temperatures between September and October 2016 was 15.5 °C. These are the largest temperature differences for the period after 1900. Closely similar differences between September and October mean temperatures were recorded in 1912 (13.6 °C), 1901 (13.4 °C), and 1961 (13.1 °C). In all of these cases, the mean monthly October temperature was below –3.1 °C. For comparison, the differences between the average September and October temperatures in the Stolby Nature Reserve and in the village of Verkhnyaya Yesaulovka in 2016 were 15.4 °C and 15.0 °C, respectively (Weather in Krasnoyarsk, 2022).

The closest value in terms of temperature difference, where phenology data can be checked in the Annals of Nature of the Stolby Nature Reserve (the annals are kept since 1925) is 13.1 °C in 1961, which, according to the Annals of Nature (Goncharova, 2016—2020), did not lead to the disturbance of coniferous forests in the Stolby Nature Reserve. At the same time, September stood out not so significantly, the deviation from the norm of the average daily temperature in September amounted to +2.1 °C, and the deviation from the norm of the average daily temperature in October amounted to –5.6 °C (Weather in Krasnoyarsk, 2022). Thus, the combination of abnormally warm September and abnormally cold October resulted in a disruption of fall senescence of larch in 2016. In the literature, a similar event was reported in 1994 by R.G. Norby et al. (2003), when high temperatures in the fall at higher elevations caused leaves to remain green until the first sustained subzero temperatures in the fall. Consequently, the leaves were killed and fell before nitrogenous compound reutilization was completed.

Additionally, it is necessary to discuss the dynamics of autumnal aging of larch needles in the village of Verkhnyaya Esaulovka, because despite the amplitude between the average temperatures of September and October of 15.0 °C and even stronger temperature decrease in early October and generally colder October, the trees had time to shed their needles. In 2016, by the time the temperature dropped sharply in early October (Fig. 3, B), the unopened needles of larch had a distinct yellow coloration (Fig. 1, C). In 2017, the content of chlorophyll *a* in the conifers of trees in the Verkhnyaya Yesaulovka area on September 26th projected to the content of chlorophyll *a* in the conifers of trees in Krasnoyarsk recorded on October 6th, 2017 (Fig. 2). Earlier, as compared to Krasnoyarsk, needle aging of trees in the Upper Yesaulovka area could occur in 2016, when the dynamics of needle aging could be accelerated by low average daily and especially minimum temperatures in September (Fig. 3, A, B)

In Verkhnyaya Yesaulovka v. in September, the differences in $T_{min,}$ on average compared to Krasnoyarsk and the Stolby Reserve, which were 2.and 3.1 °C, respectively, were even less than in Krasnoyarsk in 2017 (in which the needle fall was normal), by 2.0 °C. In addition, the near-zero values of minimum temperatures in the first and second decade of September could initiate the hardening process (Fig. 3, B) and strengthen the frost resistance of needles by the time of freezing in early October 2016 (Tumanov and Krasavtsev, 1959). All this allowed larch in Verkhnyaya Esaulovka v. to complete its leaffall no later than mid-October 2016. Similar conditions could also manifest themselves in the lower elevations of the Stolby Nature Reserve, where, as noted above, larch leaffall was normal.

Smaller differences are present between the low-mountain (meteorological station Laletino) and middle-mountain (meteorological station Stolby) of the Stolby Reserve in September 2016, where $T_{min}$ in the low-mountain was 1.1 °C lower than in the middle-mountain. Also, the difference between $T_{(s.\,c.)}$ and $T_{(min)}$ of September and October in the lowlands was 0.8 °C lower than in the midlands, and the difference between $T_{s.c.}$ was the lowest among all studied variants in 2016, indicating that even this difference could be sufficient for the coniferous larch to undergo coniferous growth. However, the influence of factors not taken into account in the study (precipitation distribution, soil type, topography, site illumination, etc.) cannot be excluded.

In general, the obtained results confirmed the opinion of the authors of the article (Xie et al., 2018) that several mechanisms are involved in the process of autumn aging of Siberian larch needles, taking into account the dynamics of average and minimum temperatures (Galvagno et al., 2013). In 2016, a special role was played by high average and minimum temperatures in September, which delayed the aging of needles, and a sharp drop in temperature in early October without subsequent warming, which disrupted photosynthesis in larch conifers, stopped color change in needles and preparation for leaf fall.

Taking into account climate forecasts, the expected global warming will increase the period of active vegetation of deciduous trees, during which sharp temperature fluctuations will also increase (Richardson et al., 2013; Xie et al., 2018). Under these conditions, the phenomenon of disruption of fall needle senescence in Siberian larch*, which* occurred in Siberia in 2016, may become more frequent. However, for a countryside area such as Mansky District, such phenomena will be less noticeable, as despite the abnormal temperature drop in early October, larch had time to complete its leaf fall. It is also worth noting that hot September was repeated in subsequent years, but there was no such cold October, indicating that October was the main anomaly and it is the sharp drops in temperature in early October that pose the greater danger. If we assume that the share of reabsorbed useful substances in aging conifers is comparable to the share of decayed chlorophyll molecules in 2016 in Krasnoyarsk, then individual Siberian larch trees did not have time to reutilize more than half of the substances contained in conifers and in accordance with published results (May, Killingbeck, 1992) reduced their vegetative and reproductive potential.

## CONCLUSION

Based on the above, the main factor that caused the disturbance of coniferous growth in Krasnoyarsk and in the Stolby Reserve in 2016 should be considered not a sharp frost in early October, but the general dynamics of temperatures in September and October, where anomalously warm temperatures in September, delaying the process of autumn senescence, were replaced by anomalously cold temperatures in October, which led to disruption of the process of leaf fall. However, this did not cause disruption of coniferous growth in the v. Verkhnyaya Esaulovka and in the area of the weather station Laletino, as due to lower minimum temperatures, even with similar dynamics, trees were able to develop resistance to low temperatures and complete the process of leaf fall.

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