# POST-FIRE RESTORATION OF PINE FORESTS IN THE BADARY AREA, TUNKINSKIY NATIONAL PARK, RUSSIA

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Received: 15.03.2022. Revised: 27.11.2022. Accepted: 03.12.2022.

A morphological variety of pyrogenic transformations characterises burnt areas of the Badary area of the Tunkinskiy National Park (Russia), from heavily damaged areas with a partially remained forest stand to bare spaces of tens of square metres. This enabled us to study the dynamics of the post-fire reproduction of *Pinus sylvestris* (hereinafter – pine) forests in areas with various environmental conditions. The main goal of our study was to determine the nature of the pyrogenic transformation of ecosystems and to evaluate the success of the forest reproduction. The studies were based on the geobotanical monitoring in two burnt-out areas, differing in the degree and area of wildfire damage due to a creeping fire in 2010. Between 2014 and 2020, we considered the multi-temporal specificity of the species composition of the forest stand, shrub layer, and plant communities. The emergence of the first shoots of undergrowth and new growth has been recorded. The projective cover and the dynamics of the species abundance in all forest layers were fixed. The analysis of the natural reforestation dynamics revealed a similarity of the main geobotanical indicators. Pine seedlings dominated in the undergrowth of the study sites, with a small proportion of *Betula pendula*. The shrub layer consisted of *Rosa acicularis*. *Rhododendron dauricum* has been found there only at the late stage of the study. In the herbaceous layer, the largest proportion was represented by meadow species, with a small participation of forest plants. Differences were revealed during the emergence of first seedlings of undergrowth and new growth, as well as in the size of projective cover of species in all forest layers. The first pine seedlings on a heavily burnt-out study plot were recorded a year earlier than on a less transformed plot. Nevertheless, the height increment and the projective cover of the undergrowth were significantly higher on the burnt-out area of a medium damage degree. On the heavily fire-damaged area, we observed pine seedlings planted by the staff of the Tunkinskiy National Park. A satisfactory rate of seedling survival at the initial stage and further deceleration of growth parameters have been noted. The obtained results indicate the reforestation success and, therefore, a favourable forecast of post-fire recovery of light-coniferous forests in the Badary area of the Tunkinskiy National Park.

**Key words:** artificial forest plantation, burnt-out area, geobotanical survey, monitoring, natural regeneration, succession, wildfire

## Introduction

The pyrogenic impact is one of the most considerable factors in the dynamics of biogenic landscape components. Secondary post-fire forests occupy a wide area in the south of Eastern Siberia (Chernykh & Zolotov, 2006; Krasnoshchekov et al., 2010; Sukhomlinov, 2012). The damage degree ranges from 30% to 85% in the forested area of the Siberian taiga (Dorzhiev et al., 2017). Studies analysing the wildfire impact on Protected Areas aimed to preserve unique and standard natural objects, protecting the forest fund, and reproducing ecosystems become relevant with an increase in the wildfire frequency (Chernykh & Zolotov, 2006; Sofronov et al., 2008; Evdokimenko & Krasnoshchekov, 2017; Dancheva & Zalesov, 2018; Rozhkov & Kondakova, 2019; Suleymanova et al., 2019; Kadetov & Gnedenko, 2021; Kharitonova & Kharitonova, 2021).

More than 90% of the area of the Tunkinskiy National Park is occupied by forests, threatened by wildfires each year. Over the period of 1974–2015, in the Tunkinskiy National Park, the wildfire monitoring statistics indicate that in 1996–2002, the highest wildfire impact occurred. However, the wildfire of low intensity and a small area preceded this (Sofronov et al., 2008). In 2002–2016, the wildfire-damaged area occupied 147 km$^2$ (Ivanyo et al., 2017). This is just over 1% of the Tunkinskiy National Park area. Unique natural complexes are often exposed to pyrogenic effects. These also affected *Pinus sylvestris* L. (hereinafter – pine) forests of the Badary area as a natural standard for the mountain-hollow light coniferous forests of the region. Previously, the Badary area (Fig. 1) had the status of a regional sanctuary. After the foundation of the Tunkinskiy National Park in 1991, pine forests, being a habitat and nesting place for a lot of animals, were designated as a reproduction site of the special regime zone. Forest preservation and reforestation activities have a priority for this area. The needs to strengthen capacities in this area are associated with the wildfire frequency in pine forests: in the Badary area, the wildfire severity was higher in 1996, 2001, 2003, 2010, 2015, and 2016. The transformation scale reached 32% of this area (Akharzhanova, 2004; Maksyutova et al., 2019). Here, pine forests are basically characterised by a high wildfire hazard (Sofronov et al., 2008; Volokitina & Sofronova, 2011; Tsvetkov, 2013; Dorzhiev et al., 2017; Evdokimenko & Krasnoshchekov, 2017), which explains the reason for frequent wildfires (Pobedinskiy, 1965; Sannikov, 1992). The highest intensity is observed in spring during the period of targeted grass fires (Sofronov et al., 2008; Lekhatinov & Lekhatinova, 2010). In 2019, 12 wildfire events were registered in the Tunkinskiy National Park, including six ones, which were caused by careless fire handling (Nefedieva, 2019). The total wildfire-damaged area reached almost 5.6 km$^2$. In addition, 11 uncontrolled grass fires were registered on an area of about 0.5 km$^2$ (Nefedieva, 2019). Possibly, the reason of periodic wildfires in the Badary area are deliberate arsons, since cutting down fire-damaged forests is a profitable business (Lekhatinov & Lekhatinova, 2010; Lazareva & Afonina, 2014; Tararuev, 2017; Vasiliev, 2017). Thus, the pyrogenic impact is the main factor in the transformation of the pine forests in the Badary area.

Issues related to the causes, scales and consequences of the wildfire impact on the landscapes receive a high attention in the literature (Akharzhanova, 2004; Elaev et al., 2013; Lazareva & Afonina, 2014; Ivanyo et al., 2017; Kiselev et al., 2019; Maksyutova et al., 2019). In these sources, fluctuation features of the long-term wildfire activity are revealed; factors of their occurrence are indicated; ecosystem characteristics at fire-damaged areas are presented at the initial stage of regeneration. The relevance of predicting a successful regeneration of pine forest loss for preserving the landscape uniqueness and biological diversity of the Tunkinskiy National Park was noted by various authors (Akharzhanova, 2004; Lekhatinov & Lekhatinova, 2010; Lazareva & Afonina, 2014; Kiselev et al., 2019).

However, there is a lack of long-term data on post-pyrogenic progressive successions for a predictive assessment. A tool proving effectiveness of solving this problem is long-term monitoring observations of post-fire regeneration (Ne'eman, 1997; Kavgacı et al., 2010; Moreira et al., 2012; Matveev & Matveeva, 2017; Keane, 2018). Often, results are being obtained in the monitoring and assessment of the biocenosis status cast doubt on reliability of the prospects for ongoing demutation processes (Thanos & Doussi, 2000; Eugenio et al., 2006; Ürker et al., 2018; Shinkarenko et al., 2021). One of options for minimising the risk of natural regeneration loss are reforestation activities (Kobechinskaya et al., 2009; Babintseva et al., 2010; Alfaro-Sánchez et al., 2015; Granados et al., 2016; Keane, 2018). In 2016, the Tunkinskiy National Park staff carried out artificial forest planting of 390 000 pine seedling. This has been performed for the first time in a 15-year period on an area of 1.3 km$^2$ due to the low abundance of natural seedlings in the Badary area (Gulgonov, 2017). In the Tunkinskiy National Park, there are sites with a varying degree of pyrogenic transformation, and areas of naturally regenerating and artificially planted pine seedlings. This fact allows us to consider the Tunkinskiy National Park as a model area to identify the particular dynamics of the post-fire regeneration of unique pine forests in sites with various environmental conditions. This study was aimed to identify the nature of the pyrogenic transformation and to determine the regeneration success.

## Material and Methods

The Badary area of the Tunkinskiy National Park is a sandy massif located in the centre of the Tunka depression and rising in the form of a flat, rounded summit with a height of 780–855 m a.s.l. Its surface is represented by ridges and hollows formed under influence of aeolian processes. Badary area is characterised by a markedly continental climate. According to data of the Tunka meteorological station in the centre of the depression, the mean monthly temperature is -24.2°C in January and 18.7°C in July. The mean annual temperature is 0.6°C (Vasilenko & Voropay, 2015). The absolute minimum was -40.1°C, and the maximum was 32.6°C. The annual precipitation is about 300–350 mm. Western and northern winds prevail in accordance with the latitudinal location of the depression and the deeply incised river valleys descending from the north, originating from slopes of the Tunkinskie Goltzy Range.


**Fig. 1.** The location of the Badary area in the Tunkinskiy National Park, Republic of Buryatia, Russia.

The landscape-forming units of the Badary area are piedmont sub-taiga pine geomes (Mikheev & Ryashin, 1977; Atutova, 2018), which are characterised by a combination of gray forest soils and soddy-slightly podzolic sandy loamy soils (Letunov, 1962). Gently sloping pine grass groups of facies with shrub undergrowth of *Rhododendron dauricum* L. represent the vegetation of the study area (Atutova, 2018). However, there are no natural pine forests remained, which is caused by frequent wildfires that destroyed 80 km$^2$ of forest plantations per wildfire season (Lekhatinov & Lekhatinova, 2010). The most widespread forest vegetation complexes are represented by secondary birch-pine grass forests with shrubs.

The study included the analysis of mapping materials and remote sensing data in order to select reference areas, field studies, data processing, long-term analysis and assessment of post-fire regeneration. The degree of pyrogenic disturbance of landscape complexes was the criterion for the selection of key sites. The herbaceous layer, shrubs, and trees have been completely destroyed by wildfires. After the middle-severity wildfires, forest stands with incompletely burnt undergrowth remains fragmentary, and the grass cover dies out (Kalinin, 2008; Kharitonova & Kharitonova, 2021). In the pre-field period, we analysed multi-temporal and multi-scale topographic maps, forest inventory materials, as well as multi-temporal satellite images from 1986 to 2013, provided by Google Earth. As a result, we identified fire-damaged areas with various degrees of damage, and areas that had not been exposed to pyrogenic effects for a long time (Fig. 2).

Analysis of multi-temporal data showed that, until 2010, study site A and study site B were not damaged by wildfires. The identity of the indication signs of the vegetation cover on each analysed satellite image until 2010 indicates similar forest communities within an area covering all three sites. This serves as an additional criterion for reliability of the study (reference) site selection. An analysis of data from the Global Forest Watch also makes it possible to attribute the latter to areas that have not been subjected to a transformative impact for a long time.

Site A is a moderately burnt area, as testified by the remaining forest stand at the beginning of the study in 2014. It is located in the eastern part of the Badary area at an altitude of 766 m a.s.l. on a gentle southeastern slope. Site A was situated at 70 m from the edge of the fire-damaged area of 2010. In mid-July 2018, traces of spring grass wildfire were observed on site A.

Site B is a severely burnt area (without any forest stand), located 250 m from the forest edge at an altitude of 781 m a.s.l., and 437 m northeast from site A. It is a gentle southeast slope. In 2010, the main wildfire passed through site B. Here, the study started in 2016, after pine seedlings were planted in late May 2016.

A reference site is an unburnt area. Geobotanical characteristics obtained here are a reference indicating a favourable course of the regeneration process in fire-damaged areas. The burnt area is located on a gentle eastern slope at the eastern edge of the Badary area at altitude of 786 m a.s.l., 3.3 km from site A, and 3.0 km from site B. The inclusion of charcoal in soil horizons and the small thickness of the forest litter (up to 3 cm) indicate frequent wildfires here (Kiselev et al., 2019). The vegetation is represented by medium-aged pine forests (45–50 years) with single specimens of *Larix sibirica* Ledeb., *Betula pendula* Roth., and an undergrowth of *Rhododendron dauricum* and patches of true moss-grass-subshrub forests. These are secondary forests, regenerated after wildfires about half a century ago. In absence of surviving natural pine forests in the Badary area, a reference site was selected, remote from the recently fire-damaged areas.

The time series of observations covers the period between 2014 and 2020. The analysis of the main patterns of composition and distribution of the vegetation cover was based on geobotanical descriptions adopted in the practice of field landscape studies (Pashkang et al., 1969; Zhuchkova & Rakovskaya, 2004). On sample (20 × 20 m) plots, undergrowth features were considered (forest stand structure, abundance based on Drude (1890) (hereinafter – Drude abundance), and average height), as well as characteristics of the shrub layer and plant communities (Drude abundance, average height, and projective cover). Scientific names are presented according to POWO (2023).

The species composition of the tree undergrowth has been registered as a formula of ten units, taking into account tree abundance. To estimate the abundance values, we used the scale of Drude (1890). The used symbols are cop.3 (plants are very abundant), cop.2 (there are many individuals), cop.1 (there are quite some individuals), sp. (plants are found in a small number, scattered), sol. (plants are found in a very small number, a few specimens). The projective cover was identified visually using a ten-fold step for the grass layer, a five-fold step for the shrub layer, and a single step for plant communities. Finally, we obtained a number of regeneration sets, describing features of the post-fire recovery of plant communities under certain landscape-ecological conditions. Based on them, we consistently solve problems presented above.

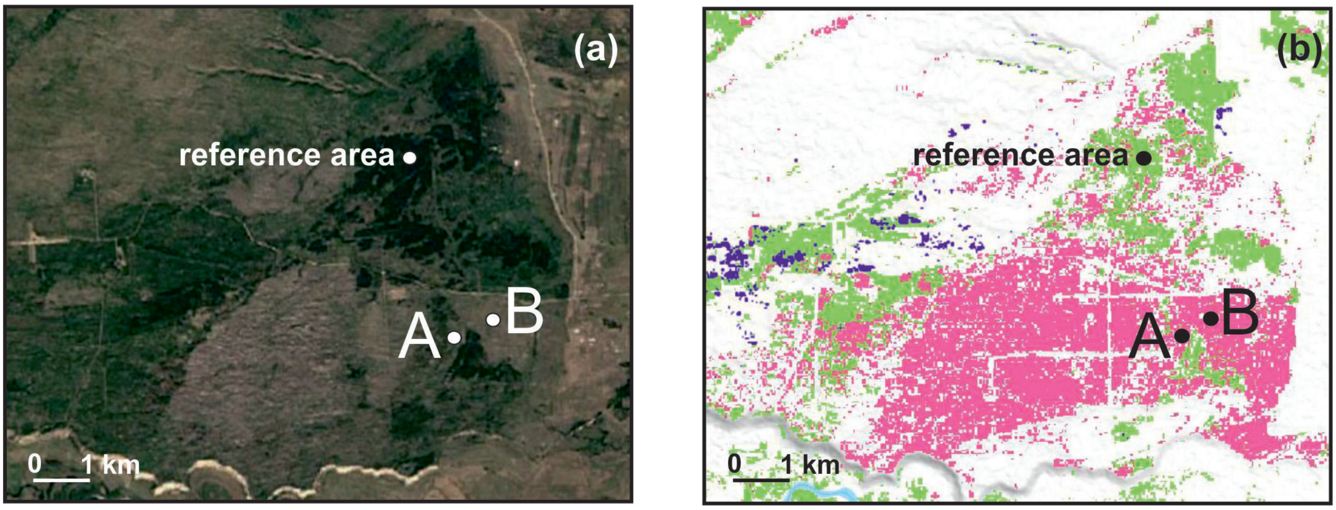


**Fig. 2.** The study sites (A, B) in the Badary area of the Tunkinskiy National Park, Russia. Designations: (a) satellite image from 2020 with study sites; (b) a fragment of the Global Forest Watch resource map (blue –regenerating tree cover; pink – canopy cover lost due to wildfires; green – canopy cover and areas without canopy cover (e.g. bushes, swamps, cropland, fallow land, pastures) are shown in white).

## Results

While solving the problem of predicting the prospects for the regeneration of fire-damaged plant communities, we compared them with characteristics of natural plant communities, which are not damaged by wildfires. On the reference site, the average height of pines was 15 m, and the crown density was 0.8 m. The last fact, limiting the access of solar radiation, explains the absence of light-demanding pine undergrowth there. We found *Rhododendron dauricum* with an average height of 40–60 cm, and rarer *Rosa acicularis* Lindl. with an average height of 15–25 cm.

The poor herb layer, hindered by coniferous litter, has a projective cover of 30%. *Pleurozium schreberi* (Willd. ex Brid.) Mitt. is presented in fragments. The sub-shrub *Vaccinium vitis-idaea* L. is widely spread, and *Rubus saxatilis* L. is abundant. Other herbaceous plants are scattered and have a low abundance. These species are *Calamagrostis obtusata* Trin., *Carex pediformis* var. *macroura* (Meinsh.) Kük., *Thalictrum minus* L., *Lathyrus humilis* (Ser.) Fish. ex Spreng., *Maianthemum bifolium* (L.) F.W.Schmidt, *Equisetum sylvaticum* L., *Galium boreale* L.

At the initial stage of the study on site A, single specimens of *Betula pendula* were noted before the wildfire event and its renewal after that. The average height of sparse *B. pendula* renewal was 0.9–1.0 m. We found a few individuals of one-year-old pine seedlings. The herbaceous layer cover was 40% during this year. *Rhododendron dauricum* and *Rosa acicularis* were found in a small number with an average height of 15–20 cm. *Rubus saxatilis* was noted in a very small number. *Artemisia sericea* Web. ex Stechm. and *Trifolium medium* L. were scattered. *Vaccinium vitis-idaea* and *Vicia cracca* L. were found in a small number. The highest abundance was found for *Calamagrostis langsdorffii* (Link) Trin., *Chamaenerion angustifolium* (L.) Scop., *Geranium pratense* L., and *Sanguisorba officinalis* L.

Late July 2016, pine seedlings were abundant, with an average height of 25–30 cm (Fig. 3). The tree cover reached 20–30%, and the herb layer 50%. *Calamagrostis* species still dominated. *Geranium pratense*, *Rubus saxatilis*, *Trifolium medium*, *Artemisia sericea* and *Chamaenerion angustifolium* were quite abundant. Some individuals of *Ranunculus propinquus* C.A.Mey. were found. *Chrysanthemum zawadskii* Herbich was noted in a small number of individuals. The average height of shrubs was 15 cm. An increase in abundance of *Vaccinium vitis-idaea* was observed. *Rosa acicularis* and *Rhododendron dauricum* were still rare.

In the first half of July 2017, a high number of *Vaccinium vitis-idaea* individuals was observed. The abundance of *Rosa acicularis* remained at the same level, while *Rhododendron dauricum* increased slightly. The average height of shrubs was 25–35 cm. Among the above-mentioned dominants, a small number of *Aster alpinus* L. individuals was found. The undergrowth cover was within 30–40%. The pine dominated, with an average height of 50–55 cm. The ground cover was 60%.

Mid-July 2018, signs of the spring grass fire have been registered. The wildfire did not damage the abundant pine undergrowth; its average height increased to 70 cm. The average height of single *Betula pendula* seedlings was 160 cm. The abundance and average height of shrubs did not change. Due to the lack of dead-standing trees, the ground layer was clearly visible; its projective cover remained at last year's level. The composition and abundance of herb layer did not change considerably either. *Pleurozium schreberi* was represented by a few small patches.

Early August 2020, a remarkable increase in height of pine undergrowth (up to 2.5 m) has been noted in comparison with the data of 2018. Its average height was about 1.6 m. The projective cover was 70%. In the herb layer, along with the above-mentioned species, *Hieracium umbellatum* L. was found in a small number of individuals. *Pleurozium schreberi* abundance slightly increased. The height of the herb layer varied from 10 cm to 85 cm; its projective cover was 70%. The average height of the shrub layer was 15 cm. *Rosa acicularis* and *Rhododendron dauricum* were found in a small number of individuals, with an average height of 35–40 cm.

During the study on site A, the process of the forest stand dieback has been observed. The rest of the remained dead trunks were cut down in the first post-fire year; then they were stockpiled or randomly fell out.

In the first year of the study on site B, we observed cracked and splintered remains of fell out trunks and branches. The surface ground was disturbed with planting furrows made by heavy logging machinery (Fig. 4). In July 2016, the average height of two-year-old pine seedlings, planted in cut furrows in May 2016, was 8–10 cm (Fig. 5). Meanwhile, 80-cm root suckers of *Betula pendula* and pine seedlings have been registered. Based on the number of nodes, pine seedlings appeared here two years after the wildfire. The average height of the pine undergrowth was 25–30 cm; its total projective cover was 15–20%. The shrub layer is represented by *Rosa acicularis*. The projective cover of the herb layer was 60%, dominated by *Calamagrostis* spp. and *Carex* spp. Common species were also *Chamaenerion angustifolium*, *Artemisia vulgaris* L., *Geranium pratense*, *Sanguisorba officinalis*, *Trifolium medium*, *Galium verum* L., *Hieracium umbellatum*, *Achillea millefolium* L., *Vicia cracca*, *Aster alpinus*, *Rubus saxatilis*, *Artemisia sericea*, *Astragalus adsurgens* Pall. The average height of the herb layer was 40 cm.

In July 2017, no changes were observed in both composition and distribution of the undergrowth, shrub and herb layers. The projective cover of the herb layer had increased to 70%. The average height of the artificially planted pine individuals was 10 cm, while the height of naturally regenerated ones was 50 cm. The average height of *Betula pendula* individuals was 100–110 cm. The dieback and falling out of the fire-damaged forest continued, thereby increasing the wood-debris amount.


**Fig. 3.** Post-fire reforestation periods at site A in the Badary area of Tunkinskiy National Park, Russia. Designations: a – 2014, b – 2017, c – 2020.


**Fig. 4.** Periods of post-fire reforestation at site B in the Badary area of Tunkinskiy National Park, Russia. Designations: a – 2016, b – 2017, c – 2020.

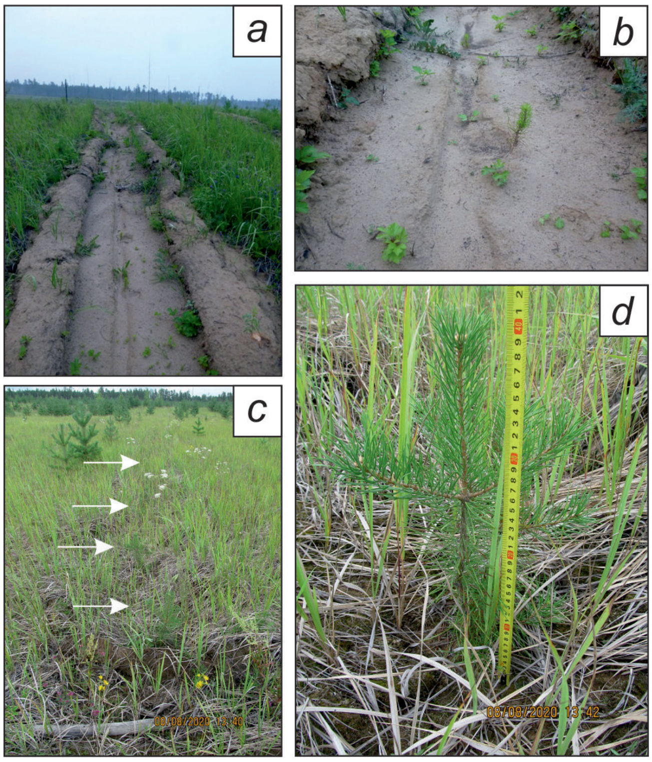


**Fig. 5.** Conditions of artificially planted pine seedlings on site B in the Badary area of Tunkinskiy National Park, Russia. Designations: a – recently-dug-up forest planting furrow, July 2016; b – *Pinus sylvestris* seedlings, July 2016; c – forest planting furrow with pine undergrowth marked by arrows, August 2020; d – pine sprouting, August 2020.

In July 2018, the average height of the undergrowth of *Betula pendula* and *Pinus sylvestris* was 110 cm and 70 cm, respectively. The height of the artificially planted pines did not exceed 20 cm. The total projective cover of the pine undergrowth was 20%. In addition to *Rosa acicularis*, rare, up to 15–20 cm in height, individuals of *Rhododendron dauricum* were found. *Pleurozium schreberi* was found in shaded areas with wood-debris. The projective cover of the herb layer was 70%; its average height was 50 cm.

In August 2020, the projective cover of birch-pine undergrowth was 35–40%; its height varied in the range of 0.4–2.5 m. The average height of *Betula pendula* was 120 cm. The height of artificially planted and naturally regenerated pine individuals was 40 cm and 130 cm, respectively. The average height of the shrub layer was 70 cm. The height of the herb layer varied from 10 cm to 95 cm; its projective cover was 90%. During our five-year study, the abundance of *Chamaenerion angustifolium*, *Galium verum*, *Achillea millefolium*, *Vicia cracca*, *Aster alpinus* decreased, while the abundance of *Carex duriuscula* C.A.Mey., *Sanguisorba officinalis*, *Trifolium medium*, *Rubus saxatilis*, *Artemisia sericea*, *Astragalus adsurgens*, *Vaccinium vitis-idaea* increased. The abundance of other species in the herb layer did not change.

Based on the results of seven years of the study, it can be assumed that reforestation of the fire-damaged areas is quite successful. On site A, the maximum height of pine individuals reached 2.5 m from 2013 to August 2020 (Table 1). The height of the rare *Betula pendula* undergrowth was about 3.0 m. The successful demutation process was evidenced by an increase in abundance of the herb vegetation (*Vaccinium vitis-idaea*, *Rubus saxatilis*, *Pleurozium schreberi*, *Carex duriuscula*), followed by the meadow forbs, which were common at the initial succession stage there. Slow-decomposing and hard coniferous litter is a limiting factor for a more intensive regeneration process in all forest layers, as well as debris-strewn forest.

On site B, a low growth rate of artificially planted *Pinus sylvestris* was observed over the 5-year period. The average height of pine individuals increased from 8 cm to 40 cm, although artificial planting can be considered effective; the survival rate of pine seedlings was estimated at 70–80%. Reforestation efforts and badly organized wildfire response measures resulted in littering of this area with wood debris. In addition, the furrows and ruts of logging machinery contributed to the decrease of natural regeneration. In the last study year, the projective cover of naturally regenerated pine undergrowth did not exceed 30%. Nevertheless, the average height of individuals had changed from 30 cm to 1.3 m over the 5-year period.

## Discussion

Based on the obtained results (Table 1), some features of pyrogenic successions were identified. We confirmed that post-fire natural reforestation in former pine forests occurs without changes in species composition (Sannikov, 1992; Tsvetkov, 2013). It was demonstrated that 10% of naturally regenerated plants of the undergrowth were *Betula pendula*; the remaining 90% were *Pinus sylvestris*.

Over a seven-year period, the anthropogenic influence (i.e. littering the area with remains of fire-damaged forest stand and heavy equipment traces) constrained the constant increase in projective cover of pine undergrowth. In addition, unsatisfactory reforestation was associated with a considerable proportion of the forest stand loss after its burning. This is clearly seen on the heavily burnt site B, where the projective cover of undergrowth is uneven and amounts to 30%.

**Table 1.** Characteristics of the post-fire regeneration on the study sites in the Badary area of Tunkinskiy National Park, Russia

| | Parameters | Site A | | | | | Site B | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2014 | 2016 | 2017 | 2018 | 2020 | 2016 | | 2017 | | 2018 | | 2020 | |
| Site description | Vegetation before wildfire | *Pinus sylvestris* with single specimens of *Larix sibirica* Ledeb. and *Betula pendula* Roth. with undergrowth of *Rhododendron dauricum* L. green-moss-herb-subshrub forest | | | | | | | | | | | | |
| | Year of the last wildfire | 2010, and spring grass wildfire of 2018 | | | | | 2010 | | | | | | | |
| | Pyrogenic features | Edge part (flank) of the ground fire | | | | | Area of the main part of the ground fire | | | | | | | |
| | Negative environmental factors | Most of the remained forest stand has been cut down and stored or chaotically felled out, which is a deterrent to recovery, coupled with abundant coniferous litter. | | | | | The area is littered with wood debris. Furrows cut with heavy equipment for artificial forest planting contributed to the reduction of the cover of naturally regenerated forest. | | | | | | | |
| Undergrowth | Composition (formula[1]) | 1P9B | 2B8P | 2B8P | 1B9P | 1B9P | 2B8P | | 1B9P | | 1B9P | | 1B9P | |
| | *Betula pendula* Roth. | | | | | | | | | | | | | |
| | Average height, m | 0.9 | 1.2 | 1.4 | 1.6 | 1.8 | 0.8 | | 1.0–1.1 | | 1.1 | | 1.2 | |
| | Projective coverage, % | 5 | 5 | 5 | 5 | 5 | 3 | | 3 | | 5 | | 5 | |
| | *Pinus sylvestris* | | | | | | | | | | | | | |
| | Natural (⸙) and artificial reproduction (✣) of *Pinus sylvestris* | ⸙ | ⸙ | ⸙ | ⸙ | ⸙ | ⸙ | ✣ | ⸙ | ✣ | ⸙ | ✣ | ⸙ | ✣ |
| | Average height, m | 0.06–0.10 | 0.25–0.30 | 0.5 | 0.7 | 1.5 | 0.3 | 0.08 | 0.5 | 0.1 | 0.7 | 0.2 | 1.3 | 0.4 |
| | Projective cover, % | 5 | 30 | 40 | 50 | 70 | 15 | 5 | 25 | 3 | 30 | 3 | 40 | 5 |
| Shrub layer | Average height, m | 0.20 | 0.25 | 0.30 | 0.40 | 0.40 | 0.3 | | 0.3 | | 0.5 | | 0.7 | |
| | Projective cover, % | 15 | 20 | 20 | 25 | 30 | 30 | | 30 | | 30–35 | | 40 | |
| | Drude abundance for dominant species[2] | | | | | | | | | | | | | |
| | *Rosa acicularis* Lindl. | sp. | sp. | sp. | sp. | sp. | cop.1 | | cop.1 | | cop.1 | | cop.1 | |
| | *Rhododendron dauricum* L. | sol. | sol. | sol. | sp. | sp. | – | | – | | sol. | | sol. | |
| Herb layer | Average height, m | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | | 0.4–0.5 | | 0.5 | | 0.5 | |
| | Projective cover, % | 40 | 50 | 60 | 60 | 70 | 60 | | 70 | | 70 | | 90 | |
| | Drude abundance for dominant species[2] | | | | | | | | | | | | | |
| | *Calamagrostis langsdorffii* (Link) Trin. | cop.2 | cop.3 | cop.3 | cop.3 | cop.3 | cop.2 | | cop.2 | | cop.2 | | cop.2 | |
| | *Carex duriuscula* C.A. Mey. | – | sp. | cop.1 | cop.1 | cop.1 | sp. | | sp. | | cop.1 | | cop.1 | |
| | *Chamaenerion angustifolium* (L.) Scop. | cop.2 | cop.2 | cop.1 | cop.1 | sp. | cop.2 | | cop.2 | | cop.2 | | cop.1 | |
| | *Artemisia sericea* Web. ex Stechm. | sp. | cop.2 | cop.2 | cop.2 | cop.2 | sp. | | sp. | | sp. | | cop.1 | |
| | *Geranium pratense* L. | cop.1 | cop.2 | cop.2 | cop.2 | cop.2 | cop.2 | | cop.2 | | cop.2 | | cop.2 | |
| | *Sanguisorba officinalis* L. | cop.1 | cop.1 | cop.1 | cop.1 | cop.1 | cop.1 | | cop.1 | | cop.1 | | cop.2 | |
| | *Trifolium medium* L. | sp. | cop.2 | cop.2 | cop.2 | cop.2 | cop.1 | | cop.1 | | cop.1 | | cop.2 | |
| | *Vicia cracca* L. | sp. | cop.1 | cop.1 | cop.1 | cop.1 | sp. | | sp. | | sp. | | sol. | |
| | *Rubus saxatilis* L. | sol. | sp. | cop.1 | cop.1 | cop.1 | sp. | | sp. | | sp. | | cop.1 | |
| | *Vaccinium vitis-idaea* L. | sol. | sp. | cop.1 | cop.1 | cop.1 | – | | – | | sol. | | sp. | |
| | *Pleurozium schreberi* (Willd. ex Brid.) Mitt. | – | – | – | sol. | sp. | – | | – | | sol. | | sol. | |

*Note*: [1] – B – *Betula pendula*, P – *Pinus sylvestris* L.; [2] – Drude abundance for dominant species: cop.3 – plants are very abundant, cop.2 – there are many individuals, cop.1 – there are quite many individuals, sp. – plants are found in a small number, scattered, sol. – plants are found in a very small number, a few specimens.

The forest regeneration through the pine dominance is also associated with its light-demanding preferences. The regenerated pine seedlings were found two years later in open areas of site B, characterised by high illumination, sun heating, and dry soils. On site A, the pine regeneration on the remained forest stand began a year later. The coniferous litter preserved in some sites prevents the seed reproduction and causes the uneven spatial development of renewal vegetation (Marañón-Jiménez et al., 2013; Dancheva & Zalesov, 2017).

On site B, a sufficient survival rate of pine seedlings has been recorded on recently dug up and well-lit sites with forest planting furrows. At the same time, the absence of biologically highly active litterfall (Tsvetkov, 2013; Solovyova, 2018) in plantation furrows explains a low renewal rate of artificially planted *Pinus sylvestris* at the initial succession stage. Later, the overgrowth of plantation furrows with a well-developed herb cover and prevailing tall *Calamagrostis* spp. plants did not contribute to the active growth of pine seedlings either, due to the high shading and competition for moisture and nutrients. In this connection, the managed burning treatment is favourable for an effective way to promote post-fire pine regeneration, besides of weeding and loosening (Belov, 1973; Kovaleva et al., 2012; Matveev & Matveeva, 2017). The spring grass fire, recorded in 2018 on site A, did not have negative consequences in the development of vegetation renewal, but it contributed to the thinning of plant communities. This resulted, that we did not record an increase in projective cover of the herb layer, which was observed previously in 2017–2018. At the same time, an increase in the projective cover of pine undergrowth renewal was revealed from 50% in 2018 to 70% in 2020. Thus, a managed burning treatment of the dry vegetation cover is an additional incentive for the reforestation success, as evidenced by the growth of geobotanical parameters in the restored forest stand.

The degree of the wildfire damage explains a series of stages in derivative associations of the subshrub and herb layers (Groot et al., 2004; Kovaleva et al., 2012; Vallejo et al., 2012; Roberts et al., 2019). The fireweed-reed-grass post-pyrogenic stage of the vegetation development often observed in fire-damaged areas under similar environmental conditions has been recorded five years after the wildfire on site B with a strong degree of the wildfire effect (Kovaleva et al., 2012; Gongalsky, 2015). Green mosses and subshrubs were not recorded. The reed-grass-forb stage with moss-cowberry-forb micro-groups has been established five years later, i.e. ten years after the wildfire. At this stage of vegetation development, a shrub layer with *Rhododendron dauricum* and *Rosa acicularis* appears. This confirms that the process of demutation of perennial herbs begins immediately after the wildfire, while the green moss recovery starts several years later (Volokitina et al., 2013). Over the entire study period on site A with a moderate wildfire degree and a considerable degree of the forest stand preservation, the reed-grass-forb stage with cowberry-forb plant micro-associations has been recorded with the appearance of moss-cowberry-forb plant micro-associations at later stages of the vegetation regeneration. An increase in abundance and height of renewed trees leads to a decrease in the site illumination level, resulting in an increase in the forest stand density in the soil moisture content. Meadow-forb plant associations dominated at the initial stage of forest regeneration have been supplemented with typical forest species later.

The success of the reforestation is determined on the basis of the age (height) of the undergrowth and its area (abundance) (Sofronov et al., 2008). At the end of the study, a considerable pine participation in the vegetation renewal has been revealed, regardless the fire-damaged area and the percentage of the survived forest stand. Sofronov et al. (2003) suggested that the presence of at least one renewed pine individual of 1.5 m in height per 10 $m^2$ indicates a successful reforestation. A visual evaluation of the overgrowth of burnt areas with pine seedlings in 2020 made it possible to conclude that this indicator was much higher, which evidences on the successful post-fire pine regeneration in the Badary area of Tunkinskiy National Park.

Conditions of the vegetation development (lighting and shading intensity, presence or absence of wood debris, and site vulnerability to the anthropogenic impact) adjust the regeneration and affect the regeneration of artificial plantations. Nevertheless, despite the low increase in height of the artificially planted seedlings, their survival rate was considered satisfactory. In the last study year, the visual evaluation of planting furrows showed that, on a 4-$m^2$ area, there were more than two pine seedlings of 0.21–0.50 m in height or four ones of 0.11–0.20 m in height. Based on Sofronov et al. (2003), this value is considered a successful reforestation.

The stimulating role of wildfires in the natural regeneration of light-coniferous forests is often observed due to the emergence of a higher number of seedlings in burnt areas, compared to one under the canopy of undisturbed forests (Belov, 1973; Kobechinskaya et al., 2009; Heras et al., 2012; Vallejo et al., 2012; Zlenko et al., 2015). This is consistent with our results. If we compare background green-moss-grass-subshrub pine forests with single individual of *Larix sibirica* and *Betula pendula* with *Rhododendron dauricum* and undergrowth absence with fire-damaged areas with abundant wood regeneration, in the absence of frequent wildfires, there is a tendency for effective post-fire reforestation and the formation of highly productive subtaiga light-coniferous geosystems.

## Conclusions

In the Badary area of Tunkinskiy National Park, fire-damaged areas are characterised by a variety of pyrogenic transformations, ranging from conflagrations with a partially preserved forest stand to open areas of several square kilometres. Long-term data allowed us to analyse the dynamics of post-fire regeneration and identification of demutation processes in pine forests.

At this demutation stage, morphometric indicators of undergrowth in young pine forests in moderately burnt areas characterised the regeneration process as quite successful. Despite the later start of the forest reproduction than in heavily burnt areas, the abundance of pine seedlings is higher there. The projective cover of natural pine seedlings over a seven-year period was almost twice higher than in the heavily burnt areas.

In heavily burnt areas, indicators of the natural pine reforestation were characterised by high values of the renewal rate and projective cover, which can be generally considered a marker of successful regeneration. Observations of the artificially planted pine seedlings in the heavily burnt areas in 2010 showed a satisfactory survival rate of pine seedlings. However, an increase in the pine renewal height is limited by shading of the high herb layer.

On both study sites, positive dynamics are confirmed by the shrub emergence in the undergrowth existed here before the wildfire and satisfactory development of shrubs. It has been confirmed that the floristic composition of post-fire plant communities has not changed in most cases; a gradual restoration of the fire-damaged plant community was noted. A convincing indicator of the effective restoration of damaged pine green-moss-grass-subshrub forests is the increased abundance of forest species in plant communities among the meadow-forbs plant communities, common here at the initial stage of the pyrogenic succession.

The obtained results can be used in determining and predicting the dynamic trends of the demutation process in fire-damaged pine forests. They replenish an informative database on patterns of post-fire successions, taking into account regional specifics of sites. It is advisable to continue monitoring studies to eliminate constraining factors for successful reproduction of the unique pine forests in the Badary area of the Tunkinskiy National Park.

## Acknowledgements

This study has been performed within the state assignment (registration number: AAAA-A21-121012190017-5).

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# ПОСЛЕПОЖАРНОЕ ВОССТАНОВЛЕНИЕ СОСНОВЫХ ЛЕСОВ УРОЧИЩА БАДАРЫ (НАЦИОНАЛЬНЫЙ ПАРК «ТУНКИНСКИЙ», РОССИЯ)

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Гари урочища Бадары Тункинского национального парка (Россия) характеризуются морфологическим многообразием пирогенных трансформаций – от пожарищ с частично сохранившимся на корню древостоем до безлесных пространств в десятки гектаров. Это позволило нам изучить особенности динамики послепожарного восстановления сосновых боров на участках с различными экологическими условиями. Основная цель нашего исследования заключалась в определении характера пирогенной трансформации биогеоценозов и в установлении степени успешности лесовосстановления урочища Бадары Тункинского национального парка. Исследования опирались на мониторинговые данные геоботанических наблюдений на двух участках гарей, отличающихся степенью и площадью огневого поражения в результате низового пожара 2010 г. За период 2014–2020 гг. рассмотрена разновременная специфика породного состава древостоя, кустарникового яруса и живого напочвенного покрова. Отмечен период появления первых всходов подроста и подлеска. Установлены величина проективного покрытия и динамика обилия видов всех лесорастительных ярусов. В ходе анализа динамики естественного лесовосстановления выявлена схожесть основных геоботанических показателей. В подросте рассматриваемых площадок доминировали всходы *Pinus sylvestris*, лишь небольшой процент приходился на долю *Betula pendula*. Кустарниковый ярус состоял из *Rosa acicularis*, среди которого на поздних этапах наблюдения был отмечен *Rhododendron dauricum*. В травяном ярусе наибольшую долю составляли луговые виды с небольшим участием лесных. Различия выявлены во времени появления первых всходов подроста и подлеска, а также в величине проективного покрытия видов во всех лесорастительных ярусах. Первые всходы *Pinus sylvestris* на сильно выгоревшем ключевом участке зафиксированы годом ранее, чем на менее трансформированной территории. Тем не менее, прирост по высоте и проективное покрытие подроста было значительно больше в пределах гари средней степени поражения. На сильно пострадавшей от пожара территории проведено наблюдение за искусственно посаженными сеянцами *Pinus sylvestris*. Отмечена удовлетворительная приживаемость сеянцев на начальном этапе и дальнейшее замедление параметров роста. Полученные результаты свидетельствуют об успешности лесовосстановления и, как следствие, о благоприятном прогнозе послепожарного восстановления светлохвойных лесов урочища Бадары Тункинского национального парка.

**Ключевые слова:** гарь, геоботаническое наблюдение, естественное восстановление, искусственная лесопосадка, лесной пожар, мониторинг, сукцессия