The influence of soil hydrothermal regime on post-fire recovery process in the ribbon-like pine forests of Western Siberia

A A Malinovskikh and I V Gefke
Altai State Agricultural University, Barnaul, Russia

E-mail: ivgefe@mai.ru

Abstract. The features of the hydrothermal regime and the vegetation cover of burnt-out areas in the ribbon-like pine forests of Western Siberia have been studied on a zonal-typological basis. Dry forest growth conditions after a fire are characterized by a weak development of the ground cover and natural regeneration than fresh and moist forest growth conditions. As we move from the dry steppe subzone to the southern forest-steppe, the forest growing conditions on the burnt areas improve thanks to an increase in the annual amount of precipitation and soil moisture.

1. Introduction
Forest fires are one of the threats to the modern world and rational nature management. Every year, from 4.5 to 27 thousand fires occur in the forests of Siberia, which damage forest plantations on a total area of 3.5 to 18 million hectares [1]. According to the data of ground-based and space monitoring, the fire rate of the forests of Western Siberia is increased; in this large region, from 1.5 to 6 thousand fires are annually recorded, which spread over an area of 15 to 250 thousand hectares. In recent decades, there has been a steady increase in the number of forest fires and the area covered by them. Obviously, in the near future, the dynamics of forest fire in Western Siberia will tend to grow. This is due to the fact that the main cause of fires in forest ecosystems is the anthropogenic factor (80-90% of all cases of fires). Forest fires in Western Siberia cause enormous economic damage, consisting of fire-fighting measures, costs of fighting fires, losses from the fires themselves, amounting to 2-5 billion rubles annually.

Forest fires can have both positive and negative effects on the forest biogeocenosis. During running ground fires, the lower tiers of forest vegetation partially burn out, the forest litter burns out, thereby intensifying the processes of reforestation [2]. During intense ground and crown fires, damage or death of the main component of the forest - the stand, occurs, which leads to the formation of a burnt wood or burnt area, initiating the onset of pyrogenic restorative succession. Pyrogenic successions in forests are still poorly studied for several reasons, including their high duration in time, geographic variability in space, multifactorial nature, and complexity. According to the leading researchers, the time of complete stabilization (relaxation) after fires for all the main components of pine forests is at least 120-140 years [3, 4]. It has been established that the restoration of individual forest components, its post-fire renewal depends on environmental factors; however, this issue is poorly studied at the regional level. The study of post-fire recovery processes is of theoretical importance as a basis for the development of forestry measures for forest reproduction.
2. Materials and methods

The purpose of this work is to study the hydrothermal regime of sod-podzolic soil, the degree of development of the living ground cover before and after a fire in the ribbon-like pine forests of Western Siberia on a zonal-typological basis in order to establish the features of the restoration process.

The objects of research are burnt areas of different years, on which the succession and reforestation process takes place, located within the steppe and forest-steppe zones in the forest fund of the ribbon-like pine forests of Western Siberia. The fires were formed as a result of the passage of persistent crown fires and are located within the following natural subzones:

- dry steppe - Korostelevsky bor (environs of the village of Uglovskoye), burnt area in 1997 with a total area of 25800 hectares;
- arid steppe - Srostinsky bor (environs of the village of Volchikha), burnt area of 1997 with a total area of 10,414 hectares;
- arid steppe - southern part of the Barnaul belt (environs of Tokarevo village), burnt area of 1999 with a total area of 16 hectares;
- southern forest-steppe - the northern part of the Barnaul belt (environs of the city of Barnaul), 2006 burnt area of 4 hectares.

The greatest scientific interest is represented by large burnt areas in the steppe zone, at the same time, smaller burnt areas located in the forest-steppe zone are important for understanding and comparing the results of the reforestation process as a whole for ribbon-like pine forests. Research on burnt areas in the Korostelevsky and Srostinsky pine forests has been carried out since 1998, on burnt areas in the southern and northern parts of the Barnaul belt since 2008.

Research methods were chosen to achieve the purpose and obtain reliable results: the method of trial plots, the method of accounting plots, geobotanical descriptions, accounting for undergrowth, determination of soil temperature and moisture [5, 6]. To determine the closeness of the relationship between the parameters of the hydrothermal regime and the vegetation cover, the linear Pearson correlation coefficient was used [7].

Field work scheme. Two options were studied on the burnt area (experiment) and in a living forest (control): the top (dry forest growth conditions) of a sandy ridge and an inter ridge depression (fresh or wet forest growth conditions), where temporary test plots of 0.25 hectares of rectangular shape were laid. The test plots did not go beyond the “boundaries” of the mesorelief element. Brief taxation characteristics of pine stands on the control plots are presented in table 1.

Table 1. Taxation characteristics of forest stands before the fire (control).

| № variant | Forest type (FGC) | Composition | Age, years | Height, m | Diameter, cm | Bonitet class | Density, units | Stock for 1 ha, m³ |
|-----------|------------------|-------------|------------|-----------|--------------|---------------|---------------|------------------|
| Korostelevsky pine forest (environs of the village of Uglovskoe) |
| 3, top | Sbp (A1) | 4C3C2C1C | 105 | 18 | 28 | IV | 0.4 | 100 |
| 4, lowland | Trb (A3) | 6C3C1B | 105 | 22 | 28 | III | 0.5 | 160 |
| Srostinsky pie forest (environs of the village of Volchikha) |
| 7, top | Sbp (A1) | 10CP | 90 | 20 | 28 | III | 0.4 | 150 |
| 8, lowland | Svb (A2) | 10C+2C | 90 | 22 | 24 | II | 0.7 | 240 |
| Barnaul pine forest, southwestern part (environs of Tokarevo village) |
| 11, top | Sbp (A1) | 4C3C2C1C | 135 | 23 | 32 | III | 0.3 | 100 |
| 12, lowland | Trb (A3) | 8C2C | 120 | 27 | 36 | II | 0.7 | 250 |
| Barnaul pine forest, northeastern part (environs of the city of Barnaul) |
| 15, top | Sbp (A1) | 6C2C2C | 85 | 21 | 24 | III | 0.7 | 190 |
| 16, lowland | Svb (A2) | 8C2C+2C | 95 | 23 | 32 | II | 0.8 | 260 |
The burn stands are similar to the control plots in terms of location, FGC, composition and structure of stands, underbrush, undergrowth, ground cover. On each trial plot, at the beginning, middle and end of the growing season, the living ground cover (LGC) was studied, soil samples were taken for moisture, the soil temperature was measured, and the undergrowth of the main and secondary types was recorded. Three main types of forest growing conditions (FGC), characteristic of the pine forests of Western Siberia, have been studied: dry forest growing conditions (A1), type of forest dry forest of gentle hills (Sbp); fresh forest conditions (A2), forest type fresh (depression) pine forest (Svb); wet forest growing conditions (A3), type of forest grass (wet) pine forest (Trb). Data are for May-September 2019.

3. Results
In the ribbon-like pine forests of Western Siberia, the nature of the mesorelief affects the distribution of moisture and heat in the soil, the composition and structure of vegetation [8] (table 2, table 3).

Table 2. Parameters of the hydrothermal regime of soils and ground cover during the growing season in the ribbon-like pine forests of Western Siberia. (numerator – burnt area, top, denominator - control, top).

| Location                        | Month | Soil, depth 20 cm | Ground cover |               |               |
|---------------------------------|-------|-------------------|--------------|---------------|---------------|
|                                 |       | T, °C             | W, %         | Number of     | Total         |
|                                 |       |                   |              | species       | projective    |
|                                 |       |                   |              |               | cover %       |
| Steppe zone, subzone of dry steppe |       |                   |              |               |               |
| Korostelevsky pine forest (Uglovskoe) | May  | 14.5              | 3.57         | 13            | 10            |
|                                  |       | 10.5              | 2.13         | 21            | 12            |
|                                  | July  | 23.5              | 0.68         | 14            | 20            |
|                                  |       | 19.5              | 1.54         | 25            | 25            |
|                                  | September | 16.5         | 0.83         | 12            | 30            |
|                                  |       | 13.0              | 1.86         | 19            | 25            |
| Steppe zone, subzone of arid steppe |       |                   |              |               |               |
| Srostinsky pine forest (Volchikha) | May  | 9.0               | 2.49         | 12            | 12            |
|                                  |       | 5.0               | 5.20         | 15            | 80            |
|                                  | July  | 21.0              | 1.40         | 17            | 30            |
|                                  |       | 15.0              | 2.06         | 20            | 92            |
|                                  | September | 9.5            | 1.05         | 14            | 35            |
|                                  |       | 5.5               | 2.62         | 18            | 90            |
| Barnaul pine forest, south-western part (Tokarevo) | May  | 12.0              | 3.42         | 15            | 15            |
|                                  |       | 8.0               | 2.95         | 18            | 45            |
|                                  | July  | 21.0              | 1.12         | 23            | 32            |
|                                  |       | 16.5              | 2.22         | 21            | 55            |
|                                  | September | 12.5           | 1.34         | 22            | 30            |
|                                  |       | 11.5              | 1.42         | 20            | 50            |
| Forest-steppe zone, subzone of the southern forest-steppe |       |                   |              |               |               |
| Barnaul pine forest, northeastern part (Barnaul) | May  | 6.5               | 3.90         | 17            | 18            |
|                                  |       | 4.0               | 6.12         | 17            | 5             |
|                                  | July  | 19.5              | 4.26         | 21            | 35            |
|                                  |       | 14.0              | 8.16         | 18            | 10            |
|                                  | September | 12.0           | 4.96         | 17            | 45            |
|                                  |       | 11.0              | 1.77         | 18            | 10            |
Table 3. Parameters of the hydrothermal regime of soils and ground cover during the growing season in the ribbon-like pine forests of Western Siberia.

| Location (FGC)                                      | Month | Soil, depth 20 cm | T, °C | W, % | Number of species | Total projective cover, % |
|-----------------------------------------------------|-------|-------------------|-------|------|-------------------|--------------------------|
| Steppe zone, subzone of dry steppe                  |       |                   |       |      |                   |                          |
| Korostelovsky pine forest (Uglovskoe)               | May   | 15.6              | 18.87 | 14   | 20                |                          |
|                                                    |       | 9.9               | 17.06 | 22   | 6                 |                          |
|                                                    | July  | 17.6              | 21.32 | 16   | 70                |                          |
|                                                    |       | 16.8              | 4.73  | 24   | 12                |                          |
|                                                    | September | 9.1             | 13.03 | 17   | 50                |                          |
|                                                    |       | 12.1              | 5.17  | 23   | 10                |                          |
| Steppe zone, subzone of arid steppe                 |       |                   |       |      |                   |                          |
| Srostinsky pine forest (Volchikha)                  | May   | 13.2              | 14.75 | 12   | 35                |                          |
|                                                    |       | 13.1              | 4.83  | 10   | 45                |                          |
|                                                    | July  | 20.6              | 8.41  | 17   | 80                |                          |
|                                                    |       | 18.6              | 2.27  | 11   | 55                |                          |
|                                                    | September | 15.8            | 1.39  | 12   | 40                |                          |
|                                                    |       | 16.7              | 1.89  | 12   | 50                |                          |
| Barnaul pine forest, south-western part            | May   | 11.8              | 16.00 | 17   | 11                |                          |
| (Tokarevo)                                          |       | 12.2              | 4.48  | 23   | 25                |                          |
|                                                    | July  | 22.6              | 6.75  | 16   | 20                |                          |
|                                                    |       | 21.2              | 1.74  | 26   | 65                |                          |
|                                                    | September | 24.2            | 4.22  | 17   | 18                |                          |
|                                                    |       | 22.4              | 2.63  | 22   | 50                |                          |
| Forest-steppe zone, subzone of the southern forest-steppe | May   | 15.5              | 5.32  | 27   | 12                |                          |
| (Barnaul)                                           |       | 6.9               | 5.01  | 14   | 80                |                          |
|                                                    | July  | 16.5              | 2.98  | 33   | 40                |                          |
|                                                    |       | 14.5              | 8.19  | 21   | 58                |                          |
|                                                    | September | 11.1            | 2.23  | 30   | 50                |                          |
|                                                    |       | 9.1               | 1.39  | 23   | 80                |                          |

The recovery process after a fire cannot be estimated without taking into account the natural regeneration of the main forest-forming species (table 4).

Table 4. Distribution of natural regeneration of Scots pine, depending on soil moisture on burnt-out areas in the ribbon-like pine forests of Western Siberia.

| Location (FGC)                                  | Soil moisture May, % | Soil moisture July, % | Soil moisture September, % | Density of undergrowth, thousand, ps./ha |
|------------------------------------------------|----------------------|-----------------------|---------------------------|------------------------------------------|
| Steppe zone, subzone of dry steppe              |                      |                       |                           |                                          |
| Uglovskoe, peak (A1)                            | 5.15                 | 0.46                  | 0.54                      | 0.00                                     |
| Uglovskoe, lowland (A2)                         | 12.61                | 16.54                 | 9.59                      | 0.08                                     |
| Steppe zone, arid steppe subzone                |                      |                       |                           |                                          |
| Volchikha, peak (A1)                            | 1.86                 | 1.24                  | 1.30                      | 0.10                                     |
| Volchikha, lowland (A2)                         | 22.66                | 13.06                 | 3.22                      | 37.00                                    |
| Tokarevo, peak (A1)                             | 4.88                 | 2.09                  | 2.00                      | 0.47                                     |
| Tokarevo, lowland (A2)                          | 11.96                | 17.93                 | 3.56                      | 3.40                                     |
| Forest-steppe zone, subzone of the southern forest-steppe |      |                       |                           |                                          |
| Barnaul, peak (A1)                              | 3.28                 | 3.14                  | 7.96                      | 8.10                                     |
| Barnaul, lowland (A2)                           | 7.72                 | 8.08                  | 6.4                       | 13.20                                    |
4. Discussion
The tops of the sandy ridges warm up, contain less soil moisture, the nature of the ground cover differs significantly from the descends [9]. Dry forest conditions (A1) have been formed on the tops and adjoining upper parts of the slopes. The regime of heat and moisture during the growing season of the vegetation cover on burnt areas in dry forest conditions is subject to significant fluctuations (table 2).

The soil at a depth of 20 cm on the tops of sandy ridges on burnt areas in the steppe zone warms up to 9.14.5 °C in May and contains 2.49-3.57% of moisture. In the forest-steppe zone, the soil temperature is noticeably lower - 6.5 °C, and the moisture is noticeably higher - 3.9%. The number of species in the steppe zone in phytocenoses formed at the tops varies from 12 to 23, increasing from dry to arid steppe, in the forest-steppe zone from 17 to 21. The total projective cover is small, since the plants of the ground cover have not yet fully formed vegetative organs.

In July, the soil in the steppe zone warms up at the tops to 21-23.5 °C with a simultaneous decrease in moisture in it to 0.68-1.4%, which is 1.8-5.2 times less than in May. In the forest-steppe zone, the soil temperature in the burnt area is lower than in the steppe zone - 19.5 °C, and the soil moisture is higher - 4.26%. This is due to more abundant atmospheric precipitation and no less intense evaporation. The soil cover on burnt areas in the steppe and forest-steppe zones is fully developed; therefore, the number of recorded species in communities slightly increases and the total projective cover reaches a maximum.

At the end of the growing season, the soil on the tops of the sandy ridges warms up to 9.5-16.5 °C in the steppe zone, 12.0 °C in the forest-steppe zone. The moisture content of the soil in the steppe zone remains at a low level, close to summer values - 0.83-1.34%. In the forest-steppe zone, the soil on the burnt areas contains much more moisture on the elevated elements of the mesorelief - 4.96%, the value of which even slightly exceeds the summer values. The total projective cover of the living ground cover at the end of the growing season changes upward. This is due to the development of generative organs in species from the Asteraceae, Pink (Sitenaceae), Goosefoot (Chenopodiaceae) families.

The parameters of the hydrothermal regime of soils and ground cover during the growing season in theribbon-like pine forests of Western Siberia in the lowlands between the sandy ridges are specific in nature (table 3).

In fresh and humid forest conditions, which are typical for lowlands in the ribbon-like pine forests of Western Siberia, the soil on burnt areas at the beginning of the growing season at a depth of 20 cm has a higher temperature. In the steppe zone on burnt-out areas in May, the soil warms up to 11.8-15.6 °C, which is 1-3 °C higher than on the tops of the same burnt areas. In the forest-steppe zone, this difference can be traced even more distinctly; the soil temperature in the burnt-out area in the lowland is 15.5 °C, which is 9.0 °C higher than at the top. This temperature difference between lowlands and tops is associated with a higher soil moisture content in lowlands, which contributes to soil warming in the daytime, and less intense heat transfer at night than at the tops. The living ground cover in the depressions makes its "contribution" to the microclimatic regime. Here it is denser, the number of species and their total projective cover in the communities is higher than at the tops. So, for example, in lowlands on burnt areas in the arid steppe subzone in Srostinsky pine forest, the moss and grass layers of the ground cover are well developed.

In July, the soil on burnt areas in the lowlands has higher values than in May, but less than at the tops. In the steppe zone, the soil in the lowlands in July warms up at a depth of 20 cm to 17.6-22.6 °C with a moisture content of 6.75-21.32%. In the forest-steppe zone, the soil temperature in the lowland is 16.5 °C with a moisture content of 2.98%. The moisture content of the soil decreases in relation to the period of the beginning of the growing season, except for the subzone of dry steppe, where the increase in soil moisture is associated with a local rise in the groundwater level. The living ground cover in lowlands on burnt-out areas reaches its maximum development both in the number of species in communities and in the degree of projective cover.

At the end of the growing season, the soil temperature at a depth of 20 cm on burnt areas in lowlands has lower values than in the middle of the growing season, except for burnt areas in the environs. of Tokarevo, where the soil temperature is higher than summer values. The soil moisture values at a depth of 20 cm decrease in the steppe and forest-steppe zones, which is associated with the general drying of
the soil profile for transpiration by the ground cover and young deciduous and coniferous species. Zonal differences are manifested here as follows: in the lowlands on burned-out areas in the steppe zone, there is more moisture in the soil than in similar locations in the forest-steppe zone. In our opinion, this can be explained by two factors - the closer location of the groundwater level in the lowlands in the burnt-out areas in the steppe zone and the more developed living ground cover in the lowlands in the burnt-out areas in the forest-steppe zone.

The recovery process after a fire cannot be assessed without taking into account the natural regeneration of the main forest-forming species [10]. In the previous examples, we were convinced that the leading ecological factor limiting the development of the ground cover in the belt pine forests of Western Siberia is moisture. The factor of soil moisture determines the type of forest growing conditions in specific habitats and locations of the terrain and determines the course of the renewal process in the presence of available moisture (table 4).

On burned-out areas in the ribbon-like pine forests of Western Siberia, natural regeneration of Scots pine in dry forest conditions (A1) is extremely uneven. In the subzone of dry steppe, there are no pine undergrowth on the tops of sandy ridges. In the subzone of arid steppe, the density of pine undergrowth is 0.1-0.47 thousand units / ha, which can be assessed as weak and insufficient for the formation of young stands. In the forest-steppe zone at the top of the sandy ridge, the density of pine undergrowth reaches 8.1 thousand units / ha, which is characterized as successful reforestation. In fresh (A2) and wet (A3) forest conditions, the density of undergrowth in the steppe and forest-steppe zones is noticeably higher than in dry (A1) forest conditions. Thus, in the subzone of arid steppe on burnt-out areas in Srostinsky pine forest (near the village of Volchikha), the density of pine undergrowth reaches 37.0 thousand units / ha, which is characterized as excellent reforestation.

A noticeable correlation was found between soil moisture and the density of Scots pine undergrowth. The Pearson's linear correlation coefficient between soil moisture in May and the density of pine undergrowth on burnt-out areas has a higher value (r = 0.765) than in July (r = 0.300) and September (r = 0.042). This is due to a more “uniform” level of soil moisture between relief elements in the forest-steppe zone due to the fallout of more precipitation and dense vegetation cover in the burnt-out area. The correlation between the studied parameters is statistically significant (significance level p <0.05).

5. Conclusion

The post-fire recovery process on burned-out areas in the ribbon-like pine forests of Western Siberia occurs on a zonal-typological basis. In dry forest growing conditions (A1), which are characteristic of the tops of sandy ridges, the regime of heat and moisture in the soil has a noticeable difference during the growing season compared to lowlands, which are characterized by fresh (A2) and moist (A3) forest growing conditions. The development of the ground cover is completely dependent on the hydrothermal regime, the limiting regime is the regime of soil moisture. The emergence and further development of pine undergrowth is directly dependent on the available soil moisture at the tops and in the lowlands, which is confirmed by a significant correlation between these indicators during the growing season on burnt-out areas. The successful reforestation process on burnt-out areas in the ribbon-like pine forests of Western Siberia occurs, starting from the subzone of arid steppe in depressions, in the subzone of the southern forest-steppe in depressions and on the tops of sandy ridges. Fires in the dry steppe subzone are not provided with Scots pine undergrowth, both on the tops of the sandy ridges and in the lowlands between them.

References

[1] Tsvetkov P A and Buryak L V 2014 Investigation of the nature of fires in the forests of Siberia Siberian Forestry Journal 3 25-42
[2] Sannikov S N 1992 Ecology and geography of natural regeneration of Scots pine (Moscow: Nauka)
[3] Ivanova G A, Zhila S V, Kukavskaya E A and Ivanov V A 2016 Postpyrogenic transformation of the phytomass of the stand in the plantations of the lower Angara region Izvestia of higher
educational institutions Lesnoy Journal 6 17-32

[4] Kukavskaya E A, Buryak L V, Shvetsov E G, Conard S G and Kalenskaya O P 2016 The impact of increasing fire frequency on forest transformations in southern Siberia Forest ecology and management 382 225-35 dx.doi.org/10.1016/j.foreco. 2016.10.015

[5] Andreeva E N, Bakkal I Yu, Gorshkov V V, et al. 2002 Methods for studying forest communities (St. Petersburg: NIIKhimii St. Petersburg State University)

[6] Vadyunina A F and Korchagina Z A 1986 Methods for studying the physical properties of soils (Moscow: Agropromizdat)

[7] Greig-Smith P 1967 Quantitative Plant Ecology (Moscow: Mir)

[8] Malinovskikh A A and Kupriyanov A N 2015 Pyrogenic successions in the plain pine forests of the southern part of Western Siberia (Novosibirsk: Publishing house of the SB RAS)

[9] Gefke I V, Bolotov A G and Chuguzov E P 2019 Temperature regime of sod-podzolic soils on burned-out areas in the belt forests of Altai region Bulletin of Altai State Agrarian University 8 62-7

[10] Malinovskikh A A and Savin M A 2019 Natural reforestation on burned-out areas in the ribbon-like pine forests of Western Siberia Conifers of the boreal zone 37(3-4) 223-8