Mapping the pyrogenic dynamics of forest geosystems on the northeastern shore of Lake Baikal

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Abstract. The paper considers the impact of the pyrogenic factor on the landscapes of the Barguzinskii Range. Model representative sites with natural and disturbed mountain-taiga geosystems are identified in the territory of the Trans-Baikal National Park (Svyatoi Nos Peninsula) and the Barguzinskii Nature Reserve (Shumilikha, Tarkulik, and Davsha river valleys). We used geoinformation methods, landscape interpretation mapping, field observation data, remote sensing data and traditional comparative geographical methods for assessment and mapping. The collected data are systematized in the form of a geoinformation database for individual sections and visualized in a cartographic form. We compiled vegetation maps, taking into account the features of the relief and soil types and gave a general description of the landscape state to analyze the pyrogenic impact on local landscapes. It was also revealed that the modification processes of forest geosystems caused by the pyrogenic impact are widespread across wide swathes, but have a different character. It depends on the individual spatial geographical features of the selected representative sites and the nature and time of the direct pyrogenic factor exposure, e.g., the frequency, intensity, especially the microclimate, relief, etc. The paper shows that the restorative stages of plant dynamics in the model sites are clearly traced. We have established an insignificant difference between the current and reference states in places of weak pyrogenic impact, significant local state changes in places of extensive areal impact, and significant and catastrophic changes in places of lasting and intense pyrogenic impact. Maps of the geosystem disturbance caused by both pyrogenic and natural factors for the model sites were compiled.

1. Introduction
Natural wildfires, on the one hand, are an uncontrolled combustion process and natural disaster in the natural environment, and on the other hand, a natural process that contributes to the change of successions, dynamics and transformation of landscapes. In scope and effects, the pyrogenic factor plays a huge role in the functioning of geosystems and ecosystems of various scales. Among the anthropogenic factors that disturb the vegetation cover, it is also the leading one now [1, 2]. This also applies to the disturbance of geosystems as a whole. The consequences of wildfires are both usual changes in the structure of the vegetation cover and the rearrangement of the hierarchical levels of forest vegetation, the transition of natural systems to bifurcation states, when other, even insignificant, negative impacts can lead to a change in the virgin state of communities [3].
Studies of the wildfire consequences, their impact on landscapes and individual populations are carried out in almost all disturbed areas. At the same time, despite special attention paid to the effect of the pyrogenic factor on the dynamics of forest communities and related fire-fighting measures within the boundaries of the Baikal nature territory (BNT), their distribution has increased in recent years and is ubiquitous. The study of the structure and functioning of the BNT geosystems, their transformation due to fires is the basis for assessing and predicting changes in the natural environment. The wildfires of recent years have become catastrophic for the Baikal region in general and on the shore of Lake Baikal in particular. Therefore, since the spring of 2015, large fires were recorded in federal specially protected natural areas (SPNA): in the Baikal-Lenskii, Baiakalskii, Barguzinskii nature reserves, Zabaikalskii and Pribaikalskii national parks and the Frolikhinskii nature reserve. Creeping fire (running ground and permanent ground) and crowning fires disturbed part of the subalpine, mountain-taiga and coastal landscapes, causing irreparable damage to many components of ecosystems. They affected not only remote areas with slightly disturbed geosystems, but also tourist destinations and main ecological paths, thereby causing serious damage to recreational activities. Thus, studying the processes of transformation of forest geosystems under the pyrogenic impact and mapping their pyrogenic dynamics are important both for the preservation and restoration of natural complexes and future application missions in the regional development. In addition, systematic observations of the pyrogenic impact on landscapes and their components are lacking in this area.

In this regard, the research is aimed at monitoring, studying and assessing the pyrogenic impact on the mountain-taiga geosystems of the Baikal natural territory based on the example of the northeastern shore of Lake Baikal near the Barguzinskii Range. Thus, the main focus is to promote the assessment of the restoration stages of mountain taiga geosystems after wildfires (pyrogenic modifications) on the example of changes in their plant component, to study the role of the pyrogenic factor in the formation of the structure and altered states of geosystems and to map the landscape assessment in the model sites.

2. Models and Methods

The research territory covers high-mountain alpine, mountain-taiga and coastal landscapes of the Barguzinskii Range, including the Svyatoi Nos Peninsula, within the boundaries of the Zabaikalskii National Park and the Barguzinskii Nature Reserve. There are a number of landscapes typical of Eastern Siberia (goletz southern Siberian, subgoletz southern Siberian, mountain-taiga southern Siberian, subtaiga southern Siberian, floodplain and wetlands) [4]. Due to the presence of a high conservation status and extensive nature management, indigenous plant communities have been preserved here even before the establishment of these protected areas, and the impact of wildfires can be considered a natural process of the dynamics of geosystems. The anthropogenic factor in the occurrence of wildfires is minimal due to the inaccessibility, effective protection mechanisms and the imposition of constraints on visiting this territory. It was also revealed that natural fires have a significant impact on the formation of local landscapes and their components. In 2015 and 2016, crowning and ground forest fires of varying intensity destroyed significant areas of taiga and coastal geosystems. But currently, we have an opportunity of studying and assessing the features of the geosystem restoration in natural conditions with minimal anthropogenic impact using the example of damaged landscapes. Thus, the analysis of successive processes and restoration stages of landscapes typical for a given area contributes to the identification of natural patterns in the dynamics of forest vegetation, as well as the pyrogenic impact on related areas, in particular, on the environmental management and the development of ecological tourism.

We applied the methods of geoinformation analysis, the approaches of landscape-interpretive mapping [5], the botanical (description of flora and vegetation and dominant-determinant approach) and zoological (registration on permanent sample plots, visual and audio observation) methods for mapping and analysis of pyrogenic dynamics, as well as classical approaches of physical and geographical and landscape research, developed in the Sochava Institute of Geography, Siberian Branch of the Russian Academy of Sciences (SB RAS) [6, 7]. The assimilation of geoinformation technologies in the study expanded the capabilities of classical descriptive and comparative geographical approaches [8–11]. The field, descriptive and comparative geographical (descriptions of landscapes and their components,
geobotanical characteristics of the territory) methods, as well as geoinformation mapping using remote sensing data (a series of Landsat satellite images for 2009–2018), surveys of unmanned aerial vehicles (UAVs) and archived data on forest wildfires in the Zabaikalskii National Park and the Barguzinskii Reserve were used to map the types of vegetation cover and its state variables. The creation of the geographic information base, data processing and mapping were carried out using the ArcGIS software packages.

In making botanical descriptions, the main types of vegetation and groups of associations were distinguished according to the dominant principle, as exemplified by the studies of Ivanova performed in 1969 [12]. The early spring and autumn Landsat 7 satellite images (2011 and 2012) were selected to interpret the vegetation before the fires of 2011 and 2015, which allowed studying the boundaries of various associations. Images from 2016 and earlier were used to clarify the boundary and area of the forest wildfire in 2015.

For a comparative analysis, we selected several model sites in the territory of the Svyatoi Nos Peninsula and the mainland of the Barguzinskii Range in the basins of the Shumilikha, Tarkulik and Davsha rivers, where the field observations were carried out between 2016 and 2021. An analysis of the anthropogenic impact on recreational areas was provided, more than 30 geobotanical and landscape descriptions on the standard nominally undisturbed and disturbed by the pyrogenic factor areas were given, and monitoring areas were established to account for post-fire successions and changes in vegetation cover. The collected data are structured as a geoinformational database, where each unit corresponds to a set of landscape and other characteristics (main landscape features, state, pyrogenic dynamics, monitoring features, etc.). It is supplemented by the information on the remote sensing data and archives of the Priibaikalskii National Park and the Barguzinskii Reserve and continues to be filled as new information is received. As a result of cameral processing, qualitative and quantitative characteristics of geosystems and their components were given, the landscape structure was studied, and the thematic maps were compiled that characterize the current state of geosystems in the selected model sites, taking into account the pyrogenic factor.

3. Results and Discussion

Our studies have shown that the selected model sites have different degrees of accessibility, traffic, nature conservation and study. At the same time, they are similar in physical and geographical terms and suffered from natural fires in 2015. Local landscapes are at different stages of recovery dynamics, depending on the impact degree of the pyrogenic factor and local environmental features. The transformation processes of local natural systems that occur in the research area and are caused by changes in the environment under the pyrogenic impact have been identified in vast areas. They cover significant areas on the Svyatoi Nos Peninsula, but a relatively small part of the Barguzinskii Range as a whole. Burnt-out areas of various periods have been revealed (fresh, five-year-old with the restoration of pioneer vegetation (Epilobium, etc.), ten and fifteen-year-olds, as well as older ones). The repetitive character of fires complicates establishing of the exact period of the pyrogenic impact and the stage of natural recovery. Therefore, the landscapes already disturbed by fire are fire-prone to similar effects in subsequent years. At the same time, the restorative stages of vegetation dynamics in different periods are clearly traced. The anthropogenic factor does not play a significant role here due to a small number of people visiting the research area. A brief description of the pyrogenic impact in the model sites is given in Table 1.

Aiming at assessing the pyrogenic impact and the stability of local landscapes, we have compiled the vegetation maps, taking into account the relief and soil type features, and further studied the areas of the Red Data Book species and the features of the functional zoning of the park and the reserve. The data are systematized in the form of the geoinformation database for individual sections and visualized in a cartographic form. A case in point is the matter of the vegetation map “Along Doppelmair’s Path” compiled by the authors on this geoinformation basis for one of the remote and closed areas of the Federal State Budgetary Institution Zapovednoe Podlemorye, located in the territory of the Barguzinskii Nature Reserve [11] (Figure 1). It shows the characteristic types of vegetation and the succession stages of the pyrogenic dynamics of forest geosystems that have arisen over a century.
Table 1. The pyrogenic impact on the model sites of the northeastern shore of Lake Baikal

| Site                          | The features of the site                                                                 | The effects of the pyrogenic factor                                                                 |
|-------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| The Shumilikh River basin     | The site is located at the southern border of the Barguzinskii Nature Reserve, adjacent to the Sosnovka Bay, where the visit center and the Yuzhny lodge with place of accommodation are located. Near the Shumilikh River mouth, there is a wintering place, and a previously undesigned educational eco-route. In the lower part of the slope, there is a pseudo-subgoletz belt of dwarf Siberian stone pine. Higher on the slope, there are light coniferous pine-larch and larch-pine forests, turning into dark coniferous fir and fir-Siberian stone pine forests. | Indiscriminate destruction of vegetation. Soil erosion. Destruction of the tourist route. Low reforestation potential. |
| The Tarkilik River basin      | The territory is currently closed to the public, except for scientific and monitoring research. Lower on the slope, there is a pseudo-subgoletz belt of dwarf Siberian stone pine. The flattened lacustrine terraces are occupied by light coniferous pine, pine-larch and larch-pine forests, above which Siberian stone pine, fir, fir-Siberian stone pine and Siberian stone pine-fir forests form the mountain-taiga belt. Pyrogenic modifications of aspen and aspen-birch forests are revealed. | Indiscriminate destruction of vegetation after wildfires of 2015. Mean potential of reforestation. Traces of fires of various times of prescription are detected. Various stages of reforestation are observed. |
| The site of the Davsha lodge   | The site has been chosen as a “point of growth” for the creation of the ecotourism trail “Davshinskie Stolby”. There is a developed recreational infrastructure based on the Davsha lodge, including guesthouses, camping, equipped hot springs, a nature museum, and the possibility of day charter for small yachts. Actively visited by tourists. Siberian stone pine and Siberian stone pine-fir forests predominantly cover the model plots. Pyrogenic modifications of mainly aspen forests were revealed. | Partial destruction of vegetation (a significant part of the stand has been preserved). High potential for reforestation (between 2016 and 2020 the grass and shrub cover was significantly restored, abundant growth of aspen and birch). The disturbed state of geosystems allows better assessing the possibilities of establishing an educational route, highlighting the viewpoints, facilitating the clearing work, etc. The vegetation in the areas affected by the fires is rapidly renewing and does not “frighten” visitors. |
| The Svyatoi Nos Peninsula      | The site is partially accessible and actively visited by tourists. There is a route called “Trail of Trials” leading to the top of the plateau. No infrastructure. In the high- and middle-mountainous part, there are no permanent sources of running water. A significant part of the high-mountainous territory is composed of dwarf Siberian stone pine, yerniks and mountain tundra vegetation. Pine and pine-fir forests grow in the mid-mountainous part. In the lower part of the slopes, pyrogenic modifications of forests are represented by deciduous species (aspen and birch). | Partial or indiscriminate destruction of vegetation. Low reforestation potential. |
Figure 1. Vegetation types of the model site in the Tarkulik region. 1 – mountain tundra, 2 – mountain alpine-type meadows and wastelands; 3 – subgoletz woodlands and bushes; 4 – dark-coniferous mountain-taiga forests; 5 – light coniferous mountain taiga forests; 6 – waterlogged grassland; 7 – mountain-taiga light-coniferous and dark-coniferous forests at various stages of regenerative dynamics.

Figure 2 illustrates a schematic map showing the degree of disturbance of geosystems caused by natural and pyrogenic factors at the model site in the Tarkulik region.

Figure 2. The degree of disturbance of geosystems caused by natural and anthropogenic factors: 1 – nominally undisturbed geosystems, environmentally sustainable, 2 – geosystems strongly disturbed by a natural factor, environmentally sensitive, 3 – geosystems moderately disturbed by a natural factor, environmentally sustainable.
4. Conclusion
To some up, the research resulted in the creation of the geoinformation basis and the structure of the database in the GIS for individual sites, which allow annual introducing new received monitoring and additional information in the area under study, as well as expanding the database to other areas. Aiming at further tracing the landscape state dynamics, we have described the current species composition and have determined the diversity and mosaic of the vegetation cover and the stages and the degree of disturbance by the natural and pyrogenic factor. The transformation processes of local natural systems caused by environmental changes under the pyrogenic impact are common over a significant part of the studied area. The burnt-out areas of different periods have been revealed, while the pyrogenic effect is repeated in the same areas, and previously burnt landscapes are more sensitive to fires in subsequent years. The recovery stages of plant dynamics at different stages are clearly traced in the model sites. We have established insignificant difference between the current and reference states in places of weak pyrogenic impact (creeping fires of low-intensity), significant local changes with a change in state in places of extensive areal impact (permanent ground fires) and significant and catastrophic changes in places of permanent and intense pyrogenic impact (crowning and long-term permanent creeping fires). Based on the vegetation map of forest types, preliminary mapping of the fire risk analysis has been carried out. The performed analysis has become the basis for the general characteristics of the state of landscapes, taking into account the pyrogenic factor.

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