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I. S. MELEKHOV'S SCALE OF NATURAL FIRE DANGER OF FOREST ECOSYSTEMS: OVERVIEW OF MODERN RUSSIAN METHODOLOGICAL APPROACHES

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The article reviews various methodological approaches to assessing natural fire danger (NFD) and the creation, updating, and application of NFD maps, which modern domestic researchers develop. Herein we introduce and analyse the currently accepted natural fire danger assessment scale by I. S. Melekhov. As pointed out by modern researchers, the methodological drawbacks of the scale are listed. The paper reviews the development of a new methodological approach to the compilation of regional scales for assessing the natural fire danger of forests, considering the links between forest growth conditions and seasonal and climatic conditions in the regions of the Russian Federation. The methodology of mapping natural fire danger based on vegetation fuel maps proposed by a scientific group of Sukachev Forest Institute of SB RAS was studied. The works of the Mytishchi branch of Bauman Moscow State Technical University were reviewed to investigate the possibility of applying mathematical modelling methods for long-term forecasting of changes in NFD under different scenarios of forest management. The method of annual mapping of NFD classes, as proposed in CEPF RAS, is described. An example of NFD maps to assess the probability of forest fires in the Institute for Complex Analysis of the FEB RAS Regional Problems is considered. Future research areas are identified, namely, a cartographic representation of the created regional scales of NFD and the results of mathematical modelling of long-term changes in NFD.

Keywords: *natural fire danger, vegetation fuel maps, forest fires*

Fires are a crucial factor in the development of forest ecosystems. The probability of occurrence and further spread of a forest fire depends on the degree of fire danger. There are two types of fire danger in forests — natural and depending on weather conditions. In this paper, we focus on the natural fire danger (NFD) to study various methodological approaches to its assessment and the creation, updating, and application of NFD maps offered by modern domestic researchers.

In Russia, the natural fire danger of a forest district is assessed using the scale

of I. S. Melekhov (Melekhov et al., 2007). For forest fire protection services, the use of the NFD classification is regulated by Order of the Federal Forestry Agency No 287 dated 05 July 2011 "On approval of the classification of natural fire danger of forests and classification of fire danger in forests depending on weather conditions". Depending on the object of ignition (typical types of forests, logging areas, other categories of stands and treeless spaces), as well as the conditions for the occurrence and spread of fire, five classes of NFD are distinguished. The first class corresponds to the most fire-dangerous areas with the highest probability of fire occurrence and spread. In contrast, the fifth class corresponds to the areas with the least or no probability thereof.

Classification according to the classes of natural fire danger of forests is one of the critical tasks of monitoring fire danger in forests (Shur et al., 2020). Strategic and operational management of forest fire units implies the use of an NFD concept. Classes of natural fire hazard (CNFDs) as part of strategic management are necessary for planning forest fire prevention measures, a compilation of regional consolidated fire extinguishing plans and forest development projects, forest plans of the subjects of the Russian Federation, as well as forest management regulations of forestries and forest parks. Operational management includes the application of CNFDs in regulating fire monitoring and extinguishing by ground-based forest fire units.

CLASSIFICATION OF NATURAL FIRE DANGER

Let us take a look into the accepted classification of natural fire danger. The classification introduces the concept of a fire maximum, i.e. a period when the number of forest fires or the area covered by fire exceeds the average long-term values for a given area. Thus, Class I has a very high NFD, and ground and crown fires are possible during the entire fire season. Based on the object of ignition, this class includes young coniferous stands, lichen and heather pine forests, lichen, heather, reedgrass and other types of clear-cuts along dry valleys. Significant spring and autumn fire danger is reported on reedgrass and other herb types of logging areas along dry valleys. Besides, areas of selective logging of high and very high intensity, continuous logging sparing individual trees, as well as debris-strewn (cluttered) fire sites and disturbed, suppressed and severely damaged stands in the form of deadwood, areas of wind snaps and windthrows, residual stands are prone to ignition.

With a high NFD, which is typical of Class II, ground fires can occur during the entire fire season, whereas crown fires

occur during periods of fire maxima. The objects of ignition are cowberry pine forests, especially with pine undergrowth or juniper undergrowth above-average density, and larch forest with cedar elfin. Cedar forests with dense undergrowth or different ages with vertical canopy closure are also considered Class II forests. In areas with a medium NFD (Class III), ground and crown fires are possible during the summer fire maximum. This class includes the following types of forest: sorrel and bilberry pine forests, cowberry larch forests, cowberry and sorrel spruce forests, cedar forests of all types, except for streamside and sphagnum ones. It is reported that in cedar forests, fires can also occur during spring and autumn maxima.

In forests with low NFD (class IV), fires occur only during the summer maximum in all types of forests and haircap-moss logging areas. The exceptions are areas with herb forest types and meadowsweet logging areas, where ground fires may also occur during the spring and autumn fire maxima. The objects of ignition are pine forests, larch forests and forest stands of deciduous tree species in herb forest types. The classification details the objects of ignition: complex pine forests and spruce forests — linden, hazel, oak; bilberry spruce forests; sphagnum and haircap-moss pine forests; streamside and sphagnum cedar forests; cowberry, sorrel, bilberry and sphagnum birch forests; sorrel and bilberry aspen forests; larch peat moss bog forests. Class IV is also characterised by cluttered parts of solid meadowsweet and haircap-moss logging areas. With class V, there is no NFD — a fire is possible only with particularly unfavourable conditions in the form of a prolonged drought. This class includes sphagnum and streamside spruce forests, haircap-moss birch and aspen forests, and alder forests of all types.

The classification defines cases when a natural fire danger of a higher class is identified. Firstly, this is the case of coniferous forest stands, where the structure or other features contribute to the transition of ground fire to a crown fire. Such features may include a dense high undergrowth of coniferous tree species, vertical closure of the crown canopy of trees and shrubs, and significant cluttering. Secondly, for small forest plots on dry valleys surrounded by the forest stands with increased natural fire danger. Thirdly, for forest areas adjacent to railways and public roads.

It should be mentioned that the natural fire danger of a forest area can be controlled through forest fire prevention measures within the territory. It includes, among others, regulation of the stand composition, sanitary logging; prevention of forest cluttering; creation of a network of fire barriers and reservoirs, forest roads, and recreational areas (Chumachenko, Mayuk, 2012).

According to A. V. Sofronova's and A. V. Volokitina's (2017) work, the above scale was compiled by an expert method, which explains the lack of quantitative assessments of NFD classes. The scale reflects generalised natural fire danger, which takes into account readiness for ignition, seasonal duration of stay in a ready-to-ignite state, the possibility of crown fire occurrence, as well as the difficulty of extinguishing fires in cluttered areas. The authors highlighted such a drawback of the scale as the lack of characteristics of vegetation fuel (VF).

According to Yu. Z. Shur et al. (2020), the scale of I. S. Melekhov has several significant methodological shortcomings; for example, regional forest typology is not taken into account, the relationship between the periods of the fire season, predominant types of vegetation fuel and the most likely types of forest fires is not clearly defined. The scale offers no logically rigorous definition of the objects of ignition, and their CNFDs are not established. In addition, the categories of forest and non-forest lands are not fully described.

REGIONAL ASSESSMENT SCALES OF NATURAL FIRE DANGER

We will consider a new methodological approach to the compilation of regional scales for assessing the natural fire danger of forests, considering the interrelations between forest, seasonal and climatic conditions in the entities of the Russian Federation offered by the St. Petersburg Research Institute of Forestry (Shur et al., 2020). The authors introduce the concept of a "regional scale of assessment of natural fire danger of forests" to classify forest NFD for a Russian Federation entity. For each object of ignition and the period of the fire season, the prevailing types of vegetation fuels and the most likely types of forest fires are determined, e.g. running ground fire, independent ground fire, subsurface fire, crown fire. Thus, the approach makes it possible to predict the occurrence of forest fires of various types. It is proposed to consider fuels that make possible the occurrence of ground forest fires as predominant types of vegetation fuels. The proposed scale considers the categories of forest lands not covered by forest vegetation and non-forest lands in more detail.

According to the methodology, the main spatial unit for determining the CNFDs is the forest inventory allotment (Table, p. 8). However, it is possible to determine the weighted average CNFD for a forest block, district forestry, and forestry territory. The authors tested the new methodological approach in several entities of the Russian Federation, in particular the republics of Karelia, Adygea, North Ossetia-Alania; Primorsky and Krasnodar Krai; Tomsk, Rostov, Leningrad and Volgograd Oblast. Regional scales for

assessing the natural fire danger of forests were compiled based on schemes of forest types and forest growth conditions of the *Roslesinforg* Federal State Budgetary Institution.

The authors developed a regional scale for assessing NFD in the area of the Republic of Karelia, shown below. The objects of ignition for very high NFD (class I) are rocky and white moss pine forests, including incomplete stands; lichen logging areas; dead forest stands, except for fire sites, old fire sites, clearings, waste ground in rocky and white moss forest types (FTs); meadows, hayfields, dry alley pastures. The predominant types of VFs and the most likely types of forest fires are determined for the spring, summer and autumn periods of the fire season. For example, in the spring period, lichen-type VF and independent ground fires prevail in all the objects of ignition, except meadows, hayfields and pastures. The following objects of ignition are characteristic of high NFD (class II): heather and cowberry pine forests, including incomplete stands; heather logging areas; dead forest stands, except for fire sites, old fire sites, clearings, waste ground in heather and cowberry FTs. In heather pine forests, the heather or dwarf shrub type of VF prevails, as well as litterfall. In cowberry pine forests, a green moss type of VF or litterfall is predominant. Subsurface, running ground, and independent ground fires are seen in all objects of ignition during any period of the fire season.

MAPS OF NATURAL FIRE DANGER

Researchers from the V. N. Sukachev Institute of Forest SB RAS state that the most optimal form for the representation and use of the natural fire danger is in the form of maps (Abroskina et al., 2012). The Institute has developed a methodology for mapping natural fire danger based on maps of vegetation fuels (Volokitina, Sofronova, 2014). NFD mapping for long-term monitoring and the monitoring of the current NFD depending on the fire danger classes according to weather conditions is also an option.

According to the definition by N. P. Kurbatskii, vegetable fuels are plants and their residues of various degrees of decomposition that can burn during fires (Kurbatskii, 1970). VF maps are compiled based on their classification, which includes seven groups: prime conductors of burning; litterfall, humus and peat horizons; herb-dwarf shrub layers; large woody debris; a layer of shrubs and undergrowth; needles, foliage, bearing twigs and dry branches in tree crowns, tree trunks and branches (Volokitin, Sofronova, 2014). Only the prime conductors of burning in the ground cover of forest inventory allotments are displayed directly on a vegetation fuel map. Characteristics of all VF groups can be found in the pyrological description, which is attached to the map. The pyrological description can predict the spread and create an operational plan for extinguishing an active fire.

A prime conductor of burning (PCB) is a continuous layer of vegetation fuel on the soil surface, conducting flaming combustion under certain conditions (Volokitina, Sofronova, 2014). The layer includes small plant residues, including twigs up to 2 cm in diameter; mosses and lichens; vascular plants and their parts — stems of grasses and dwarf shrubs as well as small plants. The authors identify two subgroups of PCBs — «mossy», i. e. layers with a predominance of living fuel (mosses and lichens), and «litterfall» — layers with a predominance of dead fuel (fallen needles and foliage, dried herbs). The authors describe several possible ways to determine the type of PCB directly in the field, based on the inventory description of forest management materials, thematic maps of vegetation cover, and decrypting the Earth remote sensing data. In all methods, the identification guide of the PCB type by A. V. Volokitina is used (Red'kin, Volokitina, 2014). When using inventory descriptions of forest management materials, the type of PCB is established in accordance with the description of forest types, which includes a typical location on the relief; the name of the soil and its moisture regime; typical composition of the stand; bonitet; description of the undergrowth, herb-dwarf shrub layer, and moss-lichen cover; as well as the characteristics of forest regeneration.

If up-to-date forest management materials are lacking, high- and ultra-high-resolution satellite images can be used, as well as vector data of the hydrographic network and relief (Sofronova, Volokitina, 2017a). It is proposed to interpret the PCBs closed by the forest canopy by identifying pyrological categories of sites.

The spatial unit for assessing the natural fire danger based on maps of vegetation fuels is the inventory allotment (Table, p. 8). This assessment seems more accurate than methods using forest fire maps at the block level. Since the same forest area in spring, summer and autumn can have different types of PCBs, NFD mapping by periods of fire season is possible.

The method of mapping natural fire danger developed at the V. N. Sukachev Institute of Forest SB RAS was tested at the local level in the territories of the experimental farm Pogorelsky Bor, Yemelyanovsky Forestry, the Krasnoyarsk Krai (Abroskina et al., 2012) and the Yurubcheno-Tokhomskoye oil and gas condensate field (Sofronova, Volokitina, 2017b). In addition, maps of the natural fire danger of the Stolby, Sayano-Shushensky, Kuznetsky Alatau and Ubsunurskaya hollow reserves were created (Volokitina, 2017).

MODELING THE DYNAMICS OF NATURAL FIRE DANGER

The Mytishchi branch of the N. E. Bauman Moscow State Technical Univer-

sity (formerly Moscow State University of Forestry) is investigating the possibility of using mathematical modelling methods for long-term forecasting of changes in natural fire danger under different scenarios of forest management (Chumachenko, 2012; Chumachenko, Mayuk, 2012; Chumachenko, Mukhin, 2013). A conceptual, mathematical and simulation model of the dynamics of natural fire danger with a simulation step of 5 years has been developed.

S. I. Chumachenko and D. N. Mayuk (2012) identify factors that determine the natural fire danger — that is, land categories, age of stand, type of forest, predominant and admixed tree species, completeness of stands, the presence of fire-dangerous undergrowth and underbrush, as well as deadwood and cluttering, distance from public roads. The factors mentioned earlier are the main parameters of the natural fire danger dynamics model, and similar data can be found in inventory descriptions and plans of forest stand at the allotment level (Table, p. 8). Modelling includes a forecast of changes in the species and age composition of the allotment, the average taxation characteristics of the stand by layers, such as height, diameter, age, stock, etc. Due to the lack of a methodology for determining forest types when forecasting the dynamics of stands for a long period under different forest management scenarios, this parameter was replaced by the type of forest conditions.

UPDATING MAPS OF NATURAL FIRE DANGER

It is commonly known that the subjects of the Russian Federation are developing forest plans, i. e. a document defining the main directions of forest use and regeneration for the next ten years (Forest Code of the Russian Federation, 2006). A forest plan contains forest fire maps of forest districts, which usually provide information about the NFD class at the forest block level. During the ten-year interrevision period, the type of ground cover and woody vegetation changes under the influence of various destructive factors, e. g. fires, logging, and plagues. These changes render the NFD assessment irrelevant.

The Centre for Forest Ecology and Productivity RAS has proposed a method for updating CNFD maps annually (Plotnikova, Ershov, 2015). This method makes it possible to determine the class of natural fire danger through a comprehensive analysis of thematic satellite maps of vegetation cover, long-term data on fires and meteorological observations, and CNFD data from the forest plan of the entity Russian Federation. The method uses data from meteorological observations (average daily air temperature) to determine the time limits of the spring, summer and autumn periods of the fire season. Long-term fire data are used to determine fire maxima for each year under study based on the analysis of the

long-time average annual number of fires per day. Based on thematic satellite maps of vegetation cover, areas of vegetation classes within the boundaries of forest blocks are estimated (Table).

Evaluation of the method of updating CNFD maps was carried out on the territory of the Irkutsk Oblast. Long-term archives of fire data from 1987 to 2011 and meteorological observations from 2006 to 2011 were used. In the study of A. S. Plotnikova and D. V. Ershov (2015), a map of vegetation cover on the territory of Russia with a spatial resolution of 250 meters was used (Bartalev et al., 2011). Further research (Plotnikova, Ershov, 2016) was carried out using a vegetation map of the territory of the Irkutsk Oblast, which had been created based on high spatial resolution satellite data Landsat-TM\\ETM+.

Table. Key information about modern scientific research of NFD in Russia

Scientific group	Spatial level	Spatial unit	Initial data	Method
V. N. Sukachev Institute of Forest SB RAS	Local	Forest inventory allotment	Forest management materials, VF maps, high and ultra-high-resolution Earth remote sensing data, vector data of the hydrographic network and relief	NFD mapping based on VF maps
St. Petersburg Scientific Research Institute of Forestry	Regional	Forest inventory allotment, forest block, district forestry, forestry	Schemes of forest types and forest growth conditions of Roslesinforg FSBI	Compilation of regional scales for NFD evaluation
Mytishchi branch of N. E. Bauman MSTU	Local	Forest inventory allotment	Inventory descriptions, plans of forest stands	Mathematical modelling for long-term forecasting of changes in NFD under different scenarios of forest management
Centre for Forest Ecology and Productivity of the RAS	Regional	Forest block	Forest plan of the entity of the Russian Federation, forest fire maps, medium and high-resolution Earth remote sensing data, satellite thematic maps of vegetation cover, a long-term archive of data on fires and meteorological observations	Annual updating of CNFD maps

APPLICATION OF MAPS OF NATURAL FIRE DANGER

Maps of natural fire danger are used to assess the likelihood of forest fires. An example is the work of the Institute for Integrated Analysis of Regional Problems of the FEB RAS on the creation of a system for spatial forecasting of vegetation fires depending on weather and forest conditions in the south of the Russian Far East (Kogan, Glagolev, 2013). As the authors note, the possibility of fire occurrence depends on the processes of drying and moistening of vegetation, which determine its transition to a state of "fire maturity" (Kogan, Glagolev, 2015).

According to the method developed by R. M. Kogan and V. A. Glagolev, one of the values necessary to determine the probability of fires is the degree of natural pyrologic fire danger of vegetation in the spring/summer/autumn periods of the fire season. The authors use a scale (Starodumov, 1964; Telitsyn, 1988) that classifies vegetation on the territory of the Middle Amur region as one of five danger classes. A very high degree (class I) of natural pyrologic fire danger is typical of areas not covered with forest, open stands, logging areas with grass cover or reindeer lichen, as well as larch-spruce and spruce-larch mountain forests. As forests of high degree (class II) are classified broad-leaved-spruce cedar forests (northern cedar forests); small-leaved forests and sparse forests on mountain slopes; broad-leaved shrub forests on slopes; broad-leaved oak forests on eastern and western slopes. The moderate degree (class III) includes fir-spruce and spruce-fir forests with cedar, broad-leaved species (nemoral spruce forests), i. e. green moss; dwarf shrub-small herbs-green moss; forests of the middle mountain belt, as well as aspen and mixed forests on northern slopes. Moderate degree (class IV) is typical of dwarf shrub-moss larch forests with dwarf birch and sparse forests of intermountain valleys. Low degree (class V) includes sedge-sphagnum larch forests, sphagnum bog spruce forests and constantly moistened sphagnum swamps.

In the work of R. M. Kogan and V. A. Glagolev (2015 a), a description of the forest fund of the Far Eastern Federal District is given based on natural fire danger. Due to the region's climatic, forest growth, and geomorphological features, the forest fund has high fire danger and frequency of fire occurrence. The natural fire danger of the forests of the Khabarovsk Krai and the Jewish Autonomous Oblast is one of the highest in Russia: the area of plant formations with classes I–III is more than 80% and 44% of the entity territory, respectively.

CONCLUSION

The performed review showed the current state of domestic scientific re-

search on natural fire danger. Various scientific groups agree that the currently accepted scale of NFD assessment has several methodological drawbacks, such as the lack of characteristics of vegetation fuels and the relationship between the periods of the fire season, etc. To improve the assessment of natural fire danger, researchers are developing new methodological approaches, e. g. compile regional scales for assessing forest NFD, considering the relationship of forest growth, seasonal and climatic conditions in the entities of the Russian Federation, as well as create NFD maps based on vegetation fuel maps.

One of the modern lines of research of natural fire danger is mathematical modelling methods for long-term forecasting of changes in NFD under different forest management scenarios. The researchers also highlight the need for annual updating of information about the classes of NFD stated on forest fire maps in the forest plans of the entities of the Russian Federation.

The created scales and maps of NFD are used for tackling not only production tasks of strategic and operational management of forest fire formations but also scientific issues. In particular, the use of NFD maps allows increasing the accuracy of assessment of the probability of forest fires.

As noted above, maps are the most optimal representation and natural fire danger information. Therefore, the cartographic representation of the created regional NFD scales and the results of mathematical modelling of long-term NFD changes seems to be a promising line of research. One of the possible ways to improve the updating of the NFD maps is the transition to a more detailed spatial unit, which is the forest inventory allotment.

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