Landscape-climatic features of the reforestation dynamics pyrogenically transformed geosystems of the Tunkinskaya depression

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Abstract. In order to identify the features of the dynamics of the soil temperature regime during the post-fire restoration of the subtaiga light-coniferous geosystems of the Tunkinskaya depression, a study of the demutation processes in the pine forests of the Badar urochishche was conducted. Our research is based on the data of observations initiated after the fire that took place in 2010. The model key areas were selected at intact landscape complexes that did not experience pyrogenic influence, as well as the territory subjected to forest fires. Comparing the dominant composition of secondary succession biocenoses with natural plant communities in the background key area, indicators of the prospects for successful reforestation were identified. The analysis of 10-year data on the observation of the soil temperature regime from the surface to a depth of 3.2 m was carried out at the selected sites. The differences between the soil temperatures in the disturbed and natural sites, which vary during a year were revealed. During the observation period, a decrease in microclimatic differences was observed with the regeneration of vegetation cover, which indicates the restoration of the temperature regime in the pyrogenic-disturbed area.

1. Introduction
The most important characteristic of the landscape and climatic conditions of the functioning of geosystems in the soil cover's thermophysical state. In turn, the soil temperature is affected by forest fires due to an increase in insolation and a decrease in the reflectivity of the surface devoid of vegetation. Taking into account the relevance of the study of the thermophysical state of the soil cover as an indicator of the functioning of terrestrial biogeocenoses, we conducted stationary monitoring observations of the soil temperature of pyrogenically transformed geosystems of the Badar urochishche (the Tunkinskaya depression, Southwestern Cisbaikalia). The pine forests common here are the natural standard of the mountain-hollow light-coniferous forests of the region. In the course of many years of research, the dynamics of the temperature regime of soils in the process of their post-fire recovery have been traced. This made it possible to identify positive trends in the regeneration process and increase the reliability of forecasts for the restoration of landscape complexes.
2. Materials and Methods
The landscape-forming units of the Badar urochishche are the piedmont subtaiga pine genomes [1]. However, natural pine forests do not find their presence in the modern landscape structure due to periodically recurring forest fires. The largest fires took place in 1996, 2001, 2003, 2010, 2015, and 2016. For this reason, the modern landscape structure of the urochishche is characterized by the mosaic contours of the restored forests. The features of the processes of post-pyrogenic recovery successions were studied at two key sites. Site A26 (the eastern end of the Badary urochishche) is a burning formed by a fire in 2010. The A27 site is an area that has not been affected by recent fires. We take its geobotanical characteristic as a reference (background). The approach to the background indicates a favourable course of the reforestation process. The A27 site is located 3.3 km from the A26 site. Vegetation is represented by pine (Pinus sylvestris) forests with shrub undergrowth (Rhododendron dauricum) and true moss-grass-subshrub ground cover (Pleurozium schreberi, calamagrostis, Thalictrum minus, Lathyrus humilis, Maianthemum bifolium, Equisetum sylvaticum, Galium boreale, Rubus saxatilis, Vaccinium vitis-idaea). These are derived forests that are being restored after forest fires that took place here about half a century ago.

Observations of the restoration of vegetation cover and its influence on soil temperature dynamics cover a 10-year period. To measure the soil temperature at standard depths of 0-320 cm for the period from 13 October 2011 to 16 August 2020 using an autonomous atmospheric-soil measuring complex (ASMC) was used [2]. The measurements were carried out in time step of 1 hour. The correctness of the use of ASMC for long-term microclimatic monitoring is shown in [3]. The sites under consideration are characterized by a long-term seasonally freezing type of soil temperature regime [4].

3. Results and Discussion
Observations at the A26 site were started in October 2011. After the fire of 2010, the territory was characterized by the preservation of a part of the stand on the root. The dry-hardy ground cover consisted mainly of cereals (calamagrostis, carex). In September 2012, a significant presence of Artemisia sericea was observed among the dominant calamagrostis, carex. In June 2013, Geranium pratense, Vicia cracca, Rubus saxatilis were present in the grass cover among the new species. The projected coverage of the grass cover has increased from 30% to 40%. Vaccinium vitis-idaea was observed from shrubs, Rosa acicularis from shrubs.

In June 2014, a 10x10 m area element was laid near the established ASMC for conducting geobotanical monitoring studies. The continuation of the process of drying out and felling of the stand was observed. (Figure 1, inset a). In places where single specimens of Betula pendula grew before the fire, its resumption was noted. The average height of the rare undergrowth was 0.9-1.0 m. Rare specimens recorded annual shoots of Pinus sylvestris. The projected coverage of the ground cover was 40-50%. Subshrubs (Vaccinium vitis-idaea) and shrubs (Rosa acicularis and Rhododendron dauricum) with average heights of 15-20 cm are found in small numbers. Rubus saxatilis is noted in very small numbers; Artemisia sericea, Trifolium medium are scattered; calamagrostis, as well as Geranium pratense, Chamerion angustifolium, Sanguisorba officinalis are represented in the largest number.

![Figure 1](image-url). Reforestation periods in the burning area (site A26): a – 2014, b – 2017, c – 2020.
In July 2016, there were abundant young growth of *Pinus sylvestris* with average heights of 25-30 cm. The projected coverage was 20-30%, the ground cover was 50-60%. *Calamagrostis* and *carex* still dominate. Among the first encountered species of grass cover, *Ranunculus propinquus* and *Chrysanthemum zawadskii* were noted. The average height of the shrubs was 15 cm; there was an increase in the abundance of *Vaccinium vitis-idaea*; *Rosa acicularis* was still rare.

In July 2017, a fairly abundant amount of cranberry *Vaccinium vitis-idaea* was recorded; the abundance of *Rhododendron dauricum* remained at the same level, *Rosa acicularis* increased slightly. The average height of the shrubs was 25-35 cm. The projective coverage of the woody undergrowth was in the range of 30-40%. *Pinus sylvestris* dominates, with average heights of 50-55 cm (Figure 1b). The projected coverage of the ground cover was 60-70%. Among the above-mentioned dominant species of grass cover, *Aster alpinus* is also found in small numbers.

In July 2018, traces of spring grass fall were observed. The abundant undergrowth of *Pinus sylvestris* is not damaged by fire. Its average height was 70 cm. The average height of single specimens of the *Betula pendula* undergrowth was 160-170 cm. The projective coverage of woody undergrowth was estimated at 40-50%. The abundance and average height of shrubs have not changed. The projective cover of the ground vegetation remained the same – 60-70%; the composition and abundance of the herbage also did not change significantly. Rare small islands marked the appearance of *Pleurozium schreberi*.

In August 2020, an increase in the height of *Pinus sylvestris* undergrowth was noted to 2.5 m; the average height of the stand was 1.4 m (Figure 1c). The projective coverage was estimated at 60-70%. Along with the above-mentioned species, *Hieracium canadense* was observed in small quantities in the ground cover. The abundance of *Pleurozium schreberi* increased slightly. The height range of the herbage was 10-85 cm; the projective cover was 60-70%. The average height of the shrub layer is marked at the level of 15 cm. Shrubs were found in small numbers, their average heights were 35-40 cm.

According to the results of 10-year observations, a positive dynamic of reforestation at the A26 site was revealed. Since the appearance of the first shoots of *Pinus sylvestris* in 2013, its most heights reached 2.5 m by August 2020. The rare undergrowth of *Betula pendula* has a height of about 3.0 m. Also, to the abundant daughter undergrowth, an increase in the enough of forest vegetation species (*Vaccinium vitis-idaea*, *Rubus saxatilis*, *carex*, *Pleurozium schreberi*) following the meadow grass common here at the initial stage indicates the successful course of the demutation process.

The success of reforestation is confirmed by a comparison of the geobotanic characteristics of the A26 site with similar data from the background site. The average height of the *Pinus sylvestris* polygon A27 is 15 m, the closeness of the crowns is 0.8. The limiting access of solar radiation to the surface explains the absence of light-loving undergrowth of *Pinus sylvestris*. Among the shrubs, *Rhododendron dauricum* is represented with average heights of 40-60 cm, as well as the rarely occurring *Rosa acicularis* with a height of 15-25 cm. Due to the abundant coniferous fall, the ground cover has a projective cover of 30%. *Pleurozium schreberi* is presented. Among the shrubs, *Vaccinium vitis-idaea* is quite abundant. *Rubus saxatilis* also grows here. The rest of the herbaceous plants are found scattered, in small numbers. These are *calamagostis*, *Thalictrum minus*, *Lathyrus humilis*, *Maianthemum bifolium*, *Equisetum sylvaticum*, *Artemisia vulgaris*, *Galium boreale*.

Based on the results got, we confirmed that post-fire natural reforestation on the site of pine forests occurs without changing rocks [5, 6]. Within the transformed site, 10% of the naturally renewable undergrowth falls on the basal growth of *Betula pendula*. The remaining 90% belongs to *Pinus sylvestris*. During the observation period, a constant increase in the projective coverage of *Pinus sylvestris* undergrowth was recorded. This is because of her love of light. In the open treeless areas of the A26 site with abundant lighting, warming and dryness of the soil, the appearance of *Pinus sylvestris* seedlings was noted in the third post-fire year.

During the entire observation period at site A26, there was a veiny-mixed-grass post-pyrogenic stage with cranberry-mixed-grass microgroups with the appearance of moss-cranberry-mixed-grass microassociations at later stages of the development of burning. At this stage of the development
of burning, a shrub layer of *Rhododendron dauricum* and *Rosa acicularis* appears. As environmental conditions change (an increase in the height of woody undergrowth, a decrease in illumination, an increase in the moisture content of the soil horizon), meadow grass associations are gradually supplemented with forest species.

The resulting mosaic affects the amount of incoming and reflected solar radiation. A dense stand of trees, a powerful litter, a thick high grass cover more prevent the soil from warming up during the daytime and radiation cooling at night. Therefore, a decrease in the daily amplitude of fluctuations in soil temperature can be considered an indicator of stabilization and success of the demutation process.

Because of the similarity of the soil characteristics of the A26 and A27 sites under consideration [7], the temperature regime of the soil on them is very similar. However, even in the average monthly values of soil temperatures during the observation period, significant differences can be seen. On average, the soil on the disturbed site is warmer at all depths per year. The greatest differences on the soil surface are in May, in the absence of herbaceous vegetation, they reach 6.2°C. With depth, the maximum values of the differences decrease to 4.2-4.4°C, and we observe their shift for later months. In the winter months, the differences between temperatures in soil profiles become negative – the soil in the open area cools, and then freezes faster than under the canopy of a pine (*Pinus sylvestris*) forest. The temperature differences in winter are an order of magnitude smaller than in summer, which is explained by snow cover acting as a heat insulator.

In summer, in the absence of clouds, the range of daily fluctuations in the soil’s temperature surface can be 35-40°C in the open area, 10-15°C on forested land, at a depth of 20 cm – 10-12 and 2-4°C, respectively. The minimum temperatures in the diurnal variation observed at night at the two sites are almost the same (the differences do not exceed 1-3°C – the disturbed site cools down more). The consequence of the above is a more intensive warming up of the soil along the entire profile on the site where there is no vegetation cover. When the weather is cloudy at both sites, the fluctuations are only 5-7°C on the soil surface (the differences do not exceed 2-3°C during the day and -1...-2°C at night), and at a depth of 20 cm they are not traced. In winter, because of snow cover, even on a clear day in an open area on the soil surface, the daily fluctuations do not exceed 1-2°C. The difference in soil surface temperatures between the sites is 1.5-2°C during the day in clear weather and 0.5-1°C in cloudy weather.

In winter, the differences between the two sites are minimal in years when the appearance of snow cover and the transition of the average daily air temperature through 0°C occurs simultaneously. According to the Tunka weather station, such conditions were recorded in the winter of 2014-2015, 2015-2016 and 2017-2018. With a long snowless period with negative temperatures (20-30 days) we observe differences in soil temperature at all depths (-2...-3°C). Here, the vegetation on site A27 (pine (*Pinus sylvestris*) forest) prevents radiation cooling of the soil in the period before the onset of a stable snow cover. In the process of vegetation restoration, the difference in minimum temperatures decreases to -1.6°C. In summer, the soil is warmed up to a temperature of +10°C and higher was observed up to a depth of 170 cm in an open area and only up to 95 cm in a forested area [7]. Because of more intensive heating during the warm period, the soil in the open area keeps this heat longer and freezes to a lower depth. And although in the winter of 2011-2012. at site A26 (burning), the average daily soil temperature at a depth of 240 cm dropped to -1.7°C, at site A27 (forest) only to -0.8°C, at a depth of 320 cm, the minimum temperature was +0.1°C and -0.1°C, respectively.

With an increase in the projective cover of forest-growing tiers, we observe a decrease in the differences in the average monthly soil temperatures, which shows a significant influence of actively developing grass-shrub vegetation on the intake of solar radiation to the soil surface.

This influence becomes comparable, and sometimes even more significant, to the influence of the forest canopy. In the future, with the development of the tree layer, the herbaceous and shrubby vegetation on the A26 site should become less abundant, and with the restoration of the vegetation cover, a complete restoration of the temperature regime will occur.
4. Conclusion
According to the data of long-term monitoring observations, the dynamics of natural renewal of light coniferous subsurface geosystems are traced. It was revealed that the seedlings of \textit{Pinus sylvestris} were observed in the third year after the fire; the first post-fire years are characterized by the appearance of \textit{Betula pendula} roots. The further course of the reforestation process occurs with a significant predominance of the \textit{Pinus sylvestris} gene. The undergrowth of \textit{Pinus sylvestris} is characterized by high growth rates in height and a satisfactory degree of projective cover. This can be considered an indicator of the success of reforestation. In the shrub layer in the first years after the fire, \textit{Rosa acicularis} appears, later \textit{Rhododendron dauricum}. At the initial stages of recovery, meadow species predominate in the ground cover. Recent observations have shown a significant presence of forest species. This can be considered a convincing indicator of the effective restoration of the former pine green moss-herb-shrub forests.

The vegetation cover has a significant effect on the temperature regime of the soil. A site with a pine forest warms up less intensely than a site with combustion. In winter, open space is more prone to freezing. Ten-year microclimatic observations (2011-2020) showed that temperature drops at the sites are maximum in the warm season. On the soil surface, they reach 8.5°C (May 2015), at a depth of 2 to 320 cm they are -3-6°C. In winter, with a low snow cover and late formation of a stable snow cover, negative drops are recorded along with the soil profile. With natural reforestation of the pyrogenically transformed forests of the Tunkinskaya depression, the temperature regime is restored. These changes are most noticeable in the series of soil surface temperatures during the summer months.

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