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EARLY STAGES OF A LONG-TERM POST-FIRE VEGETATION CHANGES IN SIBERIAN FIR FORESTS OF SOUTHERN BAIKAL REGION (BAIKAL NATURE RESERVE)

N.S. Gamova*, **, E.A. Faronova*, Yu.N. Korotkov, T.S. Koshovskii*, T.E. Yazrikova***

**M.V. Lomonosov Moscow State University*
1, Leninskie Gory, Moscow, 119992, Russia. E-mail: bg_natagamova@mail.ru
***Baikal State Nature Biosphere Reserve*
34, Krasnogvardeyskaya Str., Tankhoy, Republic of Buryatia, 671220, Russia

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In this article we analyzed the early stages of long-term post-fire vegetation change in a burnt area of a Siberian fir forest. The study area is typical for the middle altitudes of the northern slope of Khamar-Daban Ridge; the wild fire was of a natural origin. We registered the post-fire changes in the floral composition and in the structure of the forest plant community. As a result of the fire, the structure of forest layers simplified, and the total number of species, as well as the species diversity of coenotic (eco-coenotic) groups of species decreased in the first years after the fire. We compared a post-fire forest plant community with an undisturbed one, and evaluated the participation of rare and Red Data Book plant species in the burnt area.

We established that wild fires in fir forests lead first to the complete death of a tree stand, and then to the restorative vegetation change, which, in our case, caused a change of conifer tree species to secondary small-leaved deciduous species. In the first years after the fire, the similarity coefficient of the floristic composition between the plant community of the burnt area and of the undisturbed forest did not exceed 0.5. The ranges of eco-coenotic groups of species also changed, making the Br group (taiga small herbs) dominant in all years. At the same time, some plant species of the burnt area were not recorded in the undisturbed forest, while the abundance of some rare plant species increased. The structure of the plant community in the burnt area became simpler as the number of layers, and their closeness / projective cover reduced. Within 5 years after the fire, the herb-dwarf shrub layer restored the general projective cover to the values typical for the undisturbed forest; projective cover of raspberry increased sharply; and the tree layer, formed with new growth, and the moss layer finally began to recover.

It is concluded that a single case of wild fire in a dark coniferous forest with a relatively small area of the burnt area does not cause irreversible degradation of the forest plant community. Taiga ecosystems retain the potential for restoration sufficient for a further proper and successful vegetation change.

Keywords: Khamar-Daban ridge, forest fires, Siberian fir forests, post-fire vegetation changes, rare plant species, coenotic (eco-coenotic) groups.
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Wild fires are the most important factor to form the forests, because they are the main cause of natural vegetation changes in taiga ecosystems (Isakov et al., 1986; Volokitina, Sofronov, 2011). They significantly transform the vegetation and soil cover, exposing the surface of the soil and substrate on the slopes, which can severely worsen soil erosion (Gorshkov, 1982). Wild fires can be both of natural and anthropogenic origin, but an indirect human impact has certainly increased their frequency and prevalence in recent years (Chuvieco at al., 2008; Pausas, Keeley, 2009; Girardin et al., 2010).

The Baikal Reserve is located in the southern Baikal Region, occupying the central part of the Khamar-Daban mountain range. Most of its area is covered with undisturbed forests (Aksenov et al., 2003; Potapov et al., 2021). This reserve is part of the UNESCO World Natural Heritage Site "Lake Baikal" and belongs to the central ecological zone of Lake Baikal (UNESCO …, 2022). It's affected by the natural forest fires, which is common for other mountainous regions of southern Siberia as well (Valendik, Ivanova, 2001; Ivanov, Ivanova, 2010). Most of the fires there, albeit not happening every year, are caused by lightning bolts during the thunderstorms (Gamova, 2017b). An analysis of the actual fire frequency of the Southern Baikal forests (Sofronov et al., 2008) showed the lowest rate for the territory of the Baikal Reserve comparing with other sites in this region. Indigenous dark coniferous forests of the northern slope of the Khamar-Daban Ridge are vulnerable to fires due to Siberian pine and Siberian fir being extremely sensitive to such damage both during crown fires and creeping fires (that affect trunks, including its very base).

After being disturbed by fires, forests undergo a natural regeneration, i.e. a long-term post-fire vegetation change (Melekhov, 1947), the total duration and direction of which, as well as the rates and stages of it, depend on many factors; for example, on the original type of forest and altitudinal location of the plant community, or on the degree of damage caused to the forest, as well as on the steepness of the slope, and the moisture level of the biotope. For the Baikal Region the most common stages of vegetation change are as follows: 0-1 year – black burnt area with no herb cover, 1 to 3-5 years – herb stage, up to 20-25 years – shrubs and small tree new growth with no crowns closure, up to 40 years – young coniferous forest or secondary small-leaved forest, up to 60 years – medium-aged coniferous or small-leaved forest with coniferous undergrowth, up to 80-100 years – maturing coniferous or small-leaved-coniferous forest, over 100-120 years – mature coniferous forest, possibly with some deciduous species (Gamova, 2014, 2017a). 120-150 years after the fire, if no other disturbances took place, plant communities reach the state of conditionally original type of forest. In the course of post-fire vegetation change, the floristic composition and structure of plant communities change; the soil cover undergoes significant transformation as well (Certini, 2014). The most important consequences are the change in such chemical, physical, and physicochemical soils properties as the content and composition of organic matter, pH, content and availability of biogenic elements, and accelerated soil erosion (Krasnoshchekov, 2004, 2007, 2018; Effects of Fire …, 2005; Thomaz et al., 2014).

The study of post-fire regeneration of forests growing in natural conditions of almost undisturbed territories is extremely important for understanding the features of natural long-term post-fire vegetation change and for predicting the dynamics of plant communities disturbed by wild fires.

Materials and Methods

Physical and geographical description of the study object. The southern part of Eastern Siberia is characterized by a severely continental climate of the temperate zone (Makunina, 1985); however, the northern slope of the Khamar-Daban Ridge belongs to the temperate continental climate due to the thermal effect of Lake Baikal. The ridge is part of the Khamar-Daban mountainous-bald peak-taiga climatic province (Kartushin, 1969). The climate of its northern slope in the central part is relatively mild for Southern Siberia: the mean annual temperatures vary from -0.3ºC at the Tankhoy Meteorological Station (460 m ASL) to -3.4ºC at the Khamar-Daban Meteorological Station (1420 m ASL); the mean January temperatures are -17ºC and -17.9ºC, while the mean July temperatures are 14ºC and 12.7ºC, respectively. It is shown that the annual precipitation at the studied altitudes is about 1100 mm, with its maximum in July. The depth of the snow cover is about 1.5-2 m. Both the annual precipitation and the snow cover in this part of the

Khamar-Daban Ridge are the maximal in the Baikal Region (Ladeyshchikov et al., 1977).

It is important to note that due to the long and warm autumn that is typical for this territory, as well as to the abundant precipitation and deep snow cover, the soils of the northern slope often do not freeze through in winter (Baikalia and Transbaikalia, 1965). The snow cover usually continues to melt until late spring (i.e. late May – early June), which reduces the risk of fires during the relatively rainless period of April-May (Kartushin, 1969).

The middle mountains of the Khamar-Daban Ridge in its central part are characterized by a highly dissected relief (Voskresensky, 1962; Voskresensky, Troshkina, 1971). The density of the river network is 0.28 km per 1 km^2 when taking into account all rivers over 10 km long, but it is much higher when taking into account numerous streams of shorter length (Project …, 1981). This helps to maintain the overall humidity of the territory at a significant level, working as a natural barrier to stop the fires from spreading.

Soils of mountain slopes are formed on a thin talus made of granites, gabbro and Permian monzonites of Bichurian Complex (Geological Map, 1972). The soil cover along the peaks of the ranges is dominated by coarse-humus podzols and podburs, alternating with podzolized and ferruginous lithozems, while the cover of the lower zone has soddy podburs and burozems (Ubugunov et al., 2012; Belozertseva, 2016; Krasnoshchekov, 2018; Khutakova, Altaev, 2020).

According to “Zones and Types of Zonality of Vegetation in Russia” (1999), the territory of the Khamar-Daban Ridge belongs to the Boreal class (the Khamar-Daban geographical variant of the East Sayan type of the Tuva-South Transbaikal zonality group). The mid-mountain taiga zone stretches along the windward slopes and spurs of the ridge from 500 to 1000-1200 m ASL up to 1400-1500 m in the remote valleys of large rivers far away from Baikal Lake (Molozhnikov, 2014). More than 70% of the territory of Baikal Reserve is covered with forests. Due to the high share of never freezing soils and the abundant precipitation, dark coniferous species predominate on the northern slope (Peshkova, 1985), with some nemoral relict plant species that have survived there since the Tertiary period (Epova, 1956) thanks to the peculiar temperature and water regimes of the local soils.

Forest fires in the central part of the Khamar-Daban Ridge mainly occur as a result of thunderstorms, including the dry ones. The average number of stormy days in June-August at the Khamar-Daban Meteorological Station is 16-19 (Atlas of Transbaikalia ..., 1967). However, based on the general physical and geographical conditions of the territory, it should be noted that there are not many prerequisites for the further spread of fires there. This is due to the dissected relief, density of the river net, total precipitation with a summer maximum, heavy snow cover, wide distribution of fern and tall herb types of forests, the ground cover of which is protected from drying out. Thus, only some thunderstorms cause fires. Of course, the risk may increase during the years with insufficient snow cover and subsequent early and dry spring (Valendik, Ivanova, 2001). The Khamar-Daban Ridge showed a high correlation between the seasonal number and total area of wild fires with the number of previous days without precipitation or with precipitation less than 3 mm. Additionally, the fire hazard in summer is increased by the temperature inversion up to +6-10°C that can be registered at 800-1100 m ASL, which contributes to the drying of forest litter (Sofronova, 2005).

Study area. We studied the northern slope of the Khamar-Daban Ridge in the Mishikhinskoye Forestry located in the Baikal Nature Reserve (Kabansky District, Republic of Buryatia). The burnt area is situated in the lower reaches of the Levaya Mishikha River, occupying the middle of the slope of the southeastern and eastern exposition along the left bank in the valley of the river and its unnamed left tributary (stream). The steepness of the slope varied from 15 to 30°, the overall height varied from 670 to 1000 m ASL. The burnt area was extended upward the slope, 250 m wide and 750 m long. The lightning bolt struck a protruding ridge that functions as a watershed where the valleys of the river and its tributary meet, which is typical for the mountains of Southern Siberia (Ivanov, Ivanova, 2010). The fire broke out during a thunderstorm on July 2, 2011 and lasted for

4 days, during which it has reached an area of 12.8 ha (10 ha by a creeping fire, 2.8 ha by a creeping fire + a crown fire). The location of the study site is shown in Figure 1.

The undisturbed vegetation of the territory was formed by the mature forest of Siberian fir (*Abies sibirica* Ledeb.) with Siberian pine (*Pinus sibirica* Du Tour), rowan undergrowth (*Sorbus sibirica* Hedl.) and sparse layer of bushes (*Lonicera pallasii* Ledeb., *Spiraea flexuosa* Fisch. ex Cambess.), with herb layer of *Arsenjevia baicalensis* (Turcz.) Starod. and grasses with miscellaneous herbs (*Calamagrostis langsdorffii* (Link) Trin., *Galium triflorum* Michx., *Melica nutans* L., *Milium effusum* L., *Thalictrum minus* L.) and ferns (*Dryopteris expansa* (C. Presl) Fraser-Jenk. & Jermy), with taiga small herbs (*Gymnocarpium dryopteris* (L.) Newman, *Maianthemum bifolium* (L.) F.W. Schmidt, *Phegopteris connectilis* (Michx.) Watt, *Trientalis europaea* L.). In some spots among the bushes there were red raspberry (*Rubus idaeus* L.) and elderberry (*Sambucus sibirica* Nakai), with bergenia (*Bergenia crassifolia* (L.) Fritsch.) and bracken fern (*Pteridium pinetorum* C.N. Page & R.R. Mill) in the herb layer. Siberian fir forests with *Arsenjevia baicalensis* (Turcz.) Starod. are common for the middle mountains of the windward slopes of Khamar-Daban and Barguzin Ridges with their peculiar humid Baikal zone type of vegetation (Tyulina, 1976).

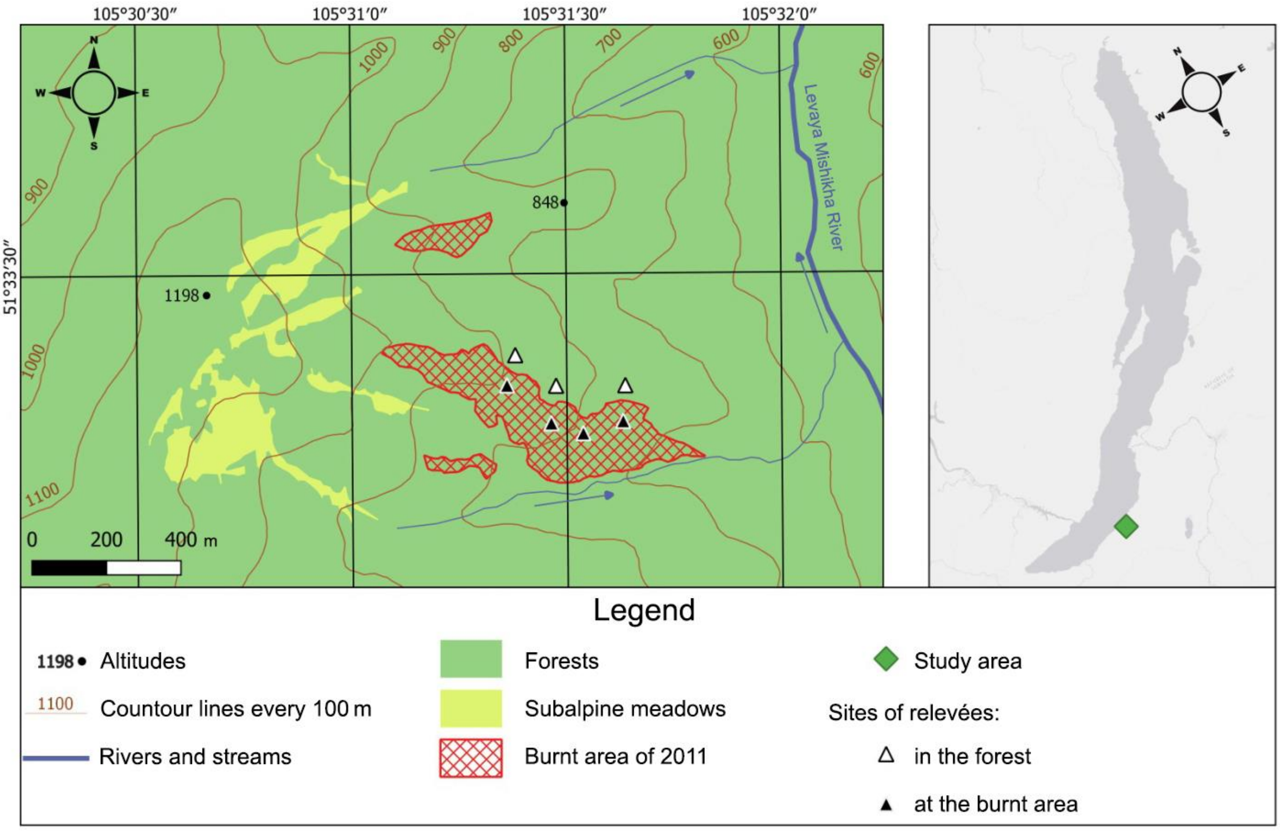

Fig. 1. Schematic map of the burnt area and the adjacent forest showing the sites of relevées.

The soil cover there was formed by variations of ferruginous burozems and ferruginous gray-humus lithozems close to bedrock outcrops. The organic horizons of the background soils were represented by litter and peaty litter O, the organomineral horizons – by the gray-humus AY and the transitional Ay/Bm and Bm/Ay. The middle horizon was the BMf structural-metamorphic horizon with signs of ferrugination. The soils had a poor depth of about 30 cm and a high skeletal structure; the granulometric composition of the upper horizons was light loamy and sandy loamy

(Koshovsky et al., 2022).

The relevées in the study area were carried out every year from 2011 to 2019 between the 3rd decade of June and the 1st decade of August on permanent key plots (10 x 10 m). Additionally, we selected reference plots for relevées in the adjacent undisturbed forest plant community according to the generally accepted methodology for conducting geobotanical studies of vegetation cover dynamics (Methods ..., 2002; Community monitoring ..., 2002). We had also collected herbarium specimens, which are stored in the Moscow University Herbarium (MW) and can be accessed online (Seregin, 2023).

To analyze the vegetation of the burnt area and the undisturbed forests, we calculated the coefficients of species' activity according to L.I. Malyshev's method (1973) and using the classic formula:

$$R = \sqrt{(A \cdot B)},$$

where A is the constancy of species (5 classes), and B is the species' abundance (10 classes). The coefficient values can vary from 0 to 7.1 (i.e. $\sqrt{50}$ for the 5th class of constancy combined with the 10th class of abundance). To provide an accurate assessment of the similarity degree of the floristic composition of the plant communities in the burnt area and the undisturbed forest, we used the Jaccard index (Kj), which is calculated using the following formula:

$$Kj = c / (a + b - c),$$

where a is the number of species in the 1st community, b is the number of species in the 2nd community, and c is the number of species found in both communities. The Jaccard index values can vary from 0 (total dissimilarity) to 1 (identical plant communities; Neshataev, 1987).

To assess the floristic diversity, we used the total species richness and the diversity of ecological and coenotic groups, or ECG (Smirnov et al., 2006), which are the groups of plant species that share ecological requirements and a certain plant community type (Zaugolnova, Smirnova, 2000). The ECG was determined according to the CEPL scales (2023) and the researches carried out in the mountains of Southern Siberia (Nazimova, 1975; Ismailova, 2007). The nomenclature of plant species is given according to the Plants of the World Online (2023).

Results and Discussion

After the fire, forest plant communities had undergone significant changes. A tree stand of Siberian pine and Siberian fir that are vulnerable to fire was completely destroyed in the studied area. Since 2013, burnt trunks began to fall out, and by 2016 almost all large Siberian pine trunks had disappeared. Among the dead fir stands, only some of the burnt trunks remained standing. By 2019, there were only single standing trunks of burnt Siberian fir trees in the area.

The new growth (the first Siberian pine seedlings) had been observed in the burnt area since 2012, and by 2013 there were 6 species: *Pinus sibirica*, *Abies sibirica*, *Betula platyphylla* Sukaczev and *B. pubescens* Ehrh., as well as *Salix caprea* L. and *Sorbus sibirica*. Since 2016, a single new growth of another indigenous dark coniferous species (*Picea obovata* Ledeb.) was found there as well. It is interesting to note that the presence of *S. caprea* in secondary post-fire forests (the presence of which was also noted in other parts of the burnt areas of the Baikal Reserve) makes the northern slope of the Khamar-Daban Ridge somewhat similar to the mountains of the Far East (Primorsky Krai), where this species is common in burnt areas, too (Komarova, 1986).

Among the tree species that were registered in the undisturbed forest, but did not grow in the burnt area until 2019, *Padus avium* Mill. can be noted. However, despite the diversity of the tree species in the burnt area, the tree new growth remained rare during all the years of our observations. By 2016, the maximum height of coniferous new growth barely reached 0.3-0.4 m, while the deciduous tree new growth was 0.5 m high. Moreover, hares (*Lepus timidus* L.) and Siberian roe deer (*Capreolus pygargus* Pall.) started eating birch and willow new growth, biting off the upper parts of their shoots, a phenomenon that was observed in other burnt areas with small-leaved new growth, since those areas served as feeding stations for animals. Since the studied area is surrounded by undisturbed forests, which provide fairly favourable conditions for possible sources of seeds, then, apparently, the lack of mass renewal of tree species can be explained by the density of shrubs and herb layers that prevent the tree growth (Gamova, 2014, 2017a). In 2017-2019, the number of new growth was increasing along with the activity of birch new growth, which, apparently, will become the main tree species of this vegetation change, forming a secondary small-leaved forest stand due to their growth rate that significantly exceeds the growth rate of dark coniferous species. At the same time, the presence of Siberian pine and Siberian fir new growth at the early stages of the vegetation change indicates that conditionally indigenous plant communities could recover in this area much faster and more successfully compared to another scenario in which their post-fire new growth would appear only at the stage of the ripe birch forest.

Tree new growth was not numerous in the undisturbed forest as well. However, the main difference between new growth in burnt areas and undisturbed forests is its age distribution, varying in the primary forests and staying approximately the same in the post-fire plant communities, where it appears in the first years after the fire and eventually forms a secondary forest stand with all the trees of the same age that acts as the indicator of past fires many years after the fire accident (Krasnoshchekov et al., 2010).

The shrub layer of the burnt area is mostly formed by *Rubus idaeus* that first appeared there in 2012. There are also a few *Sambucus sibirica*, and sometimes *Spiraea flexuosa* Fisch. ex Cambess. and *Ribes nigrum* L. The total projective cover of the shrub layer is variable. For example, in 2013-2014, raspberries peaked there throughout the entire burnt area. In 2016, a big patch of fruiting raspberry shrubs still remained at the bottom of the burnt slope, while growing much sparser at its top. By 2019, raspberries were not that abundant anymore, signifying the next stage of vegetation change with the introduction of tree new growth. It is important to note that due to their fertility, the raspberry thickets in this area are used as a feeding station by the brown bears (*Ursus arctos* L.).

The herb layer in the burnt area turned out to be the most diverse. Its composition and the total number of species changed significantly in the first few years of the post-fire vegetation change. During the summer of 2011, only 4 species began to recover there: *Bergenia crassifolia*, *Gymnocarpium dryopteris*, *Maianthemum bifolium* and *Trientalis europaea* L. Simultaneously, in 2012, i.e. in the first growing season after the fire, there were already 25 species of the herb-dwarf shrub layer. Over the following years, typical dominant species were found in the grass stand of the post-fire plant community: *Calamagrostis langsdorffii*, *Chamaenerion angustifolium* (L.) Scop. and *Pteridium pinetorum*. In 2019, bracken and reed grass were among the dominants in the middle part of the burnt slope, while there were no obvious dominants in its upper part, however, *Calamagrostis langsdorffii*, *Chamaenerion angustifolium*, *Galium boreale* L., *Pteridium pinetorum* and *Rubus saxatilis* L. were present with approximately equal abundance. In the upper part of the burnt area, the projective cover of the herb-dwarf shrub layer was reduced to 70-75%, and the shrub layer was quite sparse. Herbaceous plants under a thick canopy of raspberry and bracken were mainly represented by taiga small herbs, such as *Gymnocarpium dryopteris*, *Maianthemum bifolium*, *Phegopteris connectilis*, *Trientalis europaea*, *Viola selkirkii* Pursh ex Goldie, while *Anthoxanthum alpinum* Á. Löve & D. Löve, *Bergenia crassifolia*, *Galium boreale*, *G. triflorum* and *Melica nutans* were common in the areas with reed grass and in the areas with no obvious dominants.

The general state of plant communities of undisturbed forest and burnt areas during the post-fire vegetation change is shown in Figure 2.

The ground cover in the undisturbed forest was represented by small tussocks of green mosses (*Pleurozium schreberi* (Willd. ex Brid.) Mitt., *Hylocomium splendens* (Hedw.) Bruch et al., *Dicranum* spp.) and *Polytrichum commune* Hedw.; but no lichens were registered there. The total projective cover of mosses in the forest was about 5%. In the first few years after the fire, the moss cover was almost absent in the burnt area. Since 2013, *Dicranum* and *Polytrichum* tussocks begun to regrow there from individual plants that were preserved on elevations near the trunks which were destroyed by the fire. In the same period of 2012-2013, a liverwort (*Marchantia polymorpha* L.), which is a common species for the early stages of post-fire vegetation changes, provided most of the projective cover of the ground layer for the burnt area. In the following years, as the projective cover of grass stand and shrubs increased, the abundance of *M. polymorpha* decreased until 2016, since then this species almost disappeared. By 2019, we found no new moss species in the burnt area.

Fig. 2. Undisturbed Siberian fir forest (2.1), burnt area just after the wildfire: in 2011 (2.2), in 2013 (2.3), in 2015 (2.4), in 2017 (2.5), in 2019 (2.6).

An important indicator in the post-fire dynamics of plant communities is the total number of their species. The bar chart in Figure 3 shows the dynamics of species number in the burnt area for 2011-2019 and its comparison with the undisturbed forest.

Along with a natural but sharp decrease in the number of all species in the 1st year after the fire and a gradual increase in the number of tree and shrub species in the 2nd to 5th years, the dynamics of herbaceous plants is characterized by specific features. For example, a relative maximum of species (29 in total) was registered in 2013, but in 2014-2016 this number slowly decreased. This feature, a “burst” in the number of herbaceous plant species, is common for many burnt forests and is associated with the fact that the community structure does not fully develop at the early stages of post-fire vegetation change (Fig. 3). In 2018-2019, the number of herbaceous plant species grew again, possibly due to a gradual decrease in raspberries during the vegetation change (which, in its turn, reduced plants competition) and an increased availability of ecological niches/resources. It should be noted, however, that at its maximum of species in 2013, the number of herbaceous plants in the burnt area reached 67.4% (29 out of 43) of the species for the undisturbed forest.

Therefore, a complete restoration of the herb layer is not finished within the first decade after fire. It is noteworthy that there are species in the forest plant community that were not found in the burnt area (i.e. in 2011-2019, a total of 14 forest species were not found in the burnt area), as well as species in the burnt area that are not typical for the forest (9 species, for the same period). However, while such species as *Chamaenerion angustifolium* or the light-loving *Rubus saxatilis* that tends to grow in the margins are common for the post-fire communities, a couple of grasses, such as *Festuca altissima* All. and *Brachypodium pinnatum* (L.) P. Beauv., turned to be more abundant and, therefore, well noticeable in the burnt areas due to, presumably, proper illumination that allows them to bear fruit annually. They can probably grow in the adjacent undisturbed forests as well, where they remain in a vegetative state due to the thicker shade and, therefore, are harder to identify among other grasses.

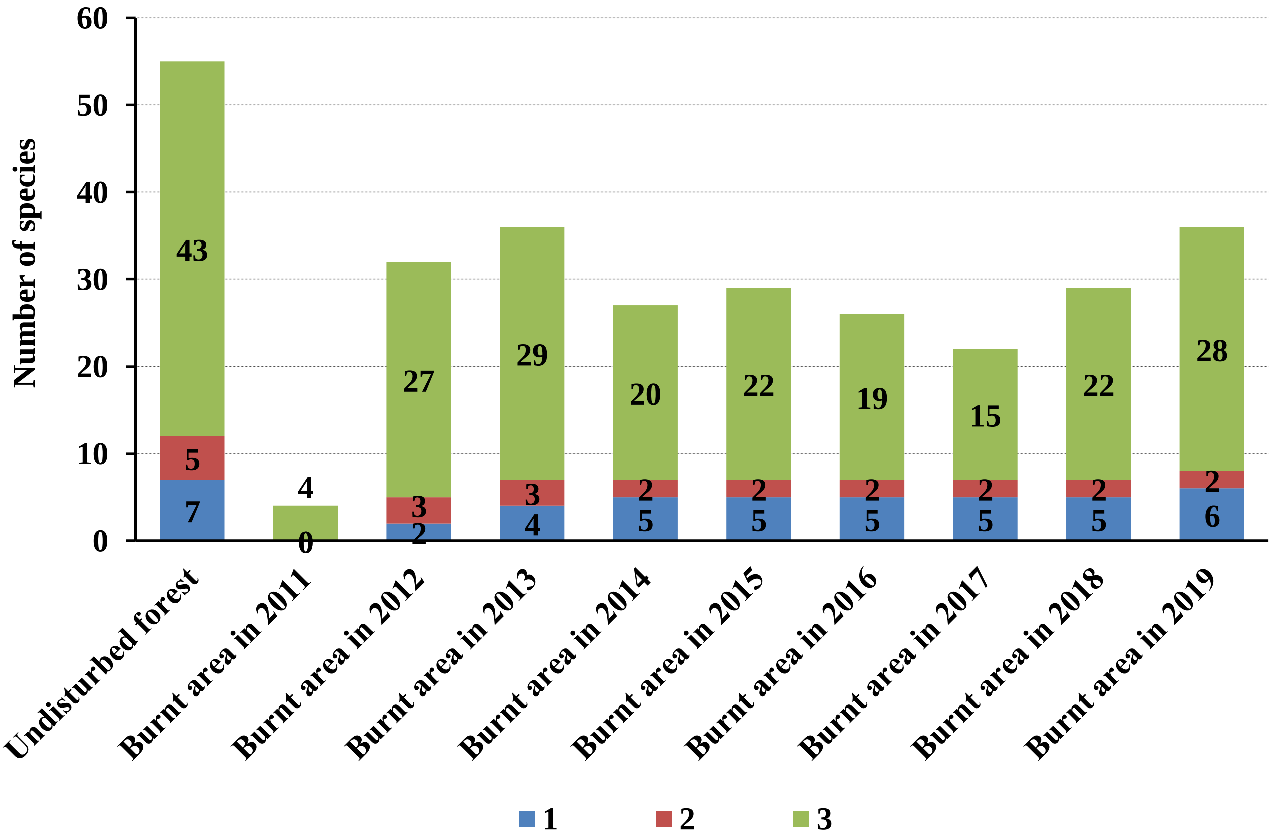

Fig. 3. Change in the number of species of trees (1), shrubs (2), herbaceous plants and dwarf shrubs (3) in 2011-2019.

It is also worth noting the rare and protected plants in the species richness of post-fire plant communities. In the lower part of the burnt area, 2 Red Data Books species, *Festuca altissima* and *Arsenjevia baicalensis*, were found (Red Data Book …, 2008, 2013), apparently, successfully spreading due to the fire reducing the plants competition. They were much more abundant in the burnt area than in the undisturbed forest. A similar phenomenon was noted in other burnt areas in the middle mountains of the northern slope of the Khamar-Daban Ridge (Alekseenko, Gamova, 2015; Gamova, 2017a), and similar recovery rates of certain rare species were typical for the burnt areas of the Sayano-Shushenski Nature Reserve (Shikalova, 2019).

An important part in the study of the recovery dynamics of post-fire plant communities is the comparison of the floristic composition of the plant communities between the burnt area and the undisturbed forest. The Jaccard index (Kj) is one of the most common and widely used indices in various botanical studies. Its dynamic is shown in Figure 4.

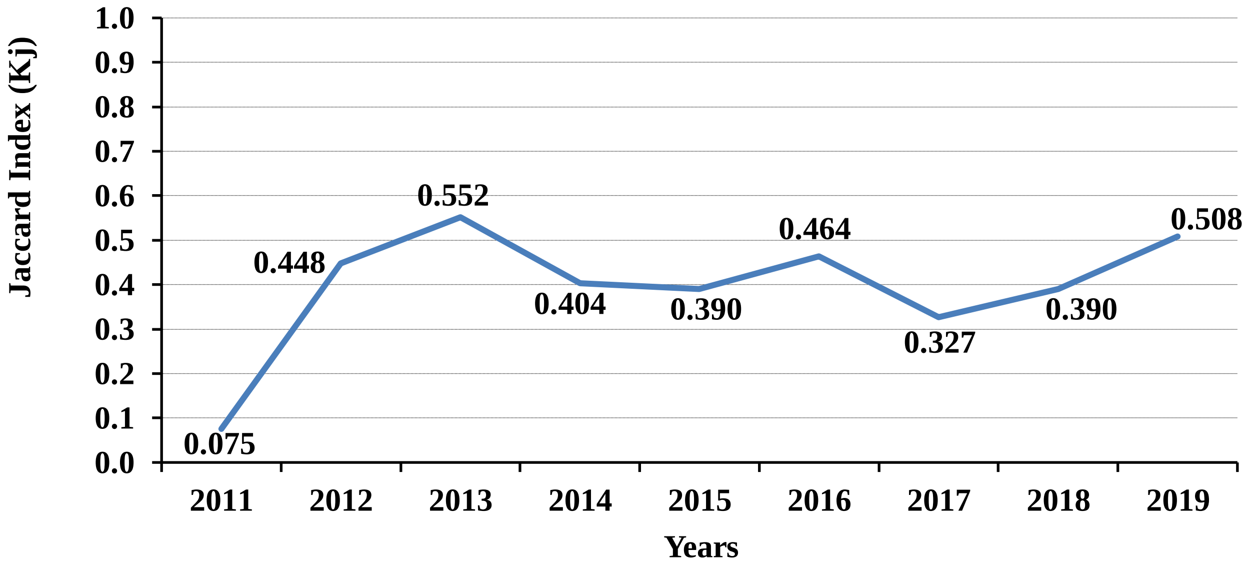

Fig. 4. The dynamics of similarity of the floral composition of burnt area and undisturbed forest in 2011-2019 (Jaccard Index).

Since the 2nd growing season after the fire, the Jaccard index value was about 0.5 and remained so for 8 years, occasionally fluctuating due to the variability of the species composition in the first years of post-fire vegetation change. Based on the experience of our study of the post-fire regeneration of Siberian fir forests of a similar group, it can be noted that Jaccard index value can increase and reach the value of 1 only at the late stages of the vegetation change, when the new growth of primary dark coniferous species gets mature and becomes part of the tree layer (Gamova, 2014, 2017a).

In addition to the general floristic diversity of post-fire plant communities, the distribution of plant species according to their ECG is significant as well. A number of groups was distinguished for the mountains of Southern Siberia and the Baikal Region; while the following ones were noted for our study area: Aa – arctic-alpine, Br – boreal (taiga small herbs), Md – meadow-forest and margin miscellaneous herbs and grasses, Nm – nemoral, Nt – nitrophilous, Pn – pine-forest, Rp – rupicolous, TH – taiga tall herbs and ferns, Wt – wetland (moisture-loving herbs, brook species). In the early stages of vegetation change, together with the dynamics of the general diversity of species, the ECG spectrum undergoes rapid changes from year to year (Fig. 5).

In the first years after the fire there is a rapid change and lasting variability in the species composition of plant communities, as reflected in our diagrams. At the same time, for all years, we noticed a clear dominance of the Boreal group (Br), which also was dominant in the undisturbed forest. Aside from it, the Nemoral group (Nm) and Taiga tall herbs (TH) were quite abundant in the burnt area. The fact that they were present in the burnt area starting from the very first year after the fire indicates a moderate or relatively low degree and depth of pyrogenic soil disturbance that does not affect the underground plant organs, such as tubers and rhizomes. However, in the case of the TH group, many large ferns disappear for a long time after the fire in our study area and in many other similarly burnt areas: for example, *Dryopteris expansa*, because its rhizomes grow close to the soil surface, and therefore suffer from fire.

The most important difference between the ECG spectra of post-fire plant communities and undisturbed forests is the Nitrophilous group (Nt) growing on the burnt areas: e.g. willowherb, elderberry and raspberry, which actively form the post-fire plant communities in the first years of vegetation change, since the soil becomes enriched with nitrogen due to the ashes left by the fire. These species can be found in the primary forests as well, but are less numerous and usually grow only along the forest edges, in the clearings and other relatively open areas. It should be noted that in our case, the presence of the Meadow-forest (Md) species *Hieracium ganeschinii* Zahn and the Arctic-alpine (Aa) species *Anthoxanthum alpinum* in the burnt area, which both grew in the adjacent forest, was not found continuously in every year of our study. Those are perennial plants, and therefore it is possible that they did not actually disappear from the post-fire plant community, but were severely oppressed while bracken, raspberry and reed grass were dominant and casted a thick shade on the bottom layers of the grass stand. We should also note the complete absence of representatives of ruderal groups in the burnt area and in the undisturbed community, which can be explained by the remoteness of the burnt area from anthropogenically transformed territories. In general, only in 2011, immediately after the fire, plant species only of 2 ECGs were found in the burnt area. Since 2012, this spectrum expanded greatly and was quite comparable to the spectrum of ECG of the undisturbed forest, which was a sign of a successful post-fire regeneration. In 2016-2019, the proportion of the Boreal group (Br) in the burnt area reached 50%, therefore corresponding to the values common for the undisturbed forest.

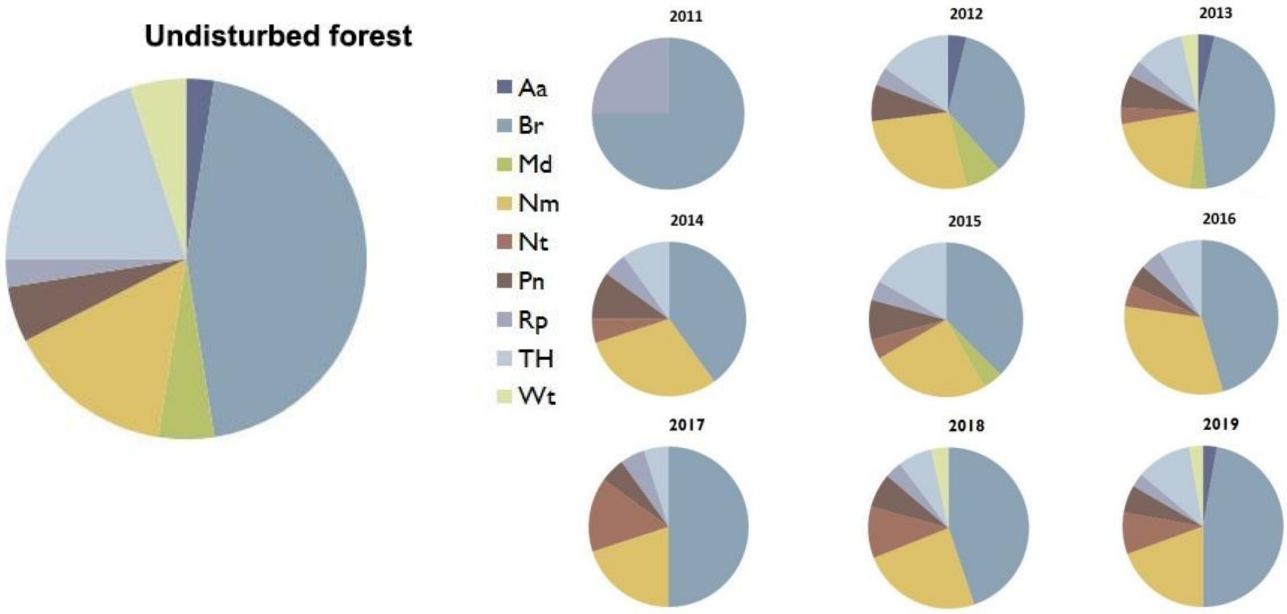

Fig. 5. Spectrums of coenotic (eco-coenotic) groups in the undisturbed forest and in the burnt area in 2011-2019.

The structure of the plant community in the first few years after the fire underwent the most significant changes, the main one being the disappearance of its tree layer, which takes at least 30-40 years to restore for the dark coniferous forests of the Baikal Region. At the same time, in the early stage of the post-fire vegetation change, a secondary small-leaved deciduous forest (in our case, birch forest) appeared. A similar situation was reported for the burnt areas along the southern coast of Lake Baikal (Sizykh et al., 2019). Changes in the total projective cover (TPC) were registered in other layers of the forest plant community as well (Fig. 6).

The TPC of the herb-dwarf shrub layer after the fire decreased from 50-95% in the undisturbed plant community to 0% immediately after the fire. However, its recovery was quite fast: 5% by the end of the 2011 growing season; 15-25% in 2012, 25-35% in 2013, 40-50% in 2014, and 70-100% in 2015. In 2016, in some plots within the burnt area, shrubs and tree new growth extruded herbaceous plants, creating local parcels where the TPC dropped to 40%, although there were some parcels where it reached almost 100%. Thus, 5 years after the fire, the TCP of the herb-dwarf shrub layer for the burnt area finally became equal to one typical for the undisturbed forest. In 2017-2019, there were slight fluctuations in the projective cover of the herb layer, but it remained within the limits close to the primary forest. The projective cover of the shrub layer in the burnt area significantly increased in the first few years after the fire due to a sharp growth of raspberries, which usually do not persist in the burnt areas for more than two decades in our region of Southern Siberia. In the study area, a gradual decrease in the projective cover of raspberries after its maximum in 2013-2015 was noticed. In total, in 2013-2019, the TPC of the herb-dwarf shrub layer together with TCP of shrub layer in the burnt area reached at least 80%. Knowing this value is important for assessing the risk of soil erosion, because sod-lost post-fire areas of steep slopes in the humid conditions of the middle mountains of the Khamar-Daban Ridge are subject to soil erosion, while the soil under the dense vegetation cover remains stable (Krasnoshchekov, Cherednikova, 2012, 2022). Therefore, the studied burnt area with the dense herb-dwarf shrub and shrub layers is not a subject to severe soil erosion.

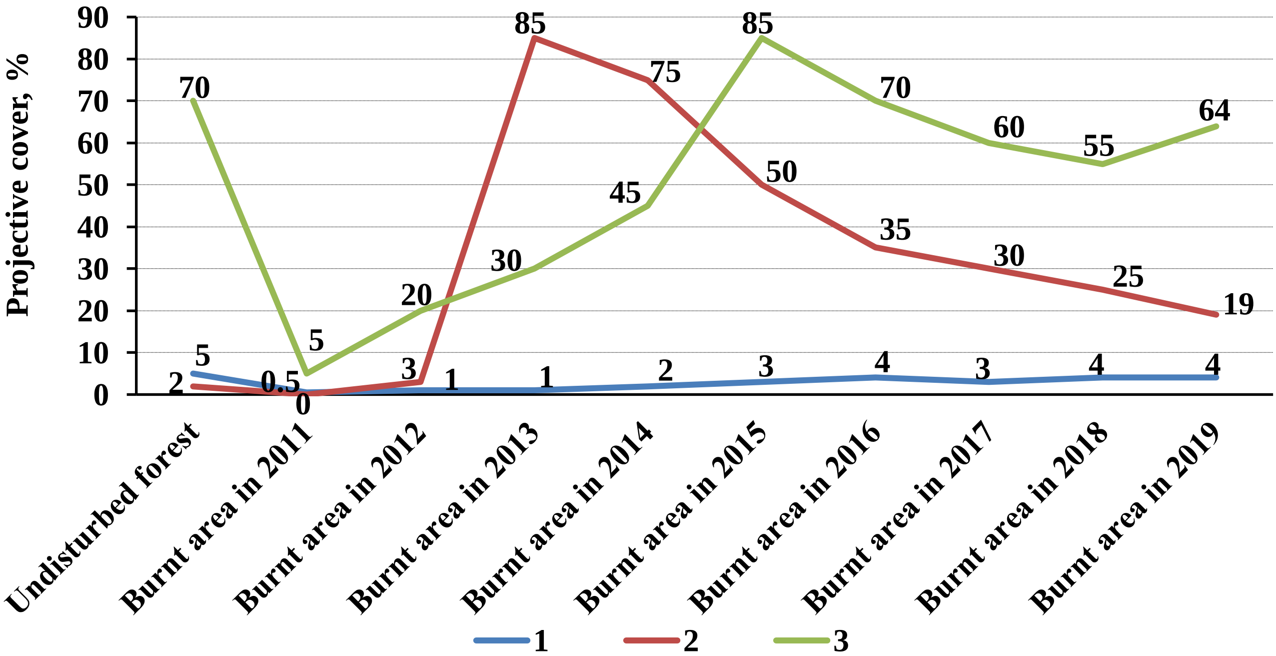

Fig. 6. Dynamics of the projective plant cover of forest new growth (1), shrubs (2) and herbaceous plants and dwarf shrubs (3) in 2011-2019.

One of the indicators of the species' participation in a plant community is species' activity, i.e. a derivative that takes into account the abundance of species on one sampling site and constancy of species presence on every relevée. The values of the activity coefficients of each species in tree new growth, shrub and herb-dwarf shrub layers are given in the Table below. As it indicates, the activities of the same species in the undisturbed forest and the burnt area are not equal. The activity of tree new growth in the burnt area increased due to a more favorable conditions of illumination, availability of mineral nutrition, and plant competition in an open area, compared to those in a tall undisturbed forest. However, shrubs showed two opposite trends. Such typical forest species as *Lonicera pallasii* and *Spiraea flexuosa*, common in the dark coniferous forests of the middle mountains of the northern slope of the Khamar-Daban Ridge, were observed in the burnt area only in 2012-2013. They were damaged by fire and have not recovered afterwards. Until 2019, their young growth was not observed in the burnt area.

Table. Species' activity in the burnt area and in the undisturbed forest.

ECG		Forest	Burnt area, years							
			2012	2013	2014	2015	2016	2017	2018	2019
Trees (under new growth, seedling)										
Br	*Abies sibirica*	3.0	–	1.7	2.6	2.8	1.4	3.2	2.6	2.8
Br	*Betula* (*pubescens + platyphylla*)	2.2	–	2.8	3.2	3.2	2.8	3.2	3.2	5.5
Br	*Picea obovata*	–	–	–	–	–	1.4	–	–	2.0
Br	*Pinus sibirica*	1.4	2.0	2.2	2.6	2.8	1.4	3.2	2.6	2.4
Br	*Salix caprea*	1.4	–	–	2.	3.2	1.4	–	2.6	3.2
Br	*Sorbus sibirica*	2.8	–	1.7	2.0	1.7	–	3.2	2.0	2.8
Shrubs										
Br	*Lonicera pallasii*	2.4	1.4	1.7	–	–	–	–	–	–
Nt	*Rubus idaeus*	4.2	2.0	7.1	7.1	6.3	6.3	5.5	6.3	4.5
Nt	*Sambucus sibirica*	1.4	2.2	2.8	3.2	3.2	2.4	2.2	3.2	4.5
Nm	*Spiraea flexuosa*	1.4	1.4	–	–	–	–	–	–	–
Dwarf shrubs and herbaceous plants										
TH	*Aconitum septentrionale*	2.4	1.4	2.2	2.0	–	1.4	–	2.0	1.4
Nm	*Anemone reflexa*	–	2.0	1.7	–	–	–	–	–	–
Aa	*Anthoxanthum alpinum*	1.7	1.4	1.7	–	–	–	–	–	1.4
Nm	*Arsenjevia baicalensis*	4.2	3.0	2.8	3.2	1.7	1.4	1.7	2.0	3.5
Rp	*Bergenia crassifolia*	1.7	2.0	2.2	2.6	2.8	2.8	2.8	2.0	2.8
Nm	*Brachypodium pinnatum*	–	–	–	–	–	–	–	2.0	1.4
TH	*Calamagrostis langsdorffii*	2.4	2.0	3.2	4.5	5.5	5.5	4.5	5.5	5.5
Br	*Calamagrostis obtusata*	1.7	1.4	1.7	–	–	1.4	–	2.6	2.4
Br	*Carex iljinii*	2.2	–	–	–	–	–	–	–	1.4
Pn	*Carex macroura*	–	2.0	1.7	2.0	1.7	–	–	2.0	3.2
Nt	*Chamaenerion angustifolium*	–	–	3.2	3.2	3.2	2.0	1.7	2.0	3.2
Br	*Circaea alpina*	2.2	–	1.7	–	–	2.0	–	–	–
TH	*Cirsium helenioides*	1.4	1.4	1.7	–	1.7	–	–	–	–
Br	*Dryopteris expansa*	4.2	2.0	2.2	2.0	2.2	2.0	–	2.0	1.4

Continuation of the Table.

ECG		Forest	Burnt area, years							
			2012	2013	2014	2015	2016	2017	2018	2019
Wt	*Equisetum hyemale*	–	–	1.7	–	–	–	–	2.0	1.4
Nm	*Festuca altissima*	–	–	–	3.2	1.7	1.4	1.7	2.6	2.4
Br	*Galium boreale*	–	2.2	2.2	2.0	1.7	1.4	3.2	2.6	1.4
Nm	*Galium triflorum*	2.2	1.4	2.2	2.0	–	1.4	1.7	2.0	1.4
Br	*Gymnocarpium dryopteris*	4.5	2.6	2.8	2.0	–	2.0	2.2	2.0	2.8
Md	*Hieracium ganeschinii*	1.4	1.4	1.7	–	2.2	–	–	–	–
Nm	*Lamium album* ssp. *orientale*	1.4	1.4	–	2.0	–	1.4	–	3.2	2.0
TH	*Lilium pilosiusculum*	–	1.4	–	–	1.7	–	–	–	1.4
Br	*Luzula pilosa*	2.2	–	2.8	2.0	–	–	–	2.6	2.4
Br	*Lycopodium annotinum*	1.7	–	–	–	–	–	–	–	1.4
Br	*Maianthemum bifolium*	3.2	3.2	4.5	3.2	2.8	2.0	2.2	2.6	3.2
Nm	*Melica nutans*	2.4	2.0	3.2	2.6	2.2	2.0	3.2	3.2	2.8
Nm	*Milium effusum*	4.2	2.6	3.2	2.6	2.2	–	–	3.2	3.2
Br	*Oxalis acetosella*	2.8	1.4	1.7	–	–	1.4	–	–	1.4
Nm	*Paris obovata*	1.7	2.2	2.2	–	–	–	–	–	–
Br	*Phegopteris connectilis*	3	2.2	1.7	–	2.8	1.4	1.7	2.6	2.8
Pn	*Pteridium pinetorum*	2.2	2.2	1.7	3.7	5.5	2.8	4.0	4.5	4.9
Br	*Rubus saxatilis*	–	1.4	–	–	1.7	–	–	–	–
TH	*Senecio nemorensis*	1.4	–	–	–	–	–	–	–	1.4
Br	*Solidago dahurica*	2.2	3.0	2.8	–	–	–	–	–	–
Br	*Trientalis europaea*	3.2	3.2	2.8	2.6	2.8	3.2	3.2	3.2	3.2
Br	*Vaccinium myrtillus*	2.4	1.4	1.7	–	–	–	–	–	1.4
Br	*Viola selkirkii*	2.2	–	2.2	2.6	1.7	2.0	1.7	–	–

Notes to Table: pink color marks the species with average activity, while dark pink marks the ones with the highest activity; the lowest values are unmarked.

At the same time, a pair of Md and Nt plant species, *Rubus idaeus* and *Sambucus sibirica*, were much more active in the post-fire community. In 2013 and 2014, the value of activity coefficient of raspberries reached its maximum of 7.1, which was never observed for any other species. The most active species in the herb-dwarf shrub layer in all years were *Calamagrostis langsdorffii* and *Pteridium pinetorum* (up to 5.5), while in the forest community their activity coefficient was twice as low. Additionally, the group of active species included *Chamaenerion angustifolium*, *Maianthemum bifolium*, *Trientalis europaea*, and *Arsenjevia baicalensis*. Some species were active only in undisturbed forests, while completely or temporarily absent in the burnt area in the first years after the fire: *Anemone reflexa*, *Anthoxanthum alpinum*, *Carex iljinii*, *Lycopodium annotinum* L., *Senecio nemorensis* L., *Solidago dahurica* Kitag., *Vaccinium myrtillus* L. They belong to different ECGs, but at the same time they are all light-demanding species. Their temporary absence from the burnt area could be explained by the thick shade cast by raspberry, bracken and reed grass that massively developed in the first years of the post-fire vegetation change. Therefore, in the future, a gradual increase in their activity can be expected. The most active species of the forest community were *Arsenjevia baicalensis*, *Dryopteris expansa*, *Gymnocarpium dryopteris* and *Milium effusum* (4.2-4.5). The last two were also found in the burnt area with an average activity coefficient, while *D. expansa* did not grow there until 2019, but, apparently, its regeneration after the fire is possible at later stages of vegetation change. *Calamagrostis* and *Pteridium* species significantly participated in the plant community at the early stages of the long-term post-fire vegetation changes in various temperate regions, sometimes even oppressing other species; for example, this phenomenon was described for Western Siberia (Malinovskikh, 2014, 2017) and the mountainous regions of Switzerland (Delarze et al., 1992).

It is also worth noting the comparative activity of species of different ECGs. In Figure 7 we show the activity dynamics for 2011-2019 in the burnt area and the undisturbed forest.

At the early stages of the post-fire vegetation change, the Nitrophilous (*Chamaenerion angustifolium*, *Rubus idaeus*, *Sambucus sibirica*) and Pine-forest (*Pteridium pinetorum*) groups were the most active ones. The presence of the first one can be explained by an increased amount of available soil nitrogen in due to the fire, while the second one was influenced by the better illumination in the burnt area compared to the forest community. The activity of these two groups in the burnt area, as well as activity of species of the Taiga small herbs group, is comparable with the activity the same groups in the undisturbed forest. It is quite noticeable that in the burnt area, the activity of many ECGs changes significantly through years, with its overall range about 4.5. In the undisturbed forest, the activities of all ECGs are quite close to each other, ranging from 1.4 to 2.5. Such a significant difference in the species' activity between these two communities is caused, on the one hand, by the obvious difference between the conditions of the burnt area and the forest, and, on the other hand, by the formation of temporary parcels in the burnt area that replaced each other during the first years after the fire, when the community structure was still not formed.

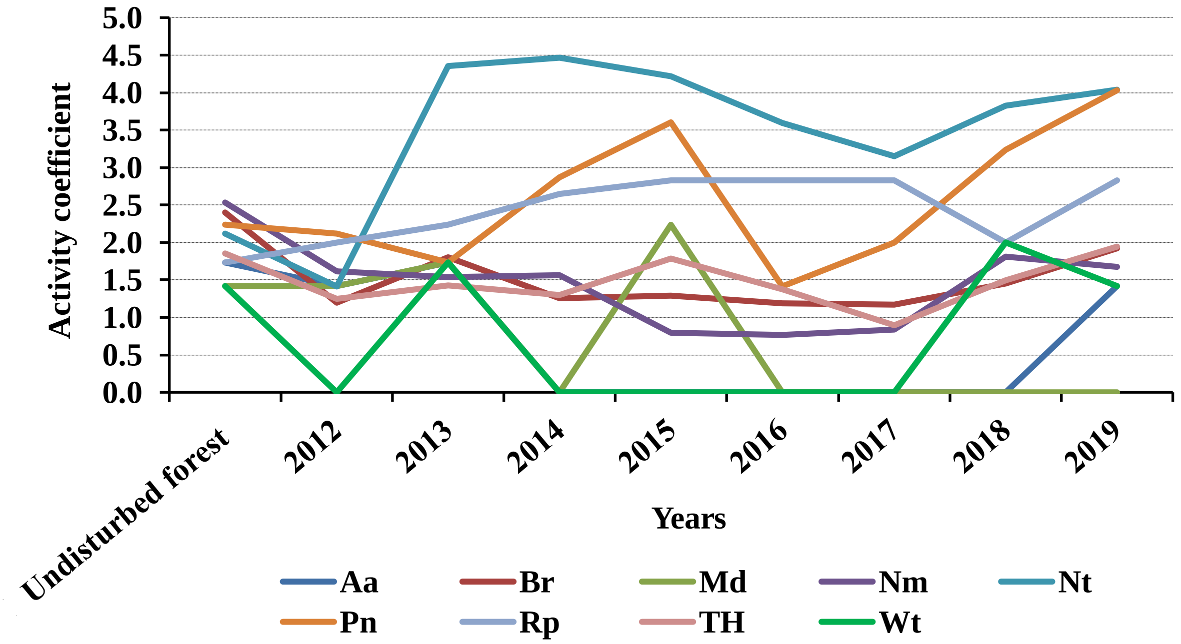

Fig. 7. Dynamics of activity of different coenotic (eco-coenotic) groups in the undisturbed forest and in the burnt area in 2011-2019.

Conclusions

This detailed study of the burnt area in the Siberian fir forest of the middle mountains of the northern slope of the Khamar-Daban Ridge is the first attempt to study the long-term post-fire dynamics of the forests of the Baikal Nature Reserve on permanent sample sites. A number of features that we noted in the early stages of the post-fire vegetation change have common features with the trends in post-fire regeneration of dark coniferous forests that were previously shown for the Baikal Region. Additionally, the mild and humid climate, as well as the wide distribution of rare or relict plant species, determines the specific features of the vegetation of burnt areas and the general course of regeneration of forest plant communities. The data obtained during this research are a part of a long-term study of burnt areas of different ages and secondary post-fire forests of the Baikal Reserve where a network of permanent sample sites has been created.

1. Wild fires in Siberian fir forests cause a complete death of the tree stand and trigger a restorative post-fire vegetation change, which under specific local nature conditions develops with the temporal replacement in tree species from the primary dark coniferous to the secondary small-leaved deciduous ones.

2. In the first years after the fire, the similarity coefficient of floristic composition in the plant community of the burnt area and undisturbed forest does not exceed 0.5. The ECG spectrum also changes, with the Br group being dominant in all years. Moreover, there can be plant species in the burnt areas that are not found in the primary forest, and the abundance of some rare species can increase.

3. The structure of the plant community in the burnt area becomes simpler as the number of layers, and their density/projective cover decrease. Within 5 years after the fire, the herb-dwarf shrub layer restores the value of total projective cover, typical for the undisturbed forest; the shrubs density increases sharply due to raspberries, and the tree layer formed by the new growth as well as the moss layer just begin to recover.

4. A single fire disturbance in a dark coniferous forest with a relatively small burnt area does not cause an irreversible degradation of the forest plant community. Taiga ecosystems retain the potential for a future recovery that is sufficient for a proper and successful vegetation change.

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РАННИЕ СТАДИИ ПИРОГЕННОЙ СУКЦЕССИИ В ПИХТОВЫХ ЛЕСАХ ЮЖНОГО ПРИБАЙКАЛЬЯ (БАЙКАЛЬСКИЙ ЗАПОВЕДНИК)

© 2023 г. Н.С. Гамова*, **, Е.А. Фаронова*, Ю.Н. Коротков, Т.С. Кошовский*, Т.Е. Язрикова***

**Московский государственный университет им. М.В. Ломоносова*
Россия, 119991, г. Москва, Ленинские горы, д. 1. E-mail: bg_natagamova@mail.ru

***Байкальский государственный природный биосферный заповедник*
Россия, 671220, Республика Бурятия, Кабанский р-н, п. Танхой, ул. Красногвардейская, д. 34

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В статье проанализированы ранние стадии восстановительной пирогенной сукцессии на гари в пихтовом с кедром лесу. Участок исследования типичен для среднегорья северного макросклона Хамар-Дабана; пожар имеет естественное природное происхождение. Отмечены пирогенные изменения во флористическом составе, а также в структуре лесного фитоценоза. Зафиксировано упрощение ярусности, уменьшение общего числа видов и разнообразия эколого-ценотических групп растений на участке гари в первые годы после прохождения пожара. Проведено сравнение послепожарного растительного сообщества с ненарушенным лесом. Оценено участие редких и охраняемых видов растений на гари.
Установлено, что лесные пожары в пихтовых лесах приводят к полной гибели древостоев

и запускают восстановительную пирогенную сукцессию, которая в данных условиях проходит со сменой пород на вторичные мелколиственные. В первые годы после пожара коэффициент сходства флористического состава фитоценоза гари и ненарушенного леса не превышает 0.5; также меняется спектр эколого-ценотических групп, во все годы доминирует группа Br (таежное мелкотравье). При этом на гари встречаются виды растений, не отмеченные в коренном лесу, а обилие отдельных редких видов увеличивается. Структура растительного сообщества гари упрощается: уменьшается число ярусов и их сомкнутость / проективное покрытие. В течение 5 лет после пожара травяно-кустарничковый ярус восстанавливает общее проективное покрытие, характерное для фонового ненарушенного леса; кустарники резко увеличивают сомкнутость за счет малины, а древесный ярус в виде подроста и моховой ярус лишь начинают свое восстановление.

Однократное пожарное нарушение темнохвойного леса при относительно небольшой площади гари не вызывает необратимой деградации фитоценоза. Таежные экосистемы сохраняют потенциал восстановления, достаточный для успешного прохождения сукцессии.

Ключевые слова: Хамар-Дабан, лесные пожары, пихтовые леса, пирогенные сукцессии лесной растительности, редкие виды, эколого-ценотические группы видов.

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