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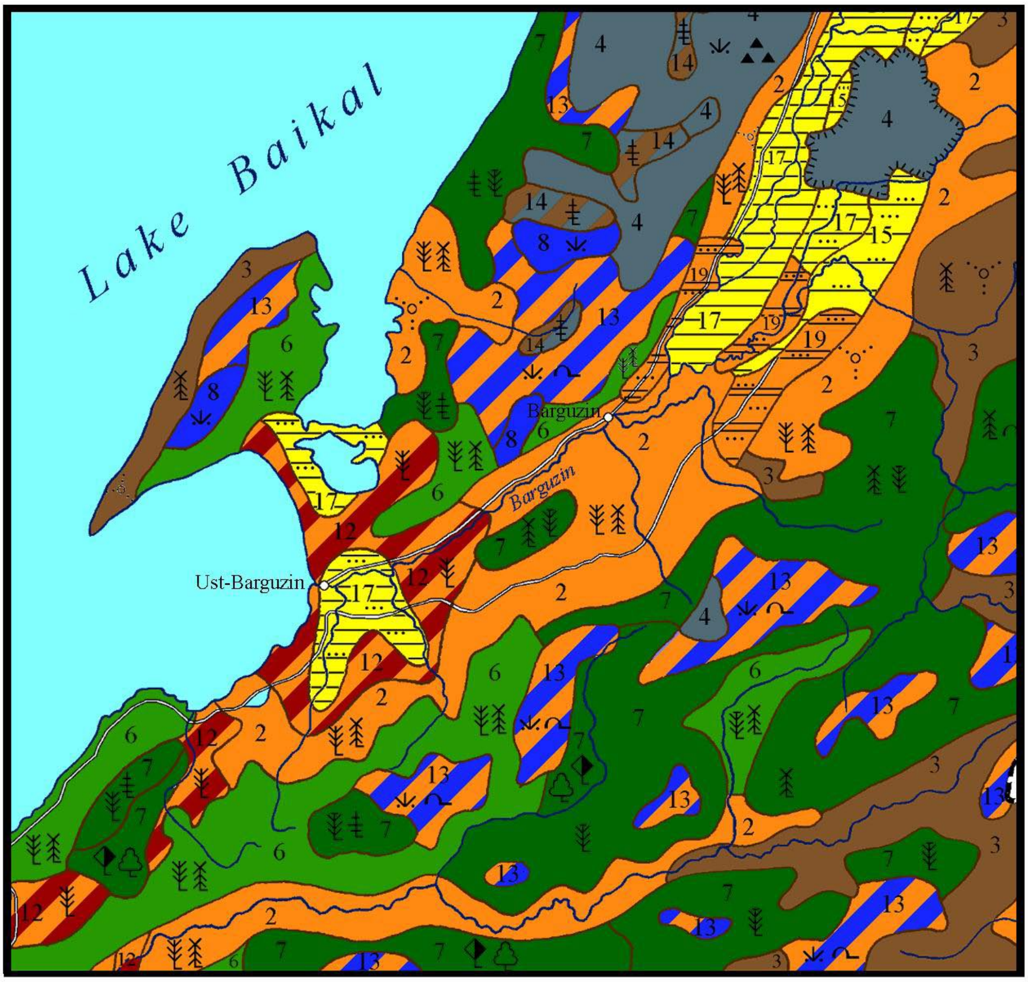

VEGETATION FUEL CLASSIFICATION AND MAPPING

International Strategy
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VEGETATION FUEL

CLASSIFICATION AND MAPPING

(Short variant of the monograph)

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This is a short English variant of the monograph "**Vegetation Fuel Classification and Mapping" (**Authors: A.V.Volokitina, M. A. Sofronov), published in Russian (Novosibirsk: SB RAS Publishing House, 2002. - 314p).

The monograph considers problems of vegetation fuel (VF) mapping. VF mapping is indispensable for the creation of the information database in the Russian system of forests and for forecasting other vegetation fires' behavior and consequences. The volume contains the scientific fundamentals of VF mapping as well as methods and techniques of VF mapping at different scales (including computer technologies together with forest inventory data).

The volume is a contribution to the Interagency Task Force Working Group on Wildland Fire of the UN International Strategy for Disaster Reduction (ISDR) and the Global Fire Monitoring Center (GFMC).

Translation was made by a post-graduate student Tatiana M. Sofronova

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Preface

The role of natural and human-caused wildfires in forest, steppe, savanna, bush and swamp ecosystems (*vegetation fires* or *wildland fires*) is significant and diverse. First of all, wildfires represent a periodically active ecological factor that often increases biodiversity. However, wildfires have an increasingly negative impact on humans and economies. Destruction of forest and agricultural resources, infrastructures and houses often result in considerable economic losses. Smoke generated by vegetation fires often affects public health by causing increased morbidity and mortality. As a consequence of climate change an increasing occurrence of climate extremes, including extreme droughts associated with increased fire occurrence and area burned, have been observed in various parts of the world. The expected combined impacts of land-use change and climate variability on fire regimes and fire severity, as well as the increasing vulnerability of human populations to the impact of wildfires, make appropriate wildland fire policies, planning and management highly topical. In the remote areas of Eurasia's boreal forests technological solutions are restricted in economic terms. The point is that wildfires are very unevenly distributed in time and space. Moreover, the major part of wildfires occurs on territories not accessible for terrestrial transport.

Given the lack of technological and financial means, successful wildfire management is possible only by making use of wildfire behavior modeling or forecasting. For this forecasting it is necessary to have information on the distribution of vegetation fuel (VF) complexes over the territory including information on the different VF species susceptible to fire. In other words, for wildfire behavior forecasting it is indispensable to have, first of all, VF maps.

This monograph aims at VF mapping which is a new trend in the pyrological science. In the monograph, data from Russian and foreign research and long-term elaborations of the authors of the monograph on the given topic (including development of VF classification and elaboration of an efficient technology for the creation of VF maps) are systematically evaluated, analyzed, and synthesized.

In VF classification, a dynamic role of VF groups and types as complexes in burning is taken into account. VF complexes are considered integral with the environment of biogeocoenoses, which influences pyrological properties and characteristics of VF.

The authors' concept of seasonal mutual transformation of VF types (within groups) is used to simplify the VF classification.

In the presented methods of VF mapping, main attention is given to the idea of simplification, reduction of expenses, and automation of the processes for VF map creation.

Questions of practical usage of VF maps for fire danger rating, for optimal aerial patrol, and for fire behavior forecast in the process of fire management are considered.

Brief contents of the monograph

The **"Introduction"** provides definitions of the necessary ideas, the general task (all-round pyrological characteristics of vegetation plots for the forecast of fire behavior and fire consequences) and its contribution, and appropriate proposals for solving ecological and economic problems of wildfires by using VF maps.

In Chapter 1 "VF classification", currently used VF classifications are analyzed at the beginning. Furthermore a developed variant of N.P. Kurbatsky's classification is given (choice of classification indications, description of VF types in groups); there is also a determiner for types of prime conductors of burning.

In Chapter 2 "Transformation of factors of VF moistening and drying in forest biogeocoenoses", the original methods and results of research of regularities of precipitation distribution over the surface floor under the forest canopy, and the results of estimation of relative quantity of radiant energy absorbed by the surface vegetation fuels under the canopy of different tree stands are given.

In Chapter 3 "Layer-after-layer VF moistening and drying on the soil", results of research of regularities of layer-after-layer moistening and drying of the prime conductors of burning from the surface floor are shown.

In Chapter 4 "VF burning in natural conditions", a problem of the choice of a minimum quantity of characteristics necessary for surface fire behavior forecast is considered. Results of research of these characteristics (and their dynamics in connection with the level of drought) according to types of prime conductors of burning are included.

In Chapter 5 "Large-scale VF mapping", a problem of determining all-round individual pyrological characteristic of vegetation plots is solved by means of creation of large-scale VF maps as a set including: 1) a map; 2) all-round pyrological description of units on the map; 3) tables with characteristics of VF types. There is a technique and technology of creation of large-scale VF maps making use of forest inventory data including a computerized version. Results of this technique's testing in different regions are given.

In Chapter 6 "Fire behavior and consequences forecasting by making use of large-scale VF maps", there is a method on surface fire spread and intensity forecasting with the use of large-scale VF maps and M. A. Sofronov's model described. There is also a way of post-fire mortality forecasting in tree stands as a result of a predicted fire.

In Chapter 7 "Medium-scale VF mapping", two methods of medium-scale VF mapping are considered, namely: "autonomous" and "conjugated" (assessed). There are examples of medium-scale VF maps for the Angaro-Yeniseisky region and the Baikal Lake basin. The use of medium-scale VF maps for choosing optimal air patrol routes is described.

In the **"Conclusion"**, results of the work are summarized and thoughts offered for further development of this topic in theory and in practice.

The authors are indebted to the Max-Planck-Gesellschaft zur Foerderung der Wissenschaften e.V., the Biogeochemistry Department, Max Planck Institute for Chemistry, Mainz, Germany, the Global Fire Monitoring Center (GFMC), and the Working Group on Wildland Fire of the ISDR Inter-Agency Task Force for Disaster Reduction for financial support in publication of the monograph.

The authors give their particular acknowledgements to Johann G. Goldammer, Head of the GFMC and the UN Working Group on Wildland Fire, for his support to produce the book volume; to Diane Quaid, collaborator of the Woods Hole Research Center (US), for improvement of the short monograph version translation.

INTRODUCTION

The problem of wood, shrub, steppe and other vegetation fires is great in Russia as well as all over the world. Wildfires annually exterminate and damage vegetation over large areas. In Russia, the annual post-fire area varies, according to different authors, from 2 up to 12 million hectares. Quite often fires become of disastrous size and exterminate not only vegetation, but also inhabited localities. To fight such fires, a lot of people and technical equipment are engaged and very large means are expended; however, the efficiency of these measures is usually low. The world experience convinces us that the solution of the problem of vegetation fires at the expense of improving and increasing technical power is unrealistic.

There is another way to solve this problem - to develop and improve *a system of fire behavior and fire consequences forecasting*. With the help of such a forecast it is possible to reveal potentially dangerous fires among arising ones and to extinguish them specifically at an early stage and at small expense. Also it is possible to detect those fires, which will not cause considerable damage - or will be even useful for forestry – and thus allow sparing the manpower and means of fighting them. Lastly, behaviour forecasting of large and disastrous fires can be useful to plan measures on their effective control. In addition, when selecting optimum terms for prescribed burning, it is also necessary to forecast probable distribution and intensity of combustion and its consequences during different weather conditions.

A system on fire behavior forecasting (BEHAVE) has been developed for a long time in the USA. A similar system (FBP) has been elaborated since 1984 in Canada. *In Russia, there is no such a system yet*. Russia needs *its own* national system of fire behaviour forecasting created on the basis of analysis and generalization of home investigations on fire nature, and taking into account the experience of the development of such systems abroad. Foreign practice has shown that for accurate forecasting it is necessary to use not *standard* (simplified) but detailed (i.e. *individual*) characteristics revealing peculiarities of each plot.

It should be noted that it is impossible to make a correct forecast without an appropriate **information database** including information on pyrological characteristics of vegetation as an object of combustion and as an object of combustion impact as well as on dynamics of these characteristics at different scales in time and space.

Pyrological characteristics of vegetation should be shown in plans and maps for practical application. Maps can represent both general one-sided assessment and characteristic of plots (e.g. assessment of their fire hazard) and detailed many-sided characteristics of all constituents in vegetation fuel complexes. Maps are considered to be *basal* for detailed characteristics to obtain various pyrological assessments. Such maps should be called **vegetation fuel maps (VF maps)**.

This monograph deals with the elaboration of a scientific VF mapping base for the creation of an information database on fire behaviour and fire consequences forecast. The main tasks were the following:

1) improvement of VF classification on the basis of obtaining, generalization and analysis of the information about vegetation fuel;

2) investigation of pyrological characteristics, including moistening, drying and burning regimes of VF for fire behaviour forecast;

3) elaboration of methods of VF mapping at different scales, and also usage of the created maps for fire behaviour forecasting (including computer technologies by making use of forest inventory data).

Our investigations were carried out in the European North, in the eastern part of the Baikal Lake basin, in the Novosibirsk region, in the Krasnoyarsk Priangarie, and Evenkia. Much of the research was conducted using original methods.

VF mapping for fire behavior forecasting is virtually a new scientific trend in pyrological science, therefore a wide range of problems are touched upon in this volume including theoretical (VF classification), experimental (study of moistening, drying, and burning processes of VF), methodical (methods of VF mapping), and practical ones (technology of VF maps creation and their application). A literature survey on each problem and description of research methods and techniques are given in corresponding chapters.

Chapter 1. **CLASSIFICATION OF VEGETATION FUELS (VF)**

The term "vegetation fuel (VF)" (American analogues: "wildland fuel", "vegetation fuel", and simply "fuel") was offered by E.V.Konev (1977), instead of the term "forest fuel ", since wildfires spread not only in the forest, but also in steppe, bog, tundra and other communities of vegetation.

In VF classification it is possible to consider three levels: a) classification of elementary parts of VF complexes, including separate plants of surface cover and undergrowth, small bushes, morphological parts of trees, wood remnants on the soil, etc.; b) classification of simple VF complexes (layers) inside biogeocoenoses (vegetation plots); c) classification of biogeocoenoses as composite VF complexes.

C*lassification of elementary parts of VF complexes* does not concern small-sized particles, which are always considered in the aggregate, in the mode of layers (for example, particles of litter, peat, etc.).

In the American fire danger rating system (NFDRS), elementary VF are subdivided into two categories: dead and live. Dead VF are divided into classes: 1) light fuel; 2) medium fuel; 3) heavy fuel, and 4) very heavy fuel - depending on the value of their time lag of drying rate. Live VF are divided into two classes: 1) grass; 2) needles, leafage, and branches (up to 6 mm). Died off and growing grasses often form a mixture of fuel -"fine fuel". This class plays an important role in " fuel models ".

Classification of VF layers. In the NFDRS, surface VF layers are classified according to time lag as well. A high layer of litter up to 6 mm thick is referred to the 1st class (1-hour time lag fuel); a layer of litter (duff) at the depth from 6 up to 25 mm – to the 2nd class (10-hour time lag fuel); a layer of duff at the depth from 25 up to 100 mm - to the 3d class (100-hour time lag fuel); layers of duff, peat, and humus at the depth from 100 up to 300 mm - to the 4th class (1000-hour time lag fuel).

When dividing all VF layers into groups, N.P.Kurbatsky in his classification (1962, 1970) took into account not only their location in the biogeocoenosis, but also their function in the fire. He distinguished seven VF groups.

M.A.Sheshukov (1988, 1973) offered "genetic" classification for the Far East composed of eight "types of forest fuels ".

Classification of biogeocoenoses (vegetation plots) as composite VF complexes. In Russia, I.S.Melekhov's scale (1947), supplemented by I.V.Ovsyannikov (1978), with division of plots into five classes "according to the degree of fire danger occurrence on them " is used for fire-prevention arrangement.

At the present time in the USA, the following things are defined: a set of 20 "fuel models" for the NFDRS and a set of 13 "fuel models" for the system of fire behaviour forecast "BEHAVE" (among which only three "models" are forest ones). Canada has its own system (FBP) of 16 standard VF complexes ("fuel types").

Analysis and generalization of the information on VF characteristics. Forest types specialists found and described hundreds of forest types in forests of different geographic regions. It is apparent that it is virtually impossible to study separately each forest type or each category of non-forest plots in pyrological terms. It's necessary to classify them and, first of all, to divide surface cover into a number of pyrological types.

When elaborating theoretical fundamentals of classification, we took into consideration information on physical properties and heating value of VF types (Amosov, 1958; Kurbatsky, 1970; Telitsin, Sosnovshchenko, 1970; Sheshukov, 1970; Konev, 1977, et. al.) and analyzed observation results of "fire maturing" on different plots and of moisture content dynamics of their surface covers in different regions (Kurbatsky, 1957 ; Sofronov, 1967, 1970; Furyaev, 1970; Musin, 1973; Vonsky, et. al, 1975; Baranov, 1976; Evdokimenko, 1977; Kostirina, 1978; Yakovlev, 1979; Lvov and Orlov, 1984, et. al). All this was combined with the materials of our research on the rate of surface floor drying out and analyzed. This contributed to development and improvement of VF classification.

Development of VF classification. The role of different VF (to be more exact, VF complexes) in combustion of vegetation plots is various and dynamic, as the actual heat emission by different VF depends on their moisture content, the structure of a layer, their location in a biogeocoenosis, the conditions and character of burning, etc. N.P.Kurbatsky (1970) divided VF into four categories: *1) conductors of burning, 2) VF keeping up combustion; 3) VF keeping back combustion; 4) VF not keeping up combustion (passively burning).*

One of the main properties of conductors of burning is *continuity of a layer*. During surface fires, conductors of burning are layers of moss, lichen, litter, cured grass or their mixtures. We call them prime conductors of burning (PCB).

In the VF classification, we are developing N.P.Kurbatsky's ideas (1962, 1970). All VF are divided by N.P.Kurbatsky into seven groups. VF of each group in different biogeocoenoses can have essential differences in their pyrological characteristic. Consequently, further development of classification was required, namely, division within VF groups into single-type complexes, i.e. VF types. Demand for detailed VF classification appeared in connection with the development of VF mapping as indispensable for fire behavior forecasting and estimation of fire hazard.

In VF classification, criteria connected with their main function – burning (i.e. with the capability to burn under different conditions, with the character of burning, and the role of VF in the process of biogeocoenoses combustion) – should be used as basic ones. In practice, VF are normally determined when they do not burn, therefore, criteria bound with burning cannot serve as distinguishing ones and cannot be used for determination to which taxonomic unit a given object should be relegated to. As distinguishing criteria we used visual external characteristics connected with factors of burning.

Classification of prime conductors of burning. At first we elaborated classification of the first group of VF – prime conductors of burning (PCB). We subdivided this group into two subgroups: 1) *mossy PCB group*, which includes layers of living fuels (moss, lichen) and 2) *litter PCB group*, which includes dead fine fuels (litter of needles, dead leaves, grasses, bark and branches). Each subgroup is divided into types.

In PCB division into types, the following criterion was used: PCB layers, which become flammable under one class of drought, were referred to one type (within the limits of a subgroup) on condition that drying out takes place under the following standard environment conditions: on a horizontal surface, under coniferous or deciduous canopy of a forest stand with medium canopy closure (0.5-0.7). If actual drying conditions do not correspond to those mentioned above, i.e. they are non-standard, proper adjustment should be introduced.

Litter PCB types may change their rate of drying due to such seasonal factors as decomposition of dead fuels, growth of fresh biomass of grass in summer and its fading in autumn. So, PCB types of this subgroup can transform from one into another during a fire season as indicated by arrows in the scheme below. The scheme shows the idea of PCB classification:

Mossy PCB subgroup:	Lc (lichen)	Dm (dry moss)	Mm (moist moss)	Bm1 (bog moss)	Bm2
Litter PCB subgroup:	Cg ⟷ (cured grass)	Ll ⟷ (loose litter)	Cl ⟷ (compact litter)	Nc1 (non conductor)	Nc2
Critical class of drought (CCD):	I	II	III	IV	Cannot burn

Note. The critical class of drought (CCD) for a PCB fuel type is a drought class under which the PCB fuel class becomes flammable. We determine a drought class based on Nesterov's index (Nesterov et al., 1968).

A detailed description of PCB types is given in Table 1.1.

Types of prime conductors of burning (PCB)

Table 1.1

PCB types (and subtypes)	**Typical areas, their attributes**	**Non-typical areas, their attributes**	**CCD**
1	**2**	**3**	**4**
Mossy PCB Subgroup			
Lichen (Lc)	1. Lichens predominate in the forest floor 2. Lichens are present in the forest floor on dry soil	Very dry, including rock outcrops, with litter of pine needles	I
Dry moss (Dm)	Forest floor is predominated by green mosses, somewhere with lichens, on drained soil in boreal and northern forests (green-moss and red whortleberry - green-moss forest types)		II
Moist moss (Mm)	Forest floor is predominated by green mosses usually with *Sphagnum* and *Polytrichum*, on insufficiently drained soil (forest types - mossy, *Aulacomnium*, moist billberry and similar)	In southern taiga on drained soil, the forest floor may be predominated by green mosses. Thin cover (up to 3 cm) of compact moss	III
Bog-moss (Bm)	Ground cover is predominated by *Sphagnum* and *Hypnum* moss species, on boggy and bog soils (without notable presence of sedge or grass)		
Subtype Bm1	Boggy forests and small bogs amidst drained plains, with peat layer up to 0.7 m thick	Ground cover is predominated by *Polytrichum*	IV
Subtype Bm2	Large bogs and bog systems		cannot burn
Litter PCB Subgroup			
Cured grass (Cg)	Forest floor is predominated by dry grass or sedge (i.e. naturally cured plants), usually in fall and spring. Not included are sedge forest types with ground cover of evergreen sedge	Bogs and swamps of sedge-sphagnum and sedge-hypnum types, with well-developed cover of sedge in spring and fall (in summer - Bm)	I

Table 1.1

1	2	3	4
Loose litter (Ll)	1. Forest floor is predominated by herbs - in spring and fall. 2. Forest floor is predominated by litter of birch and aspen fallen leaves 3. Forest floor is predominated by litter of pine and cedar fallen needles	1.Forest floor is predominated by evergreen sedge - in spring and fall 2.Matted litter of dry sedge or grass	II
Compact litter (Cl)	1. Forest floor is predominated by compact litter of fallen needles of fir, spruce or larch – in all seasons 2. Forest floor is predominated by compact litter of fallen leaves of birch or aspen, and by matted dry herbs in summer		III
Non-conductor (Nc)	Surface fuel cover too scarce for fire to spread		
Subtype **Nc1**	Fuels not providing spread of surface fire: duff, humus, turf; usually in summer. Ground fires are possible.	Live grass load exceeds PCB load in summer, so spread of surface fire is impossible	IV
Subtype **Nc2**	Absence or very scarce presence of any PCB; sands, pebble, rock outcrops, plowed fields, roads, etc.		cannot burn

Comments: *Critical drought class (CDC) is a class of drought where burning of a particular PCB becomes possible under “standard” environment conditions.

Drought class is rated according to the fire drought index (or Nesterov’s index, or the LenNIILH PV-1 index), conventional units: I DC - up to 300 units, II DC - 301-1000 units, III DC - 1001-3000 units, IV D‘ - 3001-10,000 units, V DC - over 10,000 units of the fire drought index.

** PCB for the litter subgroup is determined separately for summer and separately for spring and autumn.

General classification of vegetation fuels. In Table 1.2 a general scheme of VF classification is given. It is almost completed for the first group of VF, i.e. for prime conductors of burning. Classification for other groups of VF requires amplification in the course of future study of their pyrological characteristics. Besides, it is possible to unite biogeocoenoses into typical regional complexes with similar combinations of VF types from different groups (for more convenient identification of VF in the airborne images).

Vegetation fuel load. VF load is investigated by N.P.Kurbatsky's method (1954, 1962, 1970). Summary data are available in his paper (1970) and in E.V.Konev's monograph (1977). Information on VF load can be used in calculations on the condition that it is known what part of the load every VF group has in the burning of the biogeocoenosis under different conditions (drought, weather, phenological state) and what its role is. Burning VF load and its dynamics were poorly studied in connection with phenological and weather factors.

The general characteristics of load according to VF group is considered. It is noted that VF mapping cannot be reduced to mapping of VF load only. VF mapping is the creation of an information database with various characteristics of plots.

Chapter 2. **TRANSFORMATION OF FACTORS OF VEGETATION FUEL MOISTENING AND DRYING IN FOREST BIOGEOCOENOSES**

The main factor of surface VF moistening is rain precipitation, and the main factor of VF drying is radiant energy (i.e. a part of solar radiation). In the literature there are no information data on the distribution of rain precipitation under forest canopy. The influence of rain precipitation on moisture content of surface cover and duff is studied in the Leningrad Scientific Research Institute of Forestry (Vonsky et al., 1972, 1974, 1975, 1976).

Distribution of rain precipitation on the forest surface cover is not even. To evaluate the influence of rain precipitation on fire occurrence, fire spread and possible fire consequences, the regularities of rain precipitation distribution depending on such factors as type of stand and wind were investigated. For this purpose a large number of simple rain-gauges were placed at every experimental site. The diameter of the rain-gauges was 11 cm. We placed rain-gauges along straight lines as well as along broken lines from stem to stem. Crown projections were mapped for each experimental site.

Classification of Vegetation Fuels (VF).

Table 1.2

VF group	VF subgroup	VF type (and subtype)	Character of burning*
I. Cover of moss or lichen, fine litter (PCB)**	Mosses	Lichen (Lc)	Fl
		Dry moss (Dm)	Fl
		Moist moss (Mm)	Fl and Sm
		Bog moss (Bm)	
		subtype Bm (1)	Fl
		subtype Bm (2)	Wn
	Litter	Cured grass (Cg)	Fl
		Loose litter (Ll)	Fl
		Compact litter (Cl)	Fl and Sm
		«Non- conductor» (Nc)	
		subtype Nc (1)	Sm
		subtype Nc (2)	Wn
II. Duff, humus and peat layers of soil	Duff	Rough humus	Sm
	Peat and humus	Mull	Sm
		Turf	Sm
		Peat horizon	Sm
III. Layer of herbs and low brush (at coverage ratio 0.5 m or more)	Low brush	*Vaccinium vitis-idaea* (Vv)	Fl
		Arctostaphylos uva-ursi (Au)	Pd
		Swamp-shrub (Bs)	Fl and Pd
		And other types	
	Herb (green)	Grass (Gr)	Pd
		Sedge (Se)	Pd
		«Winter» sedge (Ss)	Fl
		Mixed herb (Mh)	Pd
		And other types	
IV. Large wood remnants (dead branches, snags, limbwood, slash)	Dead-standing and downed trees	Dead-standing trees	Sc, Sm
		Hanging limbwood	Sc
		Downed limbwood	Sc
	Slash	Coniferous foliage-covered slash	Fl
		Foliageless slash	Pd
V. Layer of young growth and shrubs	Coniferous	-	Fl
	Broad-leaved		Pd and Fl
VI. Green foliage, foliage-covered twigs, and dead limbs of live trees.	Coniferous	Crowns of young tree stands and dwarf Siberian pine thickets	Fl
		Crowns of spruce and fir stands	Fl
		Crowns of pine and larch stands	Fl
	Broad-leaved	Crowns of broadleaves stands	Pd
VII. Trunks of live trees, branches thicker than 7 mm		Healthy trunks	Sc
		Resinous trunks	Fl, Sc
		Rotten or hollow trunks	Sc, Sm

Notes: *Character of burning: Fl - burning with flame, Sm - smoldering, Sc - surface charring, Pd – passive thermal decomposition, Wn - would not burn.
**The first group of VF (PCB) - plays the leading role in fire incidence and spread.

The investigations were conducted from 1972 to 1979 and from 1994 to 1995 in different regions of Russia. 20 experimental sites were chosen in pine, spruce, larch, cembretum (*Pinus sibirica*), fir and birch stands. The distribution of 140 rainfall events under the canopy of different stands was measured for 10 field seasons.

It was established that in taiga forests the irregularity of rain distribution (RP) is the highest in spruce and fir stands, and the coefficient of fluctuations (C) there reaches 50-70% of the average quantity of precipitation penetrated through the canopy; in pine, larch and birch stands rain precipitation is distributed more evenly and its fluctuations do not exceed 10-20% in comparison with the average quantity of precipitation that penetrated through the stands' canopy. Fluctuation of precipitation under the canopy of stand increases in absolute terms when precipitation quantity increases (mm), and decreases in percentage terms (%).

In spruce and fir stands the character of throughfall distribution along the lines of rain-gauges is identical and does not depend on the quantity of precipitation or wind direction (the coefficient of correlation equals to 0.7-0.9), i.e. the location of "dry" and "moist" plots has a statical character despite the wind. The influence of wind increases when the canopy is more open. Cembretum and spruce stands are alike in this respect: even at different wind directions the coefficient of correlation is 0.6-0.7. In birch stands, the influence of wind is weak as well.

In pine and larch stands, the location of "dry" and "moist" plots has a dynamic character: it changes when the wind direction changes (the coefficient of correlation equals to 0.3-0.6). Tree crowns located on the windward side at a distance of 5-10 m from the line of rain-gauges influenced RP distribution in pine stands when the wind speed above the forest was 2-6 m/s. When the wind speed decreases to 1 m/s, the tree crowns located at a distance of 1-3m from the rain-gauges line was influenced most of all.

To reveal more clearly the regularities in RP distribution under the canopy of different stands, we distinguish the following zones of a forest plot: 1) zones between crown projections, 2) zones 0.2 m wide under the edge of crown projections, 3) zones under the middle parts of crown projections, 4) zones 0,2 m wide around the stem of each tree.

In pine and larch stands, stem zones receive enough RP – only 1.1-1.3 times less than the zones between crowns. In birch stands, RP distribution is even all over the surface cover. In cembretum, moistening of stem zones is weaker especially on the leeward side of trees.

In spruce stands, stem zones are only slightly moistened: under rain precipitation of 15mm and less the stem zone receives 4-6 times less precipitation than zones between crowns. This can result in serious damage of roots and tree mortality even when fire is not intensive.

Zones between crown projections and zones under the edges of crown projections occupy in total 60-70% of all area in stands of medium canopy closure; therefore, moisture content of VF on such plots predetermines the possibility of forest fire spread. The quantity of rain falling on these zones constitutes about 80-90% of the RP falling above the forest.

Thus, the interception of RP by the canopy of stands virtually does not influence conditions of fire occurrence due to the specific character of RP distribution on surface cover.

As a result, three typical models of RP distribution under forest canopies have been observed: 1) uneven distribution of throughfall with constant location of dry plots close to the foot of trees – this is characteristic of spruce and fir stands in taiga; 2) uneven distribution of throughfall depending on the wind direction that is characteristic of pine and larch stands in taiga; 3) relatively even throughfall distribution which is characteristic of northern Siberian larch stands with an open canopy.

Radiant energy. To investigate radiant energy as a factor of drying, its penetration under the canopy of forest, and absorption by surface VF, the calorimetric method (on the basis of temperature difference between accepting surface and environment) elaborated by M.A.Sofronov (1970) was used. As an accepting surface a standard birch veneer sheet was used to eliminate a problem with albedo. Relative quantity of radiant energy (in comparison with an open place) on sunny days was measured. Investigations were carried out from 1968 till 1995 in regions from 51° to 67° N in different stands on 36 experimental sites. As a result of generalization, the following conclusion was made: relative quantity of radiant energy absorbed by surface VF under forest canopy is directly proportional to the average sine of sun height during the day and is in good correlation with the relative density of forest in summer and does not depend on wood species (with the exception of larch stands growing on permafrost soils; these stands at any density have sparse canopy and allow 1.5-3 times more radiant energy to penetrate than typical taiga stands).

As a result of the study of VF moistening and drying factors, some amendments for the assessment of fire danger depending on phenological period and stand density were obtained; these amendments were taken into account when creating tables of critical classes of drought, which allow evaluation of the state of current nature fire danger of vegetation plots (table 2.1).

Assessment of Natural Fire Danger of Vegetation Areas

Table 2.1

PCB subgroups		Prevailing tree species				Treeless
moss	litter	pine, spruce, Siberian pine, larch, birch, aspen, fir - with foliage			larch, birch, aspen - without foliage	areas without a thick layer of shrubs
Types and subtypes of prime conductors of burning (PCB)		Relative basal area per hectare (including the second storey)				
		≥ 0.8	0.5 - 0.7[1]	≤ 0.4[2]	any	
		Critical classes of drought				
Lc	Cg	II	I	I	I	I
Dm	Ll	III	II	I	I	I
Mm	Cl	IV	III	III	III	III
Bm_1	Nc_1	V	IV (Nc_1-V)	IV (Nc_1-V)	IV (Nc_1-V)	IV (Nc_1-V)
Bm_2	Nc_2	Would not burn				

Notes: [1] for larch stands of the northern open forest zone ≥0.6;
[2] for larch stands of the northern open forest zone ≤0.5

Chapter 3. **LAYER-AFTER-LAYER VEGETATION FUEL MOISTENING AND DRYING ON THE SOIL**

It is known that moss, lichen, fine litter (i.e. prime conductors of burning) and duff can become moist due to rain precipitation and the capillary raising of soil water. Besides, due to their hygroscopic properties they can absorb water from air but this process is observed only after their drying until they reach equilibrium moisture; this has a reversible character.

According to our investigations, moistening by means of the capillary raising of soil water is practically absent in PCB of cured grass (**Cg**) and lichen (**Lc**) types; they can dry up to a flammable state on the wet duff, as can cured grass – even above water. However, the moisture of the substratum produces a great impact on the moisture regime of the compact litter (**Cl**) type.

PCB of the bog-moss type (**Bm**) absorb capillary water very actively because sphagnum is highly porous (up to 97%). Drying of moss cover occurs after subsoil waters recede by 25 cm.

Mosses of genus *Polytrichum* can also keep their high moisture content due to available water-transmitting elements.

Surface cover of green mosses (dry moss and moist moss) has a more loose layer structure and less porosity (95%) which hampers capillary raising of soil water (the same with loose litter PCB).

RP distribution under the forest canopy plays a decisive role in the moistening of lichen, dry moss, moist moss, and loose litter PCB. For example, the coefficient of correlation between rain precipitation and moisture content of moss cover is equal to 0.6-0.9.

When the very low compactness of the PCB layer (0.3-0.5 kg/m^3) consists of died off grass and sedge (cured grass PCB), there is no difference in drying and moistening rate inside a layer. Under high compactness of the whole layer (compact litter PCB) there may be considerable differences. For the correct assessment of the possibility and character of burning of vegetation plots, investigations of layer-after-layer moistening and drying of PCB were conducted.

Objects of investigations were: 1) surface lichen cover (mainly *Cladina stellaris (Opiz.*) *Brodo)* – in sparse pine stands; 2) surface moss covers: with predominance of *Hylocomium splendens (Hedw.) Shimp.* in cembretum and spruce stands; with predominance of *Aulacomnium (Hedw.) Schwaegr.* in larch stands; with predominance of *Sphagnum orientale Lyd. sav.* in cembretum; 3) surface litter cover of pine needles in pine stands.

It was established that moistening of green mosses and lichens with rain occurs in “portions”. The value of the portions depends on the quantity of rain precipitation and does not depend on the moisture of a surface cover before the rainfall. For example, 1 mm of rain precipitation increases moisture content of moss *Hylocomium* by 15%, 3 mm – by 100%, 5 mm – by 150% and so on. Therefore, one short rain, even a heavy one, does not saturate a dry surface cover. A part of the water absorbed by moss after rain increases at first and then asymptotically decreases starting with 5 mm of rain precipitation.

Drying of an upper layer of lichen cover from 150-160% (after heavy rain) to 40% (when it becomes flammable) may take 8-12 hours. Connection of moisture content of sublayers (upper layer (3-4 cm) – **Mu**, % and low layer (3-4 cm) – **Ml**,%) with Nesterov’s index (**I**, units) is expressed in the following formulas u correlation ratios ($\mathbf{c_r}$):

$$\mathbf{Mu} = 5300/\mathbf{I} + 9, \text{ at } \mathbf{c_r} = 0.75;$$

$$\mathbf{Ml} = 18700/\mathbf{I} + 11, \text{ at } \mathbf{c_r} = 0.67.$$

Process of *Hylocomium* cover drying is less intensive:

$$\mathbf{Mu} = 45000/\mathbf{I} + 15, \text{ at } \mathbf{c_r} = 0.69;$$

$$\mathbf{Ml} = 54600/\mathbf{I} + 18, \text{ at } \mathbf{c_r} = 0.63.$$

It takes much time for *Hylocomium* cover to dry into a flammable state (up to 25% of moisture content): the tops of moss are scorched on the 2nd or 3rd day after rainfall, and creeping burning is observed only on the 5th or 6th day. *Aulacomnium* cover dries even slower: upper layer (2 cm) – up to 20-40% - on the 5th – 6th day after rainfall, and the creeping spread of burning is observed on the 6th - 7th day only. Pine litter layer (2 cm) dries from 100 to 30% in 8-10 hours, i.e. a period of pine litter layer drying is the same as a period of lichen drying.

Special experiments on experimental sites protected from rainfall by a cellophane awning show that the moisture content of green moss cover on protected sites decreases in spite of periodical rainfalls (up to 16 mm). Consequently, there is no moistening of surface cover due to soil water. However, rainfalls have almost no impact on Sphagnum cover moisture content while the soil has high moisture.

The question on moistening and drying of duff is very important because its upper part can participate in burning. The coefficient of correlation between duff moisture content and the moisture content of upper and low layers has the following values accordingly: for lichen – 0.12 and 0.30; for *Hylocomium* – 0.84 and 0.89; for pine litter – 0.80 and 0.90. Thus, there is close correlation between duff moisture content and moss and pine litter layer moisture content (with the exception of lichen). Small rainfalls mainly moisten the upper moss-lichen layer while duff remains relatively dry, but such an inversion is of short duration.

Investigations of layer-after-layer drying of covers (from *Hylocomium* and pine litter) of different thickness belonging to one type contributed to the establishment of a very important consistency: speed of layer-after-layer drying (from the surface to the depth) does not depend on the thickness of moss and pine litter. As a result, the PCB of one type with a different load have the same time drying into a flammable state and the same subsequent increase of active (consuming) load. For this reason the load of fuel is not included in the list of the main classification criteria of PCB. A special, “non-conductor”, type of PCB is observed on the plots where the PCB are either absent or their load is less than critical, i.e. insufficient for fire spread.

A number of important regularities of layer-after-layer drying of the PCB in connection with weather conditions were revealed in the process of studying PCB burning.

Chapter 4. **VEGETATION FUEL BURNING IN NATURAL CONDITIONS**

Natural fire experiments can be divided into three categories: range modeling of a fire as a whole, range modeling of tactical parts of a fire edge and non-range natural experiments. Among the latter, the technique of tentative ignitions in the annular screen by the Canadian pyrologist I.G.Wright (Wright, 1967) is interesting.

With the help of laboratory experiments and range natural experiments, relative influence of wind, slope, load, moisture content and volume weight of a layer on the rate of fire spread was studied for some species of moss, lichen and litter; mathematical models for the rate of fire spread determination (Sofronov, 1967; Sukhinin, Konev, Kurbatsky, 1975; Kurbatsky, Telitsin, 1976; Konev, 1977, etc.) were created. Combustion intensity of an edge (Vonsky, 1957; Sheshukov, 1971; Furyaev, 1975; Konev, 1977, etc.) and intensity of heat emission (Valendik, Isakov, 1979) were determined by an indirect method with the help of calculations.

To forecast fire behaviour, the following investigations of PCB types in connection with a drought level were conducted: firstly, on the possibility of burning; secondly, on the dynamics of active (i.e. consuming) PCB load and the dynamics of the quantity of heat energy emitted in the process of its burning. The rate of fire spread over the surface cover was studied as well including basic (or “calm”) rate, which is very important for forecasting calculations. Observations were carried out on 13 experimental sites in Arkhangelsk region, Buryatia, and Krasnoyarsky Krai.

In terms of method, a difficult question was solved concerning direct measuring (directly in natural conditions) of the quantity of the emitted heat, i.e. the quantity of heat emitted from a surface unit of the PCB layer during consumption of an active part of a layer. The method provided for: 1) standardization of sizes of plots for fire experiments and their protection from the wind; 2) measuring of the total quantity of energy emitted in the process of burning of each experimental plot of this kind. An annular (circular) screen devised by the Canadian scientist I.Wright (1967) was used together with our heat accumulator (in the mode of a vessel filled with water). According to the data of graduation, the accuracy of the measurement of heat emitted from a layer amounts to ±7%. Concurrent fire experiments on similar plots in the screen and without the screen showed that some differences in the character of burning and in heat emission take place during wind only, mainly due to the activation of a smoldering phase.

Two to three fire experiments were carried out daily for several fire seasons. Before the experiments, samples of surface cover (moss, lichen, pine litter) were taken to determine their moisture content. Over 800 fire experiments were conducted and over 3000 samples were taken.

The dynamics of the following characteristics were investigated in connection with a drought level (i.e. with Nesterov’s fire danger index of drought): 1) thickness of the consumed layer (**Th**, cm); 2) its load (**L**, kg/m^2); 3) its moisture content (**M**, %); 4) quantity of heat emitted from a burning layer ($\mathbf{Q_l}$, MJ/m^2); 5) duration (time) of layer combustion ($\mathbf{T_l}$, s); 6) heat emission intensity ($\mathbf{I_h}$, kVt/m^2).

The quantity of the emitted heat ($\mathbf{Q_l}$) was evaluated using two ways: 1) direct measuring of water heating in the heat accumulator and 2) traditionally, using calculations (taking into account the load of consumed PCB, their moisture content and the emitted heat). Duration of layer combustion was determined in accordance with duration of flame burning in fixed points. The heat emission intensity was calculated by the quantity of heat emitted from a burning layer (**Q_l**) and the duration of layer combustion (**T_l**):

$$\mathbf{I_h = Q_l / T_l}$$

As a result of experiments, the above-mentioned characteristics for four types of PCB (lichen (**Lc**), dry moss (**Dm**), moist moss (**Mm**) and loose litter (**Ll**)) were obtained. They are shown in Fig.4.1 as series of graphs conjugated with each other by a general factor – the moisture content of the whole PCB layer. The choice of this factor is conditioned by the fact that it is a concrete physical value, which can be determined with planned accuracy, whereas the estimation of a drought level is not sufficiently accurate. The connection between the moisture content of the whole PCB layer of a given type and the level of drought (Nesterov's fire danger index of drought) was determined in particular and included published data. Thus, the connections of the above listed measured values with the level of drought were established indirectly by the moisture content of the whole PCB layer. The example of these connections is shown in a combined graph (Fig.4.1).

The conducted observations have confirmed that duration of layer combustion (**T_l**) is almost a constant value for each type of PCB ("constant of burning" – Konev et al., 1978). For example, lichen PCB have **T_l** = 60 ± 5 sec (by any depth of a consumed layer); loose litter PCB have **T_l** = 75 ± 8 sec; dry moss and moist moss PCB have **T_l** = 40 sec. As a whole, duration of layer combustion for a moss-lichen cover, litter, and cured grass layer depends mainly on compactness (volume weight) of a layer (**ρ**, kg/m^3):

$$\mathbf{T_l = a\ (2{,}2\ \rho + 5)}.$$

It was established that in the interval between minimum and maximum values of a consumed layer thickness and the same values of an active load, the connection of these values with moisture content of the whole PCB layer has a character of reverse linear dependence, for example:

$$\mathbf{Th = (1 - M / M_{cr}) \cdot Th_{max}},$$

where **Th** – thickness of consumed layer, cm;

Th_{max} - thickness of the whole layer, cm;

M – moisture content of the whole layer, %;

M_{cr} – critical moisture content, % (i.e. moisture content of a layer when surface cover becomes flammable).

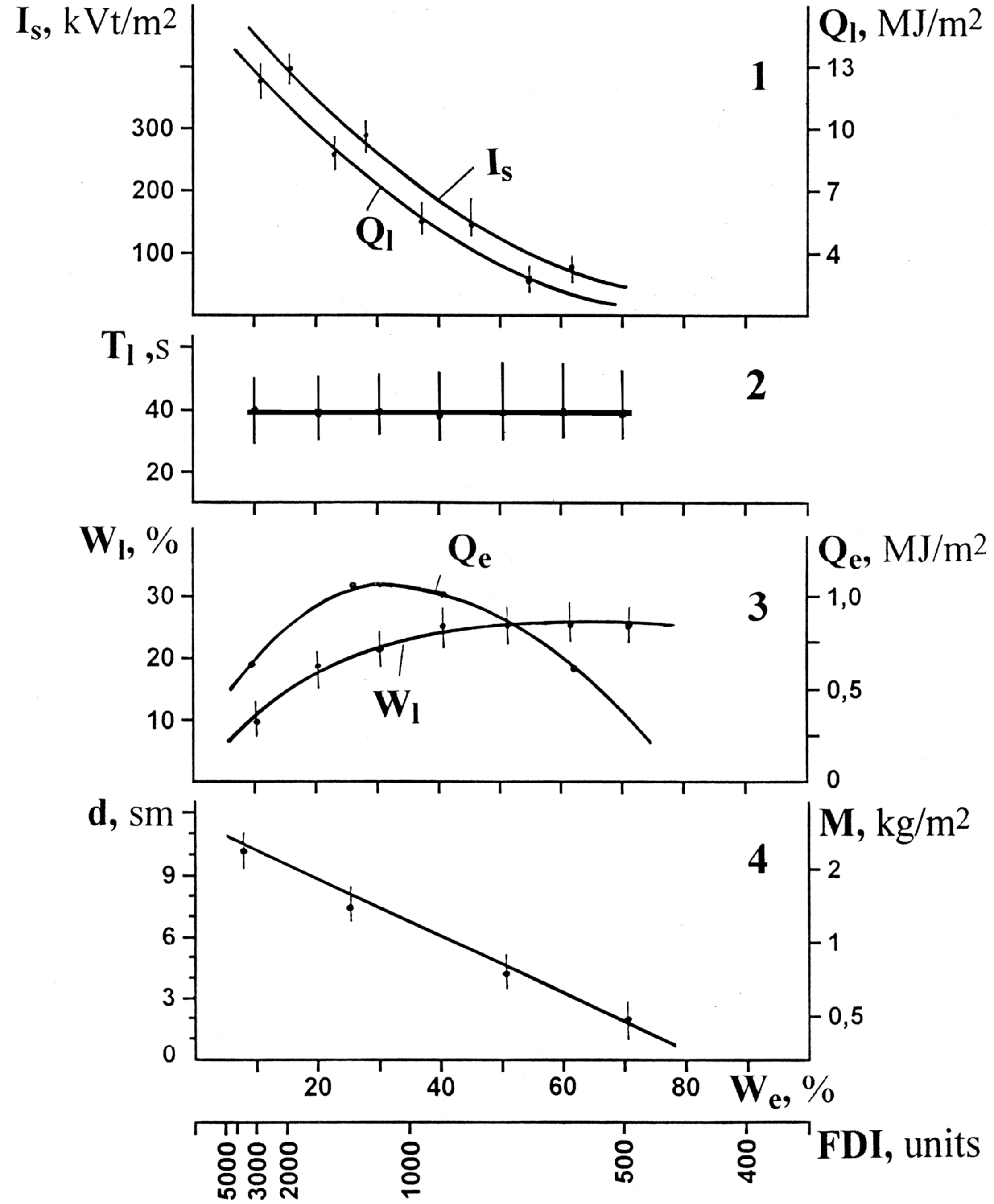

Figure 4.1. **Lichen cover.** Dependence of the following characteristics upon moisture content of the whole layer (**M_l**) and fire danger index of drought (**FDI**) using an example of lichen PCB: 1) heat emission intensity (**I_h**) and quantity of the heat emitted from the consumed layer (**Q_{cl}**); 2) duration (time) of layer combustion (**T_l**); 3) moisture content of the consumed layer (**M_{cl}**) and quantity of the heat spent for moisture evaporation from the consumed layer (**Q_e**); 4) thickness of the consumed layer (**Th**) and its load (**L**).

This formula does not disprove the conclusion made earlier that rate of drying of a certain type of surface cover (in the direction to the depth) does not depend on its thickness because the rate of **M** change is in reverse dependence from $\mathbf{Th_{max}}$ (i.e. the thicker the surface cover is, the slower its **M** changes).

The same dependence is established for the quantity of the heat emitted from a consumed layer ($\mathbf{Q_{cl}}$). It should be noted that in the process of burning of lichen PCB, 80% of the heat is emitted during a flame phase and in the process of burning of *Pinus sibirica* needles – about 65%. The quantity of heat emitted from burning dry moss cover during a flame phase decreases from 60 to 40% in proportion as the surface cover (including litter) dries. The intensity of heat emission has a reverse – close to linear – dependence from the moisture content of the whole PCB layer as well (because the duration of layer combustion is constant).

To estimate the influence of day and night fluctuations of relative air moisture on the quantity of the emitted heat ($\mathbf{Q_l}$), day and night observations on four experimental sites were carried out. It was established that $\mathbf{Q_l}$ of lichen PCB has small changes during day and night on the condition that relative air moisture at night does not exceed 85%. If it increases up to 90-95%, $\mathbf{Q_l}$ decreases rapidly (from 11 to 6 MJ/m^2). This can be explained by the fact that the value of lichen equilibrium moisture increases (by 20-25%) exactly in this interval of values of relative air moisture.

Loose litter PCB (litter of pine needles) has a stronger sensitivity to day and night fluctuations of air moisture.

As a result, the following conclusion was made: a surface cover cannot dry into a flammable state if the relative air moisture is over 85%.

We determined $\mathbf{Q_l}$ in two concurrent ways: 1) using a method of direct measuring of $\mathbf{Q_l}$; 2) using a traditional method of calculations ($\mathbf{Q_{lc}}$). Comparison of these two values allowed us to evaluate the energy of “chemical non-consumed gases” (because of the residual energy content of combustion products due to incomplete combustion) in natural conditions. For moss and lichen cover this value is considerable: 60 ± 20%. Such a large amount of “chemical non-consumed gases” is accounted for by the following: in the forest under the layer of fine fuel there is wet substance (litter, soil) owing to which heating contributes to the production of a steam-air mixture impoverished of oxygen where combustion takes place. Consequently, the coefficient of complete burning (which should be multiplied by the calculated value of $\mathbf{Q_{lc}}$) for moss-lichen cover in natural conditions is equal to 0.4±0.2. At present “chemical non-consumed gases” are neglected as if they were not very significant.

We conducted research of base rate of fire spread (**Ro**), i.e. rate of flame spread along the PCB layer of certain type under “typical conditions” (i.e. when factors are equal to “0”, or have modal meaning), namely: 1) afternoon; 2) horizontal site; 3) relative air moisture about 40%; 4) absence of wind. It is necessary to know the base rate of fire spread for every type of site for every class of drought within the limits of every period of season. It is possible to determine **Ro** by experimental burning or directly during real fires. If the conditions are not typical, Sofronov's variable coefficients can be used (Sofronov, 1965, 1967; Volokitina, Sofronov, 1995).

On the basis of generalization and analysis of our fire experiments and the experiments of Amosov (1964) and Matveev (Valendik, Matveev, Sofronov, 1979), the following important conclusion was made: the base rate of fire spread (**Ro**) is determined by heat emission intensity ($\mathbf{I_h}$). Dependence between Ro and Ih is expressed by the empirical formula:

$$\mathbf{Ro} = \mathbf{a} \cdot (\mathbf{1{,}75})^{(\mathbf{2{,}5\ I_h} - \mathbf{50}) \cdot \mathbf{10^{-2}}},$$

where **Ro** - base rate of fire spread (m/min if **a**=0.1 or cm/s if **a**=0.17);

$\mathbf{I_h}$ – heat emission intensity, kJ/m^{2}s.

As a result, the table for different PCB types characterizing $\mathbf{Q_l}$, $\mathbf{I_h}$, $\mathbf{R_o}$ and consuming fuel load ($\mathbf{L_c}$) under different forest fire index of drought was created (Table 4.1).

Pyrological characteristics of prime conductors of burning

Table 4.1 (fragment)

Forest fire index of drought	Pyrological characteristics			
	$\mathbf{Q_l}$, MJ/m^2	$\mathbf{I_h}$, kVt/m^2	**Ro**, m/min	$\mathbf{L_c}$, kg/m^2
	Lichen type of PCB (**Lc**)			
200	5.0	80	0.25	0.7
500	8.5	136	0.46	1.2
2000	10.0	156	0.64	1.3
	Dry moss type of PCB (**Dm**)			
500	3.5	80	0.14	0.5
1000	10.0	230	0.19	1.2
3000	20.0	450	0.27	2.4
and so on				

So, it is sufficient to determine experimentally only two values, namely: 1) quantity of the emitted heat ($\mathbf{Q_l}$, kJ·m^2) and 2) duration of layer combustion ($\mathbf{T_l}$, s). Using these two values all characteristics of surface fire (taking into account different factors) can be calculated.

Investigations of the regularities of drying and burning of fuel complexes give possibilities for important generalizations. The knowledge of these regularities can be used for fire behaviour forecasting and for fire control on the condition that there is information on the spatial location of fuel complexes, i.e. when vegetation fuel maps are available.

Chapter 5. **LARGE-SCALE VEGETATION FUEL MAPPING**

At present VF mapping includes preparation of information (including the GIS system) data banks for operative maps creation.

There are two methodological approaches in pyrological characteristic: the first one – by division of all vegetation plots into categories with simplified standard VF characteristics; the second one – by detailed individual characteristic of each vegetation plot in relation to VF. Historically the first approach has been developed as the simplest.

For example, in Russia (the USSR) small-scale " Schemes of Fire Prevention" and " Forest Fire Maps " (1:100000) are used in a fire-prevention arrangement where usually the whole quarters serve as mapping units; they receive a general average estimation of a fire danger class according to the scale from a forest inventory instruction.

M.A.Sheshukov (1966) suggested making " fire maps ", where each unit corresponds to one of 16 " types of fuels ", and the class of fire danger " is indicated. M.A.Sofronov has elaborated a technique of "forest fire maps " creation (Valendik, Matveev, Sofronov, 1979).

The start of VF mapping in the USA is connected with the name of Hornby (1935). Territories were estimated according to the difficulty of fire control and fire spread control during a strong drought. At present "fuel models " are borrowed from better improved systems NFDRS and BEHAVE.

Large scale vegetation fuel mapping (at scale 1:10 000 – 1:50 000) is necessary for the determination of spatial regularities of fire behaviour. It allows us to simplify fire behaviour forecasting and fire consequences thereby improving forecast accuracy. For this goal, creation of a regional information data base is necessary (on the basis of large scale vegetation fuel maps).

The necessity of fire behaviour forecasting appears, firstly, for the creation of an optimum plan for large fire control; secondly, when a great number of fires occurs and it is necessary to choose the most dangerous; thirdly, when there is danger of emergency situations because of forest and steppe fires. Consequently, the task of vegetation fuel mapping is to give characterization to vegetation sites sufficient for fire behaviour and fire consequences forecast (under certain seasonal and weather conditions).

Utilization of standard characteristics (by division of vegetation sites into a limited quantity of categories) is justified in that case only if it is necessary to give a simplified pyrological evaluation to vegetation sites which are large enough and heterogeneous inside; for example, to the whole planning quarters during fire prevention arrangement. However, the typical characteristics of vegetation are often not accurate and the fire behavior forecast can be in error. For this reason the last variant of American system "BEHAVE" gives the possibility of using concrete individual characteristics of vegetation sites instead of generalized typical characteristics, as these characteristics will accumulate in the GIS.

Our investigations showed that there is a great number of variants in the characteristics of vegetation sites. They differ from one another by combinations of groups and types of vegetation fuel, by the combination of moistening, drying and burning conditions of VF, by regional distinctions of fuel complexes (especially with respect to their load) and so on. It confirms the necessity of using this very individual approach for the pyrological description of sites which reflect the peculiarities of each site. In practice, the individual characteristics of vegetation sites usually represent a description of different combinations of typical elements, which is why it is better to call this approach individual-typical.

Such a description should include the following information:

1) the characteristic of the whole complex of vegetation fuel, i.e. of all VF groups which are available on the given site (including seasonal dynamics of this characteristic);
2) an estimation of the drying conditions of PCB on the site which is determined by the conditions of solar radiation penetration, i.e. exposition, steepness of the slope, and the degree of shading by timber and other vegetation (according to periods of a season);
3) information concerning the burning conditions of PCB on the site: about the slope which directly influences the speed of burning spread, and about the canopy closure of different vegetation layers which affects the wind;
4) information on the conditions of fire spread on the territory : its pyrological division caused by fire breaks and the presence of the sites which cannot burn;
5) vegetation characteristics for the estimation of fire consequences, especially the possibilities of stand damage and mortality; this includes the characteristic of a stand (composition, age, height, diameter, density, and relative density) and information on debris, understory, etc.

It is difficult to show the information listed above directly on the VF map. That is why we applied the way in which it is used in the process of forest inventorying, namely, a combination of the map and the detailed pyrological descriptions of every inventory unit encompassed on the map. Each inventory unit has an individual number which represents unique characteristics.

Accepted method creates the following things by large scale VF mapping: 1) vegetation fuel maps; 2) pyrological description of every inventory unit; 3) special tables for the character of burning and fire consequences forecasting based on the pyrological description and the weather condition data. Some of these tables will have a regional character (for example, tables on the load of the first and second group of VF and others).

To solve the task of large-scale VF mapping a method of individual pyrological characterization of vegetation plots was defined. Using a well-known method of forest inventory description for the third and fourth groups of VF (stand, undestory, dead trees, grasses, and small bushes) was suggested because there is quite enough information about these groups in the forest inventory data (for example, evaluation of types from the third to the seventh groups of VF (see table 1.2)).

To characterize the PCB on the site and, first of all, to determine its type (type of PCB) and the possible changes of this type during the fire season, the identifier of PCB types was elaborated and approved. Table 1.1 serves as the basis of this identifier.

At the end of the pyrological description there is an evaluation of the critical class of drought during the fire season for a certain plot; for this purpose a special table worked out on the basis of conducted investigations on PCB drying is used.

Creation of large-scale VF maps using direct description of plots in the forest has a high degree of accuracy, but it is extremely labor-consuming and rather expensive. It is expedient to create such VF maps for small areas, for example, for areas of planned prescribed burning, or for places near forest settlements and other important objects. For ordinary territories a simple method with the cheap technology of large-scale VF map creation is elaborated.

The idea of this method is to use the maximum of the forest inventory data for VF mapping: as a basis for a VF map an uncolored plan of stands is taken, and pyrological description of forest inventory units is made on the basis of forest inventory description.

Forest inventory description is, as a matter of fact, an individual characterization of every unit, and it gives quite enough information on groups 3-7 of VF and on the conditions of ground VF drying. However, this information is not enough for the characterizing of PCB (i.e. for determination of PCB types and their seasonal dynamics). Therefore, a method for determination of PCB types using forest types indicated in forest inventory unit descriptions was elaborated on the basis of preliminary pyrological characteristic of forest types. For this purpose the existing descriptions of forest types for a certain region are used and their analysis is made according to a special scheme. In the descriptions of forest types there is no information on the character of litter, therefore it is desirable to amplify descriptions under natural conditions. Finally, a table is created to show the most characteristic PCB types (during fire seasons) for every forest type used in the process of the latest forest inventory.

The main volume of the work on VF mapping can be done using a computer (including GIS) with the help of a special program. Such a program was created for PC’s in PASCAL - on the example of Bolshaya Murta forestry enterprise. (Volokitina, Klimushin, Sofronov, 1995).

The computer program includes calculation of general shading (**Sh**, %) from timber and shrub layers with the help of familiar (well-known) regularities of light penetration through a multi-layer semi-transparent obstacle:

$$\mathbf{Sh = (Sh.d' + Sh.c') + (Sh.d'' + Sh.c'') \cdot [100 - (Sh.d' + Sh.c')] + (Sh.d''' + Sh.c''') \cdot \{100 - (Sh.d' + Sh.c') - (Sh.d'' + Sh.c'') \cdot [100 - (Sh.d' + Sh.c')]\}},$$

where **Sh.d’** and **Sh.c’** - shading from coniferous-deciduous and coniferous-evergreen parts of the upper layer;

Sh.d” and **Sh.c”** – shading from coniferous-deciduous and coniferous-evergreen parts of the second layer, etc.

This estimation of shading increases the accuracy of critical classes of drought determination for vegetation plots (Table 5.1).

Assessment of critical classes of drought in relation to general shading

Table 5.1

General shading, %	Types of prime conductors of burning									
	Lc	**Dm**	**Mm**	**Bm_1**	**Bm_2**	**Cg**	**Ll**	**Cl**	**Nc_1**	**Nc_2**
	Critical classes of drought (**CCD**)									
76 – 100	II	III	IV	V	cannot burn	II	III	IV	V	cannot burn
46 – 75	I	II	III	IV	cannot burn	I	II	III	IV	cannot burn
0 – 45	I	I	III	IV	cannot burn	I	I	III	V	cannot burn

The computer program serves as a base. In order to adapt this program to natural conditions of a particular forestry enterprise, we propose to create and to include the above given table on pyrological characteristic of forest types into the program.

It should be noted that this method stipulates the same typical characteristic of all inventory units (which were assigned to one forest type) according to PCB types. Inaccurate determination of a forest type (especially when deciphering) leads to mistakes in the estimation of PCB types. In the process of forest inventory there is an opportunity to use a more accurate method, namely, to estimate inventory units according to PCB types directly during ground (terrestrial) taxation and during deciphering of airborne images.

For this purpose it is necessary to have simple and convenient identifiers of PCB types which also include a system of decipher indications for those identifiers. Since the prime conductor of burning is usually under the forest canopy and is not clearly seen in airborne images, we suggest conducting the decipherment of PCB types through recognizing in images and deciphering of the *pyrological categories of vegetation plots.* They should differ by VF types, by their seasonal dynamics and, taking into account their landscape location, by the character of the biogeocoenoses. We created an example of such a regional determiner of VF types for Krasnoyarsk Priangarie with a division into 12 pyrological categories of plots.

Large-scale VF maps are meant only for some plots where fires occur and are active, or where prescribed burning is planned. To make them efficiently, we would propose using *the information database* prepared for this purpose. This considerably reduces expenses of VF mapping.

We have elaborated three variants of information database creation. The first one includes: a) a set of forest inventory map-case as a basis; b) pyrological description in a printed form (Table 5.2); c) instructions for efficient VF maps creation and their usage (with necessary tables enclosed). The second variant differs from the first one in that pyrological description is kept in microdisks. In the third variant all information data are included in the GIS to efficiently computerize the making of maps and to forecast fire behavior.

In the monograph we analyzed the experience of large-scale VF mapping in different regions of Siberia, namely, in the north of Novosibirsk oblast and in the Surgutsk Polesye (Tumensk oblast), in Krasnoyarsk Priangarie, in the Extreme North of Central Siberia, in the Baikal Lake basin.

Chapter 6. **FIRE BEHAVIOR AND CONSEQUENCES FORECASTING BY MAKING USE OF LARGE-SCALE VEGETATION FUEL MAPS**

The most developed method of fire behaviour forecast is an American one created on the basis of physical and mathematical model of Rothermel (Rothermel, 1972) with the division of VF into classes and "fuel models ". In the Canadian system called FBP empirical information on the parameters of combustion of " fuel types " at different weather conditions is used. In the American practice it was proved that precise individual characteristics of vegetation plots were needed to forecast fire behaviour, and not rough standards.

Pyrological description (the fragment)

Table 5.2

Forest division	F. inv. unit	F. inv. plot	Square, ha	Exposure	Degree	1 canopy					2 canopy					Site index	Understory saplings			Fallen wood	Dead trees stock	Density		Shading		Type of PCB		CC	
						rel. stocking	height, m	age, years	evergreen	deciduous	rel. stocking	height, m	age, years	evergreen	deciduous		evergreen	deciduous	height, m			understory saplings	understory woody vegetation	spring, autumn	summer	spring, autumn	summer	spring, autumn	summer
7	524	1	7,0	0	0	0,7	2	15	10	0	0,0	0	0	0	0	4	0	0	0	0	0	0,0	0,1	0,7	0,7	Ll	Ll	2	2
7	524	2	9,0	0	0	0,8	16	60	10	0	0,0	0	0	0	0	3	0	0	0	0	0	0,0	0,3	0,8	0,8	Dm	Dm	3	3
7	524	3	27,0	0	0	0,7	17	55	1	9	0,0	0	0	0	0	2	0	0	0	0	0	0,0	0,0	0,6	0,8	Ll	Cl	2	3
7	524	4	23,0	0	0	0,7	15	55	6	4	0,0	0	0	0	0	3	0	0	0	0	0	0,0	0,1	0,6	0,7	Dm	Dm	2	3
7	524	5	83,0	0	0	0,6	12	65	1	9	0,0	0	0	0	0	5	10	0	1	0	0	0,3	0,2	0,6	0,7	Bm1	Bm1	4	4
7	524	6	5,0	0	0	0,4	7	40	0	10	0,0	0	0	0	0	5	0	0	0	0	0	0,0	0,0	0,4	0,5	Bm1	Bm1	4	4
7	524	7	28,0	0	0	0,7	16	60	6	4	0,0	0	0	0	0	3	10	0	5	0	0	0,5	0,1	0,6	0,7	Dm	Dm	2	3

In Russia the following variants of models were created: 1) models expressing thermal and physical processes under VF combustion (Amosov, 1958; Sukhinin, Konev, 1972; Telitsin, 1973, 1985; Konev, 1977, et. al.); 2) models of combustion spread over elementary plots of a surface fire edge (Sofronov, 1967; Konev, 1984); 3) models of fire contour spread (Korovin. 1969; Vorobyov, 1975; Dorrer, 1984) and 4) models of development of surface fires into crown ones (Grishin, et. al, 1984). The models in the second group are the most efficient; therefore VF classification should be connected with them.

In forest-fire protection practice, situations when it is necessary to forecast fire behavior and consequences are inevitable, especially when a large number of fires occur. In the case of multiple fires, there are usually insufficient means to extinguish them so we should first choose the most dangerous fires in terms of possible damage (especially when inhabited localities, industrial enterprises and other valuable places are under threat of fire) and the most difficult to fight should they spread. Secondly, in order to create an optimal plan of management of a large fire (including its control and liquidation) we must be able to stipulate and to take into account its dangerous tendencies and the dangers of its spread and development. Thirdly, scenarios of fire spread and its consequences on a definite area under different weather conditions are indispensable to choose optimal time and optimal technology of prescribed burning.

Efficient fire behavior and consequences forecasting is possible only on the basis of a large-scale VF maps (together with pyrological description of forest inventory plots) and meteorological data.

Forecasting surface fire behavior is very important since about 80% of all vegetation fires are surface fires. The method described is based on the usage of simple empirical dependences and tables.

Fire behavior forecasting includes several stages: first of all the readiness of vegetation plots around the fire center to burn is estimated in connection with the drought level, then the rate of spread and intensity of burning on the plots are forecasted according to the weather forecast together with the modeling of fire spread contour. And finally, possible consequences are estimated taking into account fire intensity and taxation characteristic of a stand on each plot.

A large-scale VF map can be easily converted into a map of current fire danger by comparing critical classes of drought on units with a class of drought on a given day (Fig. 6.1). It demonstrates whether the plots around the fire are ready to burn according to three gradations : 1) ready to burn; 2) not ready to burn; and 3) having an uncertain (transitional) state. The uncertainty of estimation is eliminated in different ways, for example, by analyzing the character of already burnt plots.

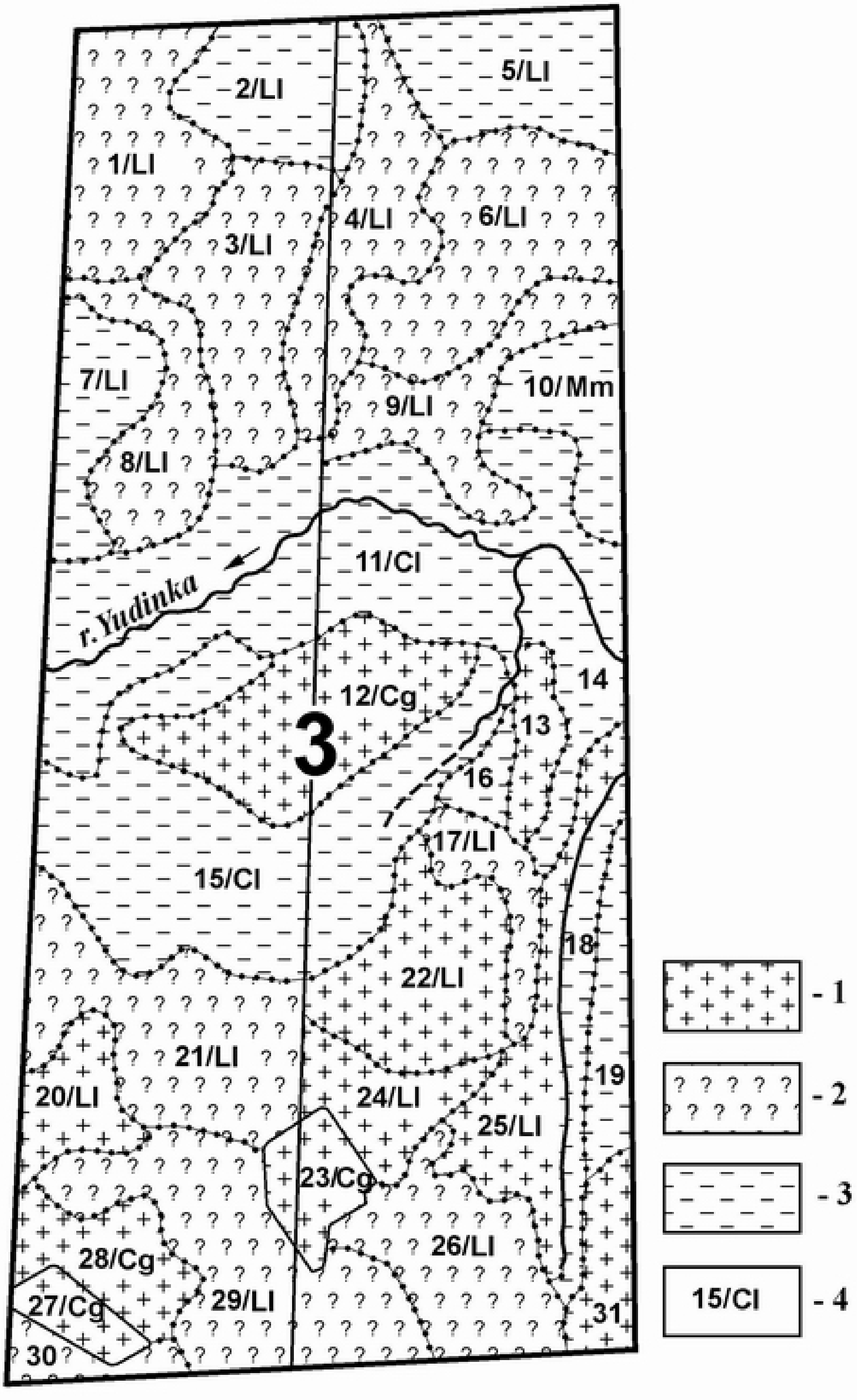

Fig. 6.1. Fragment of a map on current potential fire danger at the second class of drought for spring time made on the basis of a VF map (the western part of Yukseevsky forest area of the Bolshaya Murta forest enterprise). Conventional signs: 1 - units ready to burn; 2 - units almost ready to burn (i.e. possibility of burning is uncertain); 3 - units not ready to burn; 4 - number of a unit/type of a conductor of burning.

To estimate the rate of fire spread and its intensity, its pyrological description, the meteorological forecast and a set of worked out tables and simple formulas are used. To forecast the spread of fire contour, not only plots unable to burn are taken into consideration, but also linear breaks. In order to do this it is important to observe a certain order and sequence of operations. There are special table forms to facilitate it. In addition, a computer variant of surface fire behavior forecast is being created.

A method of forecasting the development of a surface fire into a crown fire is being developed. We have already done the analysis of a corresponding part of the Canadian system FBP which is created on the basis of factual data obtained from experimental crown fires.

Fire consequences forecast. In Russia fire consequences have been studied by many scientists (Melekhov, 1948; Molchanov, 1954; Sannikov, 1981; Furyaev, 1996 et al.). Recommendations on post-fire mortality forecast in pine, fir, larch and birch stands are discussed (Voynov, Sofronov, 1976).

For surface fire consequences forecasting one can use the research results of G.S.Voynov et al. (1976) on post-fire mortality in stands depending on the species, average diameter of a stand and height of singed scorch. We made use of G.A.Amosov's (1964) and M.Alexander's (Alexander, 1980) formulas and replaced the height of singed scorch by a calculated intensity of an edge that allows forecasting possible mortality before the actual fire.

It was established that the main sources of inevitable errors in fire behavior forecasting are : 1) unevenness of rain precipitation distribution over the territory which leads to inaccurate determination of the value of the forest-fire index of drought and class of drought especially at a distance of 25 km and over from the meteorological station; 2) insufficient accuracy of weather forecast; 3) some inaccuracies in the VF map due to errors in forest inventory data (heterogeneity of taxation units especially at the third category of forest inventory; due to errors in determination of forest types, etc.); 4) variable wind direction which influences the front edge of fire owing to the wind coming above the heated surface of burnt area; 5) some inaccuracies in fire edge plotting on the VF map.

Some inaccuracies and errors can mutually compensate for one another but some of them can cause deviations which increase with the passage of time. Therefore, in the process of fire control, regularly correcting and renewing the forecast of fire behavior is recommended .

Chapter 7. **MEDIUM-SCALE VEGETATION FUEL MAPPING**

Long-term studies make it possible to do medium-scale (1: 500 000 – 1: 1 000 000) VF mapping of the pyrological characteristic of a vegetation floor of medium-size ecosystems. On the basis of this pyrological characteristic one can judge potential fire danger and its dynamics as well as the possible character of burning and its consequences. However, such VF maps have insufficient "resolution capacity" for fire behavior forecast. They are meant for fire danger monitoring. It is also possible to divide the average potential fire danger rating into classes for efficient application in the fire-prevention policies of the territory.

It was established that practically the whole volume of mapped information at the given scale can be shown directly on the map. In each forest inventory plot one can show dominant types of prime conductors of burning (including their seasonal dynamics). Additionally, dominant tree species and the presence of a layer or thickets of flammable shrubs (Siberian dwarf pine (*Pinus pumili)*, *Rhododendron Daurica*, etc.) are indicated. Hydrographical and traffic nets are always marked. It is also useful to indicate a forest block net.

Two methods and two variants of a technique are worked out for making medium-scale VF maps.

The first method is called "autonomous". It implies the application of space images for distinguishing ecosystems. Ecosystems are united in categories-analogues within natural regions according to the vegetation depicted in the images. For the characteristic of ecosystem analogues, field work is carried out on key plots using airborne images. The "autonomous" method of map creation increases the load of a map and makes its legend more complicated. Besides, pyrological description of ecosystem analogues should be enclosed with the map including vegetation floor characteristic of ecosystems, pyrological partition of the territory, standard landscape forms of fire behavior in different periods of a season, the most probable fire consequences, etc. The autonomous method was not checked in practice because of its high cost.

The second method is called "conjugated". A conjugated VF map is a map of indirect estimation. Its creation reduces to pyrological characteristic of units on the base map (e.g., a landscape, geobotanical, forest-type, forest-fund map, etc) by means of analysis of a base map legend and other necessary information, as well as with the help of ground-truthing some typical units during field work.

The technique includes analysis of the data characterizing the nature of the territory with the aim of revealing its heterogeneity for the following specialized zoning. Then a base map is chosen to fit the scale, with a legend including a sufficiently general description of the vegetation, especially of surface cover. Further, with the help of airborne- and space images it is possible to find burned areas, young growth areas, agricultural land, etc. which are not marked on the base map. Using the created preliminary VF map, key plots are selected for field research (in every natural region).

Field research includes a description of routes and profiles with the pyrological description of points on them according to an elaborated standard form as well as carrying out observations of the fire maturing of some plots (forest types) and determination of VF load. After analyzing the obtained field data, corrections are introduced into the preliminary map, and an author's model of a VF map is created.

The first example of a conjugated VF map (1:1 000 000) was a map for trapezium O-46 in the Angaro-Yeniseisky region. The authors' models of landscape and forest-typological maps (Kalashnikov, Korotkov, Pervunin, 1990) were used as its base. The following was taken into account in the analysis: 1) zonal character of vegetation; 2) relief; 3) stand species composition; 4) character of surface cover; 5) additional information. To facilitate the analysis a table form was created.

As a continuation of this work, VF maps (1: 500 000) were created for the whole Angaro-Yeniseisky region within the Krasnoyarsk krai (11 sheets of maps for trapezium from O-45 to O-48). A map of the forest fund (1: 500 000) made by the Krasnoyarsk branch of Gostsentr "Priroda" together with the Institute of Forest Siberian Branch of the Russian Academy of Sciences in 1990 was taken as a base. Additionally the following was used: 1) a forest-typological map conjugated with the base (Institute of Forest SB RAS); 2) the map "Vegetation of the South of Eastern Siberia" (1972); 3) the map "Landscapes of the South of Eastern Siberia" (1976); 4) topographical maps; 5) remote sensing data; 6) results of field research in Krasnoyarskoe Priangarie (1984-1989). On the basis of the analysis, a work table was made with the characteristic of forest types and other types of biogeocoenoses of the forest-typological map (including information on types of prime conductors of burning, their dynamics, etc.). With the help of VF maps the pyrological characteristic of natural regions is given. VF maps form part of a series of conjugated subject-matter maps made by the Institute of Forest SB RAS and the Krasnoyarsk branch of Gostsentr "Priroda" (1995).

A VF map (1: 1 000 000) for the northern part of the Baikal Lake basin was made in 1989-1990. The map "Vegetation of the South of Eastern Siberia (1: 1 500 000) served as its base. Additionally the following maps were used: "Landscapes of the South of Eastern Siberia" (1977), "Atlas of Zabaikalie" (1967), "Schematic map of zonal high-altitude vegetation complexes of the Baikal Lake basin" (Polikarpov, Babintseva, Cherednikova, 1993); pyrological zoning of the Baikal Lake basin is also taken into consideration (according to M.A.Sofronov). A fragment of the VF map is shown in Figure 7.1.

An example of the application of medium-scale VF mapping is to accurately predict real fire hazard and the specifics of its probable spread over the territory so that optimal air patrol routes can be chosen. For this purpose the following is used: 1) a medium-scale VF map; 2) a map of ignition danger (created with the help of a method of “sliding square” using data on places and dates of fire occurrence for the last 10-15 years); 3) a meteorological map with indication of meteorological units; 4) special regional tables for calculation of forest-fire drought indices (Nesterov’s index or PV-1) using weather forecasts.

The technique was designed (including a computer program) for the Angaro-Yenisesky region making use of the medium-scale VF maps made for this region. Retrospective checking of 1990 data showed that the number of mistaken forecasts (fire occurrence and spread within forest inventory plots which were indicated as non-flammable) is only 5-6%. This proves that fire danger rating with the help of VF maps is quite accurate.

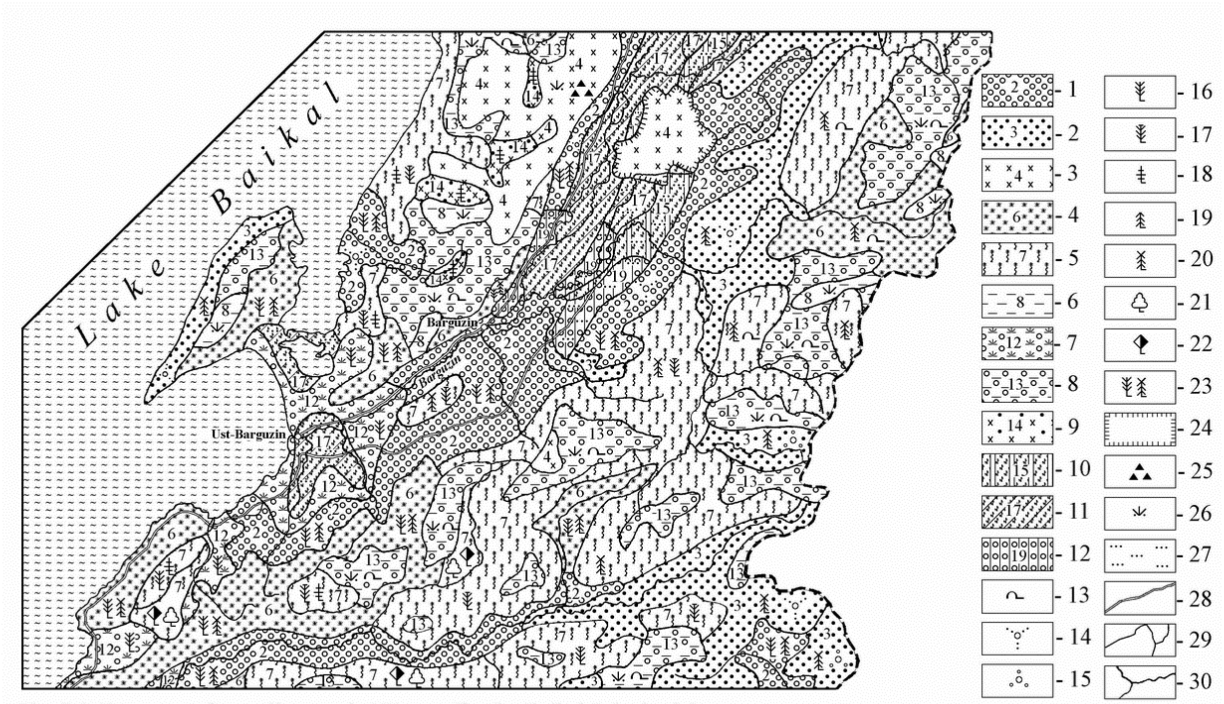

Fig. 7.1. Fragment of a medium-scale VF map (for the Baikal Lake basin). Types of prime conductors of burning (PCB types): 1 – loose litter, 2 – compact litter, 3 – non-conductors, 4 – dry moss, 5 – moist moss, 6 – bog-moss. Combinations of PCB: 7 – loose litter and lichen, 8 – loose litter and bog moss, 9 – compact litter and non-conductors. Seasonal dynamics of PCB (spring/summer): 10 – dry grass/loose litter, 11 – dry grass/non-conductors, 12 – loose litter/compact litter. Bushes: 13 – dwarf ceder-pine, 14 – rhododendron, 15 – dwarf birch. Crown: 16 – pine, 17 – cedar-pine, 18 – larch, 19 – spruce, 20 – fir, 21 – birch, 22 – aspen, 23 – crowns of combination of species. Open lands: 24 – ploughed lands, 25 – grassless lands, 26 – tundra, 27 – steppe. Other map symbols: 28 – roads, 29 – borders of forest plots, 30 – rivers, 31 – lakes.

CONCLUSION

Analysis of the problem of vegetation fires (including forest fires) and foreign experience in forest-fire protection proves that this problem can be solved by means of fire control on the basis of improvement and wide application of methods of fire hazard, behavior and consequences forecasting.

Forest, bush, steppe and other vegetation fire behavior prediction and the forecasting necessary to control them is extremely difficult and complicated. Forecasting is considered to be accurate if it reveals, first of all, all-round, detailed and true base information on the pyrological characteristics of vegetation plots. Moreover, it is critical to describe *all* vegetation plots in the regions where fires cause considerable losses. The characteristic of only separate plots and the separate categories of plots is of no great practical importance since fires can occur and spread almost in any part of territory.

World practical experience shows that accurate fire behavior forecasting can be made only by making use of all-round *individual* characterizations of vegetation plots, and not simplified standard ones. Individual all-round characteristic of plots can be put into practice if it represents a combination of *standard elements with their standard characteristics* (i.e. is, in fact, *individual-standard*).

This individual-standard characteristic of vegetation plots together with information on location and outlines of plots can be indicated in *large-scale vegetation fuel maps* (including a computer variant within GIS). Consequently, vegetation fuel fires should constitute the main part of information database for vegetation fire behavior and consequences forecast in fire control.

When creating the scientific fundamentals of vegetation fuel mapping, the authors of this monograph developed their own classification. On its basis, methods and a technology of vegetation fuel mapping were elaborated; pyrological characteristics of distinguished classification units most important for surface fire behavior forecast were investigated; and a methodical elaboration of fire behavior forecasting by making use of vegetation fuel maps has been commenced.

The developed scientific fundamentals and efficient technology of VF mapping (taking into account natural and economic conditions of Russia) can serve as a significant contribution to information database creation for the Russian system of forest and other vegetation fire behavior and consequence forecasting.

Absence of the computer variants of inventory information records in the majority of forestry enterprises interferes with the creation of an information database. Forest fire behavior forecasting becomes complicated because of mistakes in assessment of drought level (i.e. value of forest fire Nesterov's drought index or PV-1 index of LenNIILH) owing to spotted rain precipitation distribution over the territory and an extremely sparse net of meteorological stations in the taiga zone including the impact of vertical climatic zonality in mountain forests. Moreover, the meteorological service does not forecast the day and night dynamics of relative air moisture which is of great importance for forest fire behavior and consequences forecasting. The above mentioned problems require additional expansion and data.

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