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Dynamics of Pyrological Regimes at Landscape Stows in Southern Taiga of Central Siberia in 18–20th Centuries

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Abstract—Methodological aspects of investigation into the dynamics of pyrological regimes and their effect on natural ecosystems have been considered. It seems reasonable to combine different data on the history of forest fires in order to reveal the long-term dynamics of pyrological regimes. This allows one to eliminate certain disadvantages that are to some extent peculiar to separate methods.

The dynamics of pyrological regimes at the main landscape stows in southern taiga of Siberian regions near the Yenisei over the last three centuries has been analyzed. The deviations of modern pyrological regimes from those in the past are quantitatively estimated. Probable ecological and forestry consequences of changes in pyrological regimes and possible ways to govern the pyrogenic factor for the purpose of stabilizing ecosystems are discussed.

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Fires have a strong effect on the ecosystem structure, composition and functioning [1-4]. Analysis of the frequency of fires allows us to reveal the factors that control their dynamics.

At present, the frequency of fire events over several centuries is known for some regions of Eurasia [5–9] and North America [10–15]. The frequency of fires was determined in the majority of cases as an average value over three centuries and more; however, no attention has been paid to the dynamics of fire events in connection with the action of various factors. Meanwhile, the space-time regularities of fire frequency are of essential interest because they can be used to control the pyrogenic factor in order to conserve and form a definite type of vegetation. For example, under different extents of fire action on ecosystems, forest communities with a complicated mosaic vegetation form, which differ in composition, age and structure. In this situation, management of the pyrogenic factor in each specific case should imply either fire extinguishing or provision of the possibility for fire to spread within the boundaries of definite ecosystems, or the application of the prescribed prophylactic burning of the forest combustible materials (FCM).

METHODOLOGY OF THE INVESTIGATION OF THE DYNAMICS OF PYROLOGICAL REGIMES

In order to govern the pyrogenic factor, the necessary element for which should be the forecast of post-fire forest-forming process, it is extremely important to know the frequency of fires during many years and the intervals between fires that had been historically ingrained in specific ecosystems and have determined the modern look of the vegetation within the boundaries of those ecosystems. Investigations of the long-term frequency of fire events, their intensities and propagation features allowed the researchers, as early as the 1970s, to make a conclusion concerning the existence of special conditions promoting the manifestation of statistically probabilistic law at the beginning of fire events and determining the level of burning ability of natural territorial complexes (NTC) of different ranks [1]. It was proposed to express these conditions through the term “pyrological regimes” of NTC. By introducing this term, researchers stressed that in this case one speaks of the estimation of the probable frequency and intensity of the action of the pyrogenic factor on an NTC existing for a long time but not on a plantation type, which varies relatively fast with time [16]. The features of pyrological regimes are determined not by climate, which is approximately the same within a landscape, but by the ecological modes of an NTC, conditioned by a combination of its components and their interactions with each other [17]. At the same time, fires affect the components, change them, thus changing the ecological modes of NTC in general. So, the term “pyrological regime” implies a long-term process of the interaction of fires with the ecological modes of specific NTC; the results of this interaction are exhibited as the features of the post-fire dynamics of forests. In other words, fires determine not only the arrangement of the post-fire stages over the territory in agreement with the initial arrangement of NTC but also their status in time according to the fire frequency.

We accepted the long-term actual frequency of fire events as the main index of the NTC pyrological regimes. This frequency is determined by their ecological modes and by the presence of ignition sources. All the basic kinds of NTC — sites, stows, tracts, and landscapes — are united into four classes of the pyrological regime: with frequent, medium, rare and very rare recurrence of fire events. Gradations which served as the basis for assigning a class of pyrological regime to an NTC were accepted on the basis of actual recurrence of fire events during a period 270 years long. As a result, the class with the frequent recurrence of fire events unites those complexes in which the fire took place every 5 to 30 years, medium recurrence is for 31 to 70 years, rare one for 71 to 100 years, and very rare is for more than 100 years.

In succeeding years following foreign authors, some researchers in Russia started to use the term "fire regimes" to characterize the scale and depth of fire impart on forest formations. For example, using an original procedure, Gromtsev [2] investigated the "fire regime" in the so-called spontaneous forests in the landscapes of northwestern taiga for the last 3–6 thousand years. As a result of the investigation, he concluded that forest fire events are among the leading ecological factors that determine the structure and dynamics of forest communities over many thousand years.

According to Valendik and Ivanova [8], the fire regime of forest fire zones and regions is characterized by the number of fire events per 1 mln ha, periodicity of fire seasons and their duration. Evidently, the areas under study are large administrative-economic or natural territories, which differ sharply in climatic conditions. However, in our opinion, the same term and notion is inaptly used by the authors to characterize the frequency of fire events and the intervals between fires in specific types of forest, which brings about a methodological confusion and hinders investigation and classification of forest ecosystems according to the historically inherent fire frequency. We suppose that the term and notion "fire regime" should be used to characterize only large natural or administrative-economic territories sharply differing in their climatic conditions. It is reasonable to use the term and notion "pyrological regime" for ranking specific ecosystems according to the historically ingrained fire frequency which is determined mainly by the ecological conditions of vegetating plant communities. On the basis of this notion we may use the classification of forest ecosystems according to the pyrological regime for choosing the strategy and tactics of management of the pyrogenic factor.

To implement the mentioned idea, the procedures for revealing, calculating, classifying and mapping the pyrological regimes of NTC of different ranks were developed [1, 6, 18]. To determine the pyrological regime according to the indicated procedures, one should reveal the frequency (recurrence) of fire events on the basis of the affected annual rings of trees with the so-called fire-dried sites [5]. It should be noted that the international practice does not have a unified index characterizing the spatial and temporal features of the fire or pyrological regime. The following indices are usually used abroad:

1. Fire frequency is the number of fire events registered in a given ecosystem during a long time interval lasting for several decades or, more frequently, several centuries.

2. Interval between fire events, or fire recurrence, is the number of years between two consecutive fire events.

3. Fire intensity is a physical characteristic of the most probable behavior of the fire in a specific ecosystem. Most frequently, it is measured as the amount of energy released by the fire front.

4. Force of a fire, or the force of its ecological effect is (in the wide sense) the degree of changes in an ecosystem caused by a separate fire event (tree drop-off, the amount of burning FCM, etc.).

5. Fire rotation is the spatial frequency characterizing the time during which the area of an ecosystem is entirely covered with fires once more. It is determined through the recovered perimeters of former fires.

6. Fire cycle is fire turnover within the limits of a definite territory: massif, landscape, forestry district, province etc.

Research experience shows that the greatest difficulties arise when the pyrological regime is to be characterized spatially, which requires the transition from punctual data to estimations of one or another area. Since fires and their consequences vary both in space and in time, it would be most correct to determine the pyrological regimes only for a specific period of time and with respect to a uniform ecosystem. Judging from our experience, an example of the ecosystem of this kind is a geographic site incorporated into more complicated natural complexes — stows, tracts, and landscapes [1, 17].

To be valuable in the context of forestry and ecology a pyrological regime should characterize a time interval necessary at least for the recovery on a fire-site and for the complete life cycle of the native tree species after destruction by fire. Under the conditions of West and Central Siberia, this interval is 270–300 years for dark and light coniferous forest [1, 19]. Changes in the character of land-use, in the level of land development in forest areas, and the mode of forest protection from fire are accepted as the main reasons of the variability of pyrological regimes with time. These factors should also include different intensities of the action of any large fire on the ecosystem owing to the spatial and temporal nonuniformity of burning materials and weather. In addition, to use the pyrological regime of ecosystems for governing the pyrogenic factor, it is very important to take into account forest disturbance by previous fires, features of the post-fire changes in tree species, character of the post-fire recovery, and age dynamics of the communities [1, 16, 19].

The most important link in governing the pyrogenic factor is mapping of the pyrological regimes of NTC and the related post-fire dynamics of forests. For the first time in Russian and foreign practice, the maps of pyrological regimes and post-fire dynamics of forests were compiled for the rank of sites over the territory between the Kas and the Yenisei Rivers on the West Siberian Plain [1]. The maps of classes of pyrological regimes are the basis for predictions of the post-fire dynamics of forests, for estimations of fire danger, and for development of strategic plans of governing the pyrogenic factor and forest resources of the regions. They also help to explain the specific effect of landscape structure, land-use character, and the intensity of land development on the pyrological regime of forest ecosystems.

Fire frequency is known to affect, directly or indirectly, the duration of the life cycle of tree species and their changes, structure and composition of communities, accumulation of FCM; that is why fire frequency was the top-priority object for the investigation of the effect of fires on ecosystems [5, 20]. In our works, the basis for mapping the pyrological regimes was also fire frequency in elementary natural complexes, i.e. sites.

Substantial difficulties arise in attempts to carry out a spatial extrapolation of pyrological regimes because, as a rule, the data of fire frequency are of point character. However, the extrapolation is quite possible if the landscape map demonstrating the relationships between areas of NTC of different ranks in the landscape structure is available. The next rank of morphological structure is stow; its pyrological regime is determined according to our procedure as a weighted mean of the product of the areas of sites comprising it and the class of pyrological regime at each of the sites. Similarly, the weighted-mean class of a pyrological regime of tracts is calculated by multiplying the areas and classes of stows comprising the tracts; the weighted mean class of the pyrological regime of a landscape is calculated by multiplying the areas and classes of component tracts. The procedure of calculating the pyrological regimes on the basis of the morphological structure of NTC and the ratio of their areas allowed us for the first time to map the pyrological regimes of stows, tracts, and landscapes [1, 6, 16].

An opinion exists that the direct and indirect consequences of fires in different ecosystems are extremely diverse, so it is hard to generalize them for large territories because it is difficult to estimate the long-term post-fire changes on broad spatial and temporal scales. Our experience shows that the spatial generalization of the action of fires for many centuries may be actually achieved by mapping the post-fire forest-forming process through the stages of recovery-age dynamics of forests [1, 16]. The results of mapping are most optimal when they are landscape-based and involve the results of aerospace photography [21]. We determined the years of occurrence of fires resulting in the growth of young trees of mother species or replacement of conifers by deciduous species in fire-sites on the basis of the age structure of trees within the boundaries of landscapes using the aerospace photographs and carrying out additional dating of fires with model trees with fire-caused burn marks.

Worthy of note is that various data including paleoecological information on previous fires can be used to reveal the pyrological regimes of ecosystems [22]. However, all of them vary in degree of their spatial and temporal resolution, as well as in efficiency for the evaluation of various aspects of pyrological regimes. The data of any types have their own advantages and disadvantages in revealing fire frequencies and areas, ecological and forestry-related consequences. However, in our opinion, the information left by fires on tree trunks in the form of fire-caused burn marks with affected annual rings is the most reliable one for the establishment of pyrological regimes [1]. With the careful cross dating, the data of this kind may be used to estimate the point and spatial dynamics of fire frequencies during several centuries [3].

We accumulated the experience in mapping the pyrological regimes also in large territories of the West Siberian Plain and the Central Siberian plateau [16]. Mapping over large territories was based on the principle of similarity of the recovery-age stages formed under the action of identical pyrological regimes. Experience showed that the classes of pyrological regimes can be confidently extrapolated over analogous natural complexes, especially in the case when the geoinformational basis is available. The method of analogy opens the possibilities to map the pyrological regimes also in application to potential vegetation predicted within the boundaries of an NTC in agreement with the regularities of post-fire forest-forming process [23].

To reveal classes of pyrological regimes, one may also use the data from the fire certificates with propagation schemes enclosed, though this method of obtaining data has two essential disadvantages: forest fire certificates are available only for protected (secure) territories and with respect to time they are available only since the later half of the 20th century. At the same time, the fire certificates and schemes can be used to establish the spatial distribution of regions traversed by fire, which is very difficult to achieve by analyzing the fires established only on the basis of annual rings in the trees with fire-caused burn marks.

The advantage of the dendrochronological data is that they embrace large time intervals, as a rule, 300–500 years, and that they provide high accuracy of dating — a year or even a season of fire occurrence [5, 3]. Large time intervals disclose the fullest dynamics of the climatic and weather situations under which the ecosystems of large territories are affected by fires. Exact dating of fire events allows us to establish a correlation between them and such climatic parameters as temperature, precipitation, and drought index [24]. A centuries-old interconnection between the fires and the climate is important for predicting fire outbursts and estimating the effect of global climate changes on the dynamics of forest ecosystems.

To establish the long-term dynamics of the pyrological regimes, it is reasonable to unite different sources of data on the history of fires, thus eliminating disadvantages of separate methods.

ANALYSIS OF THE DYNAMICS OF PYROLOGICAL REGIMES

Investigations of the pyrological regimes were carried out over the territory of southern taiga of Central Siberia limited by the geographic coordinates 88–90° eastern longitude and 58–60° northern latitude. This territory is part of the West Siberian Plain near the Yenisei River. The objects of investigation were natural territorial complexes (NTC) as interpreted by Solntsev [25]. In the present work we restrict ourselves to analysis of the dynamics of pyrological regimes of the most representative landscape stows depending on the ecological modes of background sites (see the table).

One can see in the table that the class of the pyrological regimes within the boundaries of centuries changed in five stows of eight analyzed ones. For instance, in the tract of stepped partitioned terraced slopes with fir-wood and pineries, the class of pyrological regime changed during three centuries from IV (very rare fire events) in the 18th century to II (medium fire recurrence) in the 20th century. The background sites of this stow are larch and cedar subors on sand and clay sand, fresh and humid [1]. For the indicated sites, the features of the ecological modes include the presence of weak and medium degree of flowage, weak alluviality and floodability, relative richness of the substrate, absence of perched water and underflooding by soil and ground water.

In a stow with the plain surface of a high coniferous-forest terrace with pineries, class II of pyrological regime in the 18th century changed for class I in the 19th century and stably remained at this level during the 20th century. In this situation, the average interval between fires decreased from 50 years in the 18th century to 14 years in the 19th and remained approximately the same during the 20th century. The background sites of this stow are pineries on sand, fresh and humid; their ecological mode is characterized by the absence of such phenomena as flowage, alluviality, floodability with perched water, rising of ground water level to the plant rhizosphere zone, and relative poorness of the substrate.

In the stows with gentle concave slopes overgrown with pineries and fir woods, class II of pyrological regime in the 18th century changed sharply in the 19th century and again approached the initial level during the 20th century. Similar dynamics of the pyrological regimes occurred in the stows of plains with overwetted pineries. Very rare fire recurrence in these stows in the 18th century was replaced by the medium one in the 19th century and again decreased in the 20th century. The number of fire events and the average interval between fires decreased also in the stows of comb-like plains with abies and fir wood.

For the stows under analysis, as a rule, the ecological modes are characterized by the high level of ground water preventing fast drying of the FCM (Fig. 1).

It was established that the pyrological regimes vary substantially not only with time but also in space (Fig. 2). In this situation, the determining factor of spatial variability of fire frequency is the inhomogeneity of the ecological modes of NTC and FCM, which determines the differences in the degree of ecosystem action of fires, post-fire status and the dynamics of ecosystems. This inhomogeneity increases over larger spatial levels.

In many cases, fire frequency and correspondingly the pyrological regime in a specific ecosystem are determined by its position with respect to the neighboring ecosystems with their characteristic pyrological regimes, but in very rare cases they turn out to be adequate. This is explained by different leading factors of the ecological mode; the effect of these factors is clearly exhibited in the analysis of fire frequencies during several tens and several hundred years.

Inhomogeneity of pyrological regimes in space and in time brings complications into the estimation of their effect on ecology and on forest-forming processes. In this connection, attempts are made to find a quantitative measure of the force of ecological effect of different pyrological regimes. In Russia, forest disturbance by fire, post-fire changes in tree species, the ratio of the aboriginal to derived post-fire communities within the NTC boundaries are proposed to be used as these indices [1, 16, 26].

To estimate the intensity of ecosystem action, we compiled two types of maps of pyrological regimes. Maps of the first type characterize pyrological regimes causing short-term consequences in the form of various secessions of the overstory trees, including post-fire sparse growth and fire sites with 100 % tree secession. The maps of the second type characterize long-term consequences of the action of fires on ecosystems, expressed as the changes of the age structure and species composition, as well as the relations between native and derived communities in the structure of forest vegetation of landscapes. In Russian forest pyrology, this type of maps is associated with the maps of post-fire dynamics of forests, based on the distribution of recovery age stages [1, 23]. Both types of maps allow estimation of the forestry-related and some ecological changes arising under different pyrological regimes.

To make a more complete estimation of ecological consequences, first of all the dynamics of carbon, a method based on analysis and interpretation of the

Fire frequency in stows of southern taiga of Central Siberia in 18–20th centuries

Stow	Century	Years of fires	Interfire interval averaged over century, years	Class of pyrological regime	Background sites constituting stows
Willow-spruce floodplain at the Yenisei River	XVIII	—	—	—	Floodplain spruce forests, fresh
	XIX	1870	> 100	IV	
	XX	1935	> 100	IV	
Terrace slopes with fir and spruce	XVIII	—	—	—	Fir forests on cover loams, fresh
	XIX	1870, 1886	50	II	
	XX	1915, 1933, 1956	33	II	
Stepwise differentiated terrace slope with spruce and pine	XVIII	1700	> 100	IV	Larch and Siberian-pine subors, on sands and sandy loams, fresh and wet
	XIX	1842, 1870, 1886	33	II	
	XX	1915, 1921, 1930, 1956	25	I	
Flat surface of high terrace with pine forests	XVIII	1700, 1788	50	II	Pineries on sands, fresh and wet
	XIX	1806, 1819, 1820, 1825, 1842, 1860, 1870	14	I	
	XX	1909, 1915, 1916, 1921, 1930, 1933, 1946, 1952	13	I	
Gentle hummocky drained surface of terraces with fir, spruce, and Siberian pine	XVIII	—	—	—	Fir and spruce forests on cover loams, fresh and wet
	XIX	1860, 1870, 1886, 1896	25	I	
	XX	1915, 1920, 1946, 1956	25	I	
Gentle concave slopes with pine and spruce	XVIII	1787, 1793	50	II	Pineries on sands, fresh and wet
	XIX	1806, 1808, 1819, 1819, 1830, 1866, 1870, 1891	11	I	
	XX	1915, 1933, 1856	33	II	
Ridge-like plains with fir and spruce	XVIII	—	—	—	Fir and spruce forests on cover loams, fresh
	XIX	1860, 1870, 1886, 1896	25	I	
	XX	1915, 1933, 1956	33	II	
Flat plains with water-logged pine forests	XVIII	1793	> 100	IV	Pineries on sands, wet and water-logged
	XIX	1830, 1870	50	II	
	XX	1956	> 100	IV	

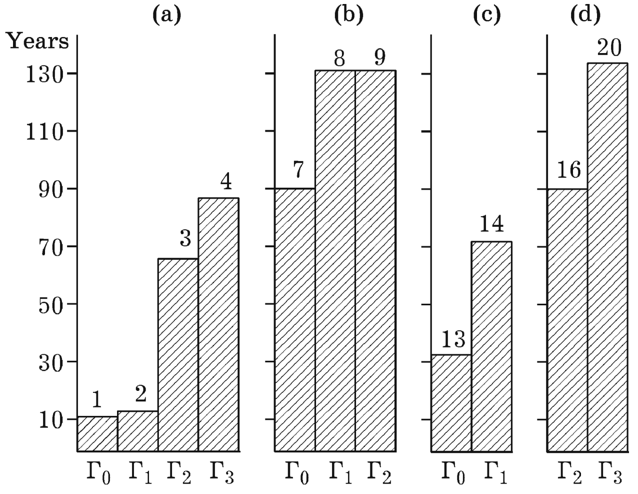

Fig. 1. Fire frequency in sites. (a), pineries on sands: fresh, wet, and water-logged; (b), Siberian-pine subors on loam-based sands: fresh and wet; (c), fir forests on cover loams: fresh and wet; (d), spruce forests with Siberian pine and Siberian-pine forests on loams: wet and water-logged. 1–4, 7–9, 13, 14, 16, 20 — site indices. G_0–G_3 — no, weak, moderate, and strong flooding by groundwaters.

maps of forest disturbance with fire and post-fire forest dynamics was proposed [27]. Estimations of the ecological effect of fires for different pyrological regimes should be necessarily taken into account in modeling the ecosystem processes, including predictions of the action of climate on ecosystems [28–30].

To clear up the dynamics of pyrological regimes, it is necessary to compile databases on the history of fires and their effect on ecosystems for spatial analysis. This problem is much more difficult than the problem of obtaining the data on the basis of point fire frequencies over time. Only integrated databases, that is, databases uniting the information on fire frequency over time and their propagation in space, may be used in the strategic planning of the dynamics of forest resources and in governing the pyrogenic factor. These databases will allow us to establish the links between fires, climate, morphological structure of landscapes, and land-use character on different temporal and spatial scales. The key problem in governing the pyrogenic factor is the necessity of periodic modification of the FCM because the amount, type and inflammability of those materials determine the intensity, scale and force of the action of fires on ecosystems. As the frequency and intensity of fires are inversely related to each other, the policy of their total suppression leads to an increase in the destructive force of the subsequent ecosystem action.

The quantitative estimation of the deviations of modern pyrological regimes from previous ones opens the possibility to estimate changes in ecosystems and to reveal the priorities in practical management of FCM. This management is possible on the basis of the concept

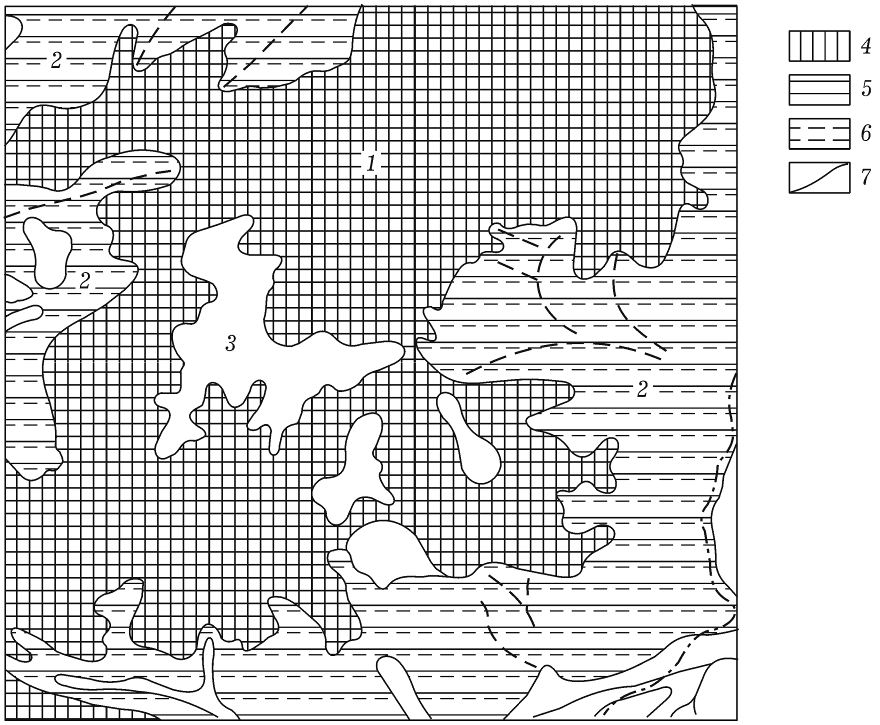

Fig. 2. A fragment of map of fire distribution within the tract “High drained pine-overgrown terrace with small oligotrophic bogs of closed sinks”. Stows: *1* — flat surface of high pine-grown terrace; *2* — stepwise differentiated terrace slope with pine and spruce; *3* — oligrotrophic bogs of sinkholes on high terraces. Areas of fires in the years: *4* — 1700, 1788, 1806, 1819, 1820, 1825, 1860, 1909, 1930, 1933, 1946, 1952; *5* — 1842, 1870, 1915, 1921; *6* — 1886; *7* — stow boundaries.

of the historical or natural range of variability of the structure of forest cover, biological diversity of ecosystems and plant species under the action of fires in the past. On the territories where the historic range of changes is not distorted spontaneous fires may be used as one of the versions of managing the FCM with the help of their mechanical treatment. The third group of regions is characterized by the possibility to get a maximal advantage in managing the FCM by combining spontaneous fires and prescribed burnings. The latter two versions of FCM management differ from the historic mode of managing but they are inevitable from the point of view of modern sustainable forestry and ecology. At present, deviations from the historic pyrological regime are estimated mainly from fire frequencies. However, when estimating substantial deviations in the context of ecological consequences, it is necessary to take into account the areas covered by fires, their spatial dynamics and force of action on ecosystems, measured as the disturbance of forests with fires, changes in the age structure of trees and post-fire changes in tree species [26, 31, 32].

The maps of pyrological regimes are efficient for the strategic management of the pyrological factor. They might be useful for revealing the trends of frequency and area of fires in the past and present predicting these parameters in the future. A comparative analysis of the trends when passing from one territory to another may give useful information on the relative contribution from land-use, climate, morphological structure of landscapes, as well as on their combined action. It also allows the relative action of land-use character and other anthropogenic factors to be inferred from the effects of climate and local growing conditions.

So, the pyrological regimes of landscape stows of the southern taiga in Central Siberia survived changes in different directions during the last three centuries. In some stows, fire frequency was stably increasing; in others, it was sometimes increasing and sometimes decreasing from one century to another. The most probable reasons of changes are, on the one hand, an increase in the amount of fire sources during the assimilation of the territory, and on the other hand, some adjustment of the pyrogenic load in the subzone of southern taiga of Central Siberia which started in the second half of the 20th century.

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