International Forest Fire News (IFFN) No. 32 (January – June 2005, 55-61)

Landscape Framework for Regional Forest Fire Monitoring

Natalia A. Marchenko
Lomonosov Moscow State University, Faculty of Geography

Introduction

Sufficiently rapid and detailed assessments of the natural environment and the current fire hazard are key to coping with forest fires. Another important element is environment impact assessments of forest fires, including carbon emissions. Actual forest fire rates of specific areas reflect the pyrogenic factor role in the transformation of forest landscapes and the need for their protection.

Landscape science offers a broad range of approaches to forest fire monitoring and information support for forest fire management decision-making. Landscape science has identification and mapping techniques for and a hierarchy of geographical landscapes (GLs) and their conditions. GLs are viewed as relatively homogeneous pieces of the environment within which its parameters vary but insignificantly compared to variations among GLs. GLs are homogeneous in terms of their terrain, geological foundation, water and climate conditions, vegetation and soils. Diurnal variations of GLs are assumed to be spacious/temporal units with relatively permanent environmental parameters changing over a year. These parameters include, among other things, burning conditions, and therefore, also fire patterns as developing under the latter.

Nowadays, current fire hazard is assessed through identifying the fire hazard classes of the weather based on Nesterov's cumulative hydrothermal index or its improved alternatives and special scales. Fire hazard classes of the weather define the ignition potential of the specified forest types. They are derived from data of base meteorological stations to be used by aerial forest fire teams and to regulate activities of forest protection services. However, such assessments do not include parameters of potential fires; they consider neither intra-seasonal, and sometimes nor seasonal differences with their variation from year to year. To track and record changes occurring in the natural environment in the course of a year, three scales are used (for spring, summer, and fall) with the dates of each season coinciding with the respective calendar dates. In addition, the scales designed for large areas (e.g., in the Primorsky Kray, for its southern, western, and eastern areas) do not allow to take into all their local specifics; whereas the classes are defined for the areas which are protected by the aerial fire teams, and occupy rather vast (about 10,000 km^2) and diverse territories with widely varying forest site and hydrothermal conditions (Marchenko 1991b, Korobeynikov et al. 1992). In montane and poorly-developed areas, the work is complicated primarily with the sparseness of the weather stations network which necessitates data extrapolation.

The above constraints and difficulties may be overcome through using the landscape and its variations as operational units, and a landscape map as a basis for mapping the fire hazards and active fires, to interpret remote sensing data. Analyzed pyrological specifics of the Southern and Middle Sikhote-Alin landscapes and their diurnal variations revealed their close relationship with forest fires and allowed to design a method for assessing the current fire hazards based on potential fire parameters.

Landscapes

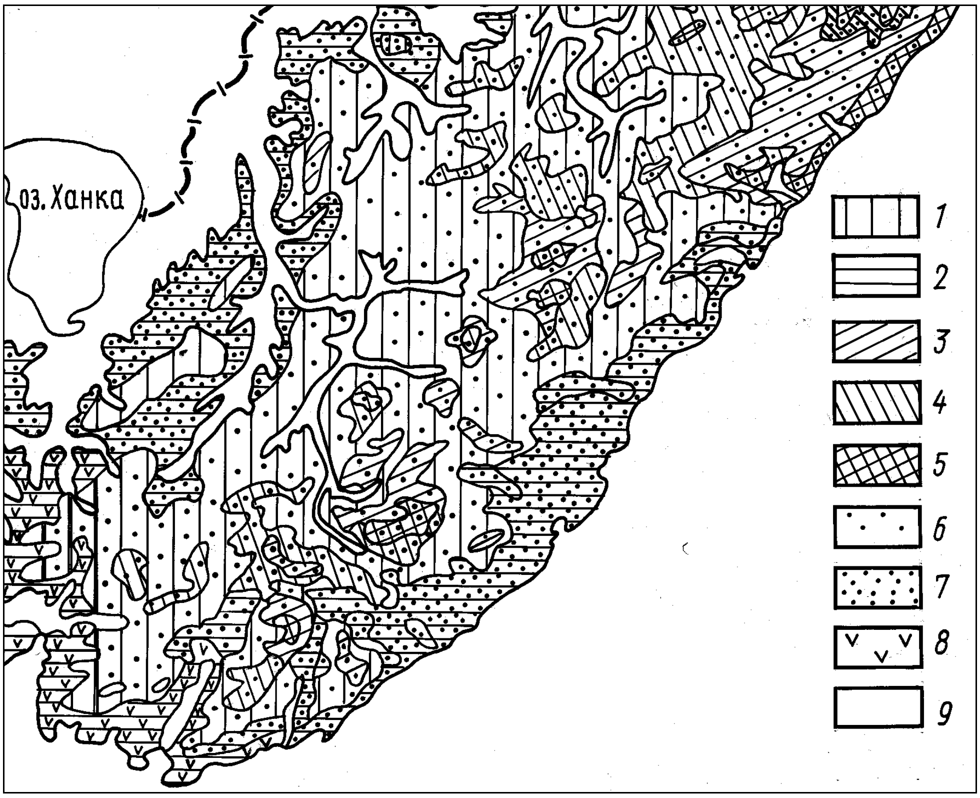
Landscape maps were drawn for the Southern and Middle Sikhote-Alin in the scale of 1 : 500,000, and 1 : 2,500,000 as based on the generalization of the first one. For these purposes, the following published maps of the Primorsky Kray were used: Geomorphology, Plant Ecology, and Soils in the scales of 1 : 500,000; as well as literature sources, and the author's own field research related to the GL patterns with such outputs as detailed descriptions of the facies, and a landscape map of the Livadiysky Ridge in the scale of 1 : 100,000 (as a key site typical of foothills/hills and low mountain landscapes in the southern part of Primorye and middle mountain landscapes which are widely spread throughout the territory under consideration). The Landscape Map of the Southern and Middle Sikhote-Alin (1 : 500,000) identifies the landscape types based on their hydrothermal conditions, zonal properties, and the altitudinal (vertical) tiers in the mountains. And within each type, it further shows the genera of the landscapes with their various terrain and vegetation. In order to identify landscape types as based on hydrothermal conditions at altitudes below 500 meters, we relied on the agro-climatic zoning of the Primorsky Kray after V.K. Khramtsova, and in the case of altitudes above 500 m, we were guided by certain vertical gradients of meteorological elements (see below), vegetation, and the altitudinal tiers in the mountains.

The legend to the landscape map is presented in both text and table forms. The table vertical lists the relief types and the terrain types: volcanic, denudational, denudational/erosional, erosional/denudational, and erosional/accumulative. The relief types identify altitudinal tiers and include: plain landscapes (No. 1 in the indices of the landscape genera), foothills/hills (below 300 m) (No. 2 in the indices of the landscape genera), low-altitudes (elevations of about 300-500 m – No. 3); middle-altitudes which are further classified into lower-altitudes (i.e. the lower tier of the middle-altitudes of 500-700 m – No. 4), middle-altitudes per se (700-900 m – No. 5) and high-altitudes with their alpine-tundra (*goltsy*) belt (above 900 m – No. 6). The table horizontal line shows plant communities: Manchurian broad-leaved forests with the hornbeam (C is the letter in the landscape genera indices), Manchurian broad-leaved forests (P), broad-leaved/Siberian pine forests with the hornbeam and needle fir (*Abies holophylla*) (X), oak forests (Q), broad-leaved /Siberian pine forests (FP), Siberian pine and broad-leaved/Siberian pine forests (PF), broad-leaved/dark coniferous forests (FT), dark conifers with broad-leaved trees (TF), fir/spruce forests (T); a combination of fir/spruce, larch, spruce/larch and small-leaved forests (R), birch/fir/spruce forests (B), elfin stone birch woodlands (BE), tundras and dwarf-tree elfin woods (E), fresh and wet reedgrass meadows, sedge and peat bogs (G). All in all, 51 landscape genera were identified within the surveyed territory. The short indexes of landscape genera are written by number (for relief) and letter/letters (for vegetation). For example, the index "2 Q" – means "foothill landscapes with oak forests" and "5TF" – means "middle-altitudes landscapes with dark conifer forests with broad-leaved trees". Actual fire occurrence map of the Southern and Middle Sikhote-Alin (see Figure1) has been created on the landscape base. The landscape indexes are used in Figure 2, where probability of forest fires in different landscapes are shown for various conditions.

Pyrological Specifics of the Landscapes

Pyrological specifics of the Southern and Middle Sikhote-Alin landscapes were defined, and their fire danger predicted through analysing the available forest fire data (about 1,000 fires) over the period of 1971-1977. The data were derived from the fire registers of the Primorye Aerial Forest Fire Centre ('Airbase') and used to compile a data bank with the description of each fire complemented with its attendant landscape and weather conditions, diurnal changes in the landscapes (see below), wind regimes, and average rates of fire perimeter enlargement (spreading speed) in km/day defined. The produced Actual Fire Incidence Map (1 : 2,500,000; Figure 1) shows two indicators of the landscape fire incidence: the relative fire area over a season per 100,000 ha, and fire frequency, i.e. the number of fires per 100,000 ha over a season (Marchenko, 1993a). The defined average and relative areas and frequencies of fires and the produced map allowed to reflect the actual fire rates in the landscapes of the Southern and Middle Sikhote-Alin at the current level of forest development and fire management which demonstrated the role of the pyrogenic factor in the dynamics of these forest landscapes and the need for their protection.

Within the surveyed territory, most of the fires (from 65 % to 90 %) were extra-small (0.2-1.0 ha) and small (1.0-10.0 ha), with extra-small fires prevailing among them; the shares of ignitions (<0.2 ha) and medium (10-50 ha) fires amounted to 10 % each, and significant (50 - 200 ha) and large fires (200-1000 ha) were substantially fewer (2%). Fires above 1000 ha occur very rarely. The absence of major and larger fires is typical of foothills and low montane landscapes. The differences in actual fire rates are accounted for by anthropogenic and natural factors. The below described trends are preconditioned by the facts that fires are mainly caused by human activities, and that the areas burned are largely dependant on fire fighting management. The most developed foothills/hills as well as low montane landscapes with oak forests contain maximum amounts of fire sources, and in general, have higher and high fire rates as measured by fire frequencies, and moderate rates in terms of their relative areas. The absence of major and larger fires is typical of foothills and low montane landscapes. Remote middle- and high mountain landscapes are located far from populated areas, so fires are detected late there and most of them are not suppressed; these landscapes have moderate forest fire rates as measured by their fire frequencies and very high rates in terms of relative areas. The largest relative area of fires is found in the high mountain landscapes with birch/fir/spruce forests where it reaches 863 ha per 1,000 ha a year or about 0.9 % of the total area. This indicator of actual fire incidence is also very high in foothills/hills landscapes with Siberian pine and oak forests located along the northern poorly-developed coast of the Japanese Sea, and high fire rates are typical of middle mountain landscapes with fir/spruce forests. Low and lower montane landscapes have moderate fire rates in terms of their fire frequency, and low rates in terms of relative areas. The differences in fires rates among areas with similar levels of development and protection, as well as fire rate variations as a function of diurnal variations of the landscapes, and no correlation between the probability of fire observation and burning of 1 ha of a forest area, on the one hand, and the diurnal changes for most of the landscapes, on the other – all these are explained by differing characteristics of fires, and in particular, by their different spreading speeds.



Legend:
Fire occurrence as measured in relative fire areas per season, ha/100,000 ha:
1 – low (< 10); 2 – moderate (10 - 30); 3 – increased (30 - 100);
4 – high (100 - 300); 5 – very high (> 300)
Fire rates as measured in fire frequency, # of fires/ 100,000 ha per season:
6 – moderate (0.5 - 2.0); 7 – increased (2.0 - 7.0); 8 – high (7.0 - 20.0)
9 – unexamined area (agricultural territory)

Figure 1. Actual fire occurrence map of the Southern and Middle Sikhote-Alin

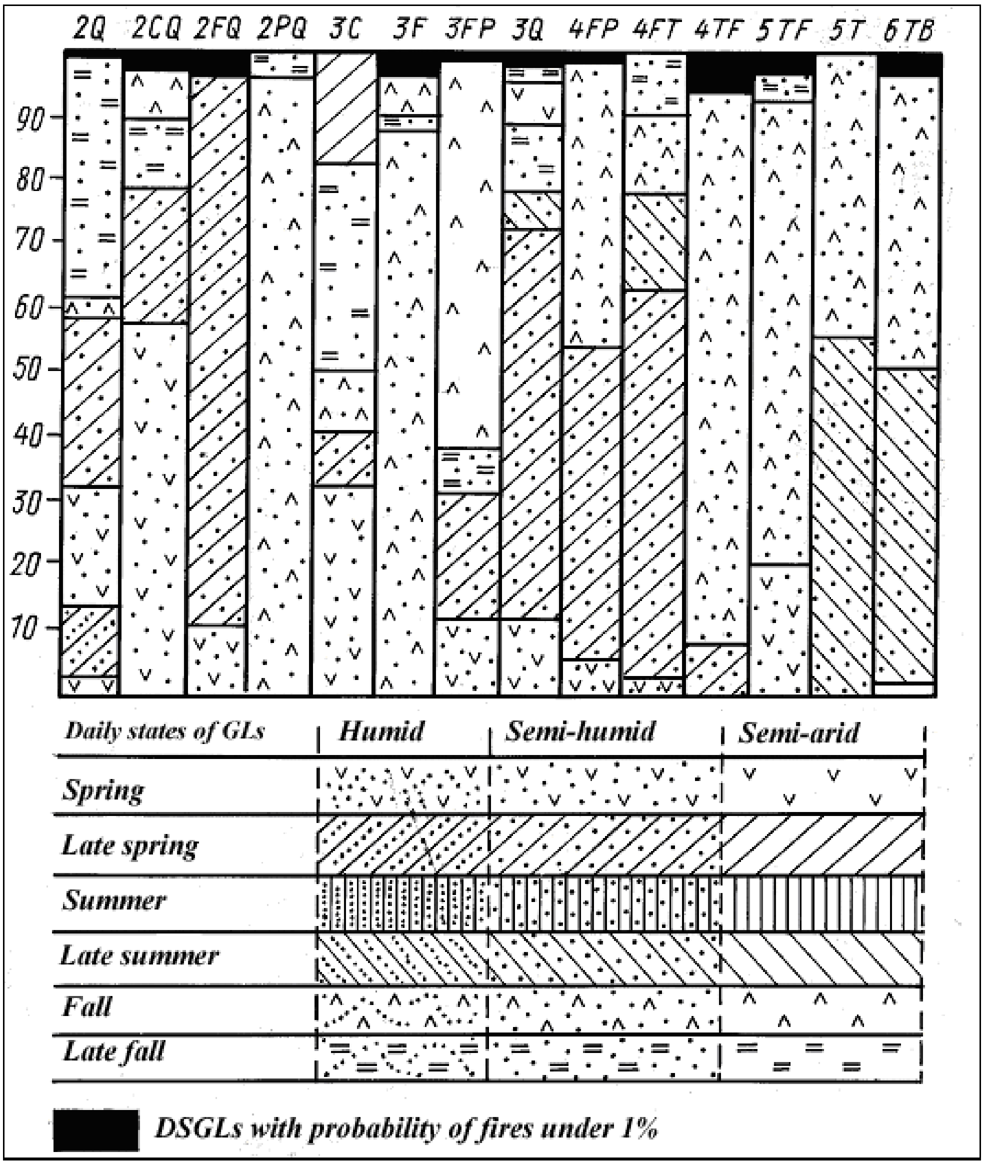
Daily States of Geographical Landscapes and Forest Fires

Assuming that the landscape is a relatively homogeneous piece of the natural environment, the Daily states of geographical landscapes (DSGL) may be regarded as spatial/temporal units with relatively permanent environmental parameters changing in the course of a year. They are classified into winter (with stable or unstable snow covers), early spring (before plant vegetation), spring (when grassy plants start vegetating), late spring (when tree and shrub plants start vegetating), summer (peaks of the vegetation processes), late summer (yellow leaves), fall (fall of the leaves), late fall (after the leaf-fall, plant vegetation termination), and pluvial (with raining) DSGL. According to the reviewed literature, temperature thresholds (5, 10, and 15) are well applicable to the identification of DSGL in the Southern and Middle Sikhote-Alin. When DSGL are classified by humidity level (humid, semi-humid, and semi-arid), the factors considered include: soil horizon moisture levels, the hydrothermal coefficient equal to the ratio of the actual total precipitation over a decade to the average decade temperature. The applied indices may also be used to estimate fire hazards. DSGL of specific landscapes cannot be identified without data on their hydrothermal conditions. However, meteorological stations providing such information are in place not in each landscape. Currently, in the Primorsky Kray, there are 48 functioning weather stations which are located primarily in valleys and along the Japanese Sea coast. Therefore, the data from these stations have to be extrapolated. To this end, vertical gradients of temperature and air moisture deficit were determined for 36 pairs of weather stations using data for the period from 1952-1965 when the network of weather stations was much denser, with several “upland” weather stations in operation) (Marchenko 1989). The data obtained show that the vertical gradients have explicit patterns corresponding to the year’s course, and depend upon the position relative to the sea, and the absolute elevation: thus, the territory is divided into foothills, low mountains, and middle mountains. And in the lower tier of the mountains, it is also divided into maritime and continental (the western slope of the Sikhote-Alin) areas. The maritime areas have the year’s pattern of temperature gradients with a negative winter minimum and a positive or slightly negative maximum. The continental areas have the reverse pattern of the year’s temperatures. In the middle mountains, the year’s pattern is smoother and identical for eastern and western slopes of the Sikhote-Alin. Annual variations of the moisture deficit gradients are less expressed. Computed vertical gradients are used to define the landscape-specific hydrothermal conditions through adjusting the data from weather stations.

Data from the weather stations in the Primorsky Kray, and the computed vertical gradients of weather elements were used to trace the dynamics of dominating landscapes in the Southern and Middle Sikhote-Alin over the period of March to November 1971-1977, and to draw curves of their natural regimes with the abscissa depicting the months and decades, and the ordinate signifying the frequency of a given state in %. A review of the curves revealed substantial particulars in the seasonal dynamics of the dominating landscapes, average commencement dates and durations of various conditions, and the most likely transitions.

From the pyrological perspective, the most important characteristics include the frequency of semi-arid and semi-humid DSGLs; termination of winter DSGLs (snow cover disappearance); as well as the succession of the spring and fall DSGLs accompanying the vegetation processes which are known to be of great importance for forest pyrology. Throughout the reviewed period, humid DSGLs prevailed, the share of semi-arid DSGLs did not exceed 20 % in any of the landscapes and decades, and in the middle mountain landscapes, they were completely absent. In low montane landscapes with broad-leaved/Siberian pine forests, they were early spring, fall and late fall DSGLs; in those with Manchurian broad-leaved forests, these were fall and late fall ones; in those with broad-leaved forests with the hornbeam, they were late fall DSGLs; and in landscapes with oak forests, they were spring and late fall semi-arid ones. In foothills/hills landscapes with broad-leaved forests with the hornbeam, and with oak forests, late spring, fall, and late fall DSGLs are possible, whereas in these landscapes with broad-leaved forests, spring and late fall semi-arid ones are found. Semi-humid DSGLs may occur almost throughout the warm period in all landscapes. But they are more likely to occur in summer than in spring (30-50 % and 10-30 %, respectively).

Each landscape has recorded periods of only humid states, and such periods vary by landscape. On Figure 2, one can see the results of forest fire data bank data processing - Relative Probability of Burning 1 ha of a forest area under different Daily state of geographical landscapes (DSGL). Different types of hatching marks different Daily States: degrees of humidification are shown on horizontal axis, seasonal variation are shown on vertical axis (see underneath picture as legend for upper picture). The forest fire data bank analysis shows that 61 % of all fires occur during the periods of semi-humid spring, late spring, fall and late fall DSGLs. Fires are the fewest during the periods of semi-arid DSGLs (3.1 %), since these ones are exclusively rare, as well as during summer humid DSGLs with already rich plant cover when the spread of fires is limited owning to higher humidity levels. Fires are rather frequent at the time of semi-humid summer and late summer DSGLs (10.2 %) as well as humid early spring, spring, fall and late fall ones (18.8 %). The relative areas of fires reflect the role of the pyrogenic factor in the dynamics of forest landscapes. This indicator reaches its highest level in foothills/hills landscapes with Siberian pine and oak forests, middle mountain landscapes with fir/spruce forests, and high-altitude landscapes where the annual relative burned area averages 0.3 - 0.93 % of the total forest area, with the greatest contribution resting with late summer and fall semi-humid DSGLs. Significant pyrogenic transformations occur in low and middle mountain landscapes with dark-conifer forests and inclusions of broad-leaved species as well (0.06 - 0.09%), primarily under late fall semi-humid DSGLs. In foothills/hills and low montane landscapes with oak forests, historic large and periodically returning fires had contributed into their plant cover evolution. Later, improved protection against fire reduced the pressure of the pyrogenic factor, but due to more frequent fires, this pressure remains substantial. Late spring semi-humid DSGLs are critical here. In the other landscapes within the surveyed territory (those of low mountains with broad-leaved/Siberian pine forests, and of lower mountains with broad-leaved/Siberian pine forests and broad-leaved/dark-conifer forests), forest fires do not cause significant modifications of the vegetation structure. The differences in actual fire rates are accounted for by anthropogenic and natural factors.



Note: The ordinate shows the probability in %, and the abscissa enumerates the landscapes; landscape indices are to be found in the text.

Figure 2. Relative probability of burning 1 ha of a forest area under different Daily State of Geographical Landscapes (DSGL) of the Southern and Middle Sikhote-Alin

The below described trends are preconditioned by the facts that fires are mainly caused by human activities, and that the areas burned are largely dependant on fire fighting management. The most developed foothills/hills as well as low montane landscapes with oak forests contain maximum amounts of fire sources, and in general, have higher and high fire rates as measured by fire frequency, and moderate rates in terms of relative areas. Remote middle- and high-altitude landscapes are located far from populated areas, so fires are detected late there and most of them are not suppressed; these landscapes have moderate forest fire rates as measured by their fire frequency and very high rates in terms of relative areas. Montane landscapes of the low and lower altitudes have moderate fire rates in terms of their fire frequency, and low rates in terms of relative areas. The differences in fires rates among areas with similar levels of development and protection, as well as among different DSGLs, and no by- DSGLs correlation with the probability of fire observation and burning on 1 ha of a forest area for most of the landscapes – all these are explained by differing characteristics of fires, in particular, by different spreading speeds.

The speed of fire spreading is equivalent to the perimeter growth rate, in km/day. In the examined landscapes, it varies from 0.0 (early spring humid DSGLs) to 6.9 (late summer semi-humid ones). Speed distribution is close to the log normal one with the most common spead at 0.17 km/day. The speed of fire spreading depends only on natural factors with the lead belonging to the wind regime followed by moistening conditions and the annual cycle phase. But the relationships are not always linear for the territory as a whole. Based on the speed of fire spread, fires were classified into 5 types.

Fires spread at less than 0.1 km/day (type 1) only with weak wind, and only under the conditions of humid and semi-humid DSGLs. They spread at 0.1-0.5 km/day (type 2) under the conditions of weak and moderate wind and all DSGLs in all landscapes; with strong wind – only under humid and semi-humid spring, late spring, summer, and fall DSGLs in landscapes with broad-leaved forests with the hornbeam, and those with oak forests, broad-leaved/Siberian pine, fir/spruce, and birch/fir/spruce forests. Spreading at 0.5 - 1.0 km/day (fire type 3) is associated with strong winds, but such speeds coupled with moderate winds are typical only of semi-humid and semi-arid DSGLs. There may be two patterns of fire spread at a high speed (over 1.0 km/day): (1) Crown fires which may occur only in closed stands with dominating confers and their abundant undergrowth and second story. Such fires occur in middle mountain landscapes with fir/spruce forests and high-altitude landscapes in late summer semi-humid DSGLs with strong winds which accounts for very high fire rates in terms of relative fire areas in these landscapes where they may spread faster than at 5.0 km/day. 2) Ground running fires may burn in sparse tree stands when the wind penetrates under the crowns both in foothills/hills landscapes with broad-leaved forests with the hornbeam, and with oak forests, as well as broad-leaved and oak forests. They spread but slightly faster than at 1.0 km/day. In foothills/hills landscapes with Siberian pine and oak forests, both patterns may be observed. The fastest fire spread is typical of middle- and high-altitude landscapes as well as of foothills/hills with Siberian pine and oak forests. The slowest fire spread is a feature of landscapes of low-altitudes and foothills/hills. Semi-arid DSGLs occur only in landscapes of foothills/hills and low mountains with deciduous forests, and are not prone to rapidly spreading fires, with the highest fire speeds inherent to semi-humid DSGLs. As regards the annual cycle phases, the slowest fire spread is typical of summer DSGLs which are more humid and coincide with the period of abundant growth of mesophytic grasses and shrubs, when even with strong winds, fires spread hardly faster than at 0.5 km/day. The fastest fire spread is observed in late summer and fall DSGLs.

Current Fire Hazard Assessment

The revealed diurnal variations of landscapes offer a new method of the current fire hazard assessment with possible fire spread rates under given conditions to be used as its criterion (Marchenko 1993b). Fires are affected by factors of qualitative nature, and these factors have non-linear relationships with their spreading speed. Some combinations of landscapes, DSGLs and wind regimes are not realistic while others are associated with quite definite types of fires as determined by their spread speed. For practical purposes, it would be quite sufficient to know the fire spread speed within the accepted gradations. In view of the aforesaid, it would be expedient to define the fire speed using the established data bank which contains such speed values, fire types, and the likelihood to deal with fires referred to the indicated types, for different DSGLs of the explored landscapes.

In contrast with the current practices, the proposed method would define not only the risk of ignition, but also characteristics of the fire and its further behaviour. Fire hazard estimation by landscape rather than by administrative parcel can provide a more specific and detailed description of the current situation based on the actual spatial/temporal differentiation of the natural environment which is of particular importance under mountainous conditions. Thereby, a very important thing is the extrapolation of data from weather stations, using certain vertical gradients of meteorological elements.

When fire hazard estimates are based on the speeds of fires which may occur under given landscape conditions, it is possible, at a certain taxonomic level, to take into account the natural conditions affecting a fire and their intra-seasonal dynamics, to project the parameters of potential fires; to obtain a sufficiently detailed description of the protected area; and, to a substantial extent, to get rid of the limitations inherent to the currently applied methods. The designed method was implemented in a GIS (Marchenko 1989), which enables to draw fire hazard maps based on data from 15 base weather stations (6 parameters). These maps depict fire hazards, with potential fire perimeter proliferation rates indicated. Verification of the method and the GIS included daily mapping of the landscape variations and current fire hazards with subsequent mapping of active fires thereon. This process demonstrated sufficiently precise simulation of the processes taking place in the surveyed landscapes: parameters of 75 out of 77 recorded fires corresponded to the projections.

Current fire hazard maps of a protected area significantly facilitate the process and save the time of decision-making with respect to aerial patrolling and fire-fighting resource manoeuvring, and hence, help to reduce the areas of destroyed forests. The precision of fire hazard estimates may be raised through using additional meteorological information (from more weather stations and sub-stations), and processing the fire data for the previous years. Detailed knowledge of landscape/geophysical characteristics of an area would allow to compute the speed of fire spread at the thermal/physical level in meters per second for all aspects, and to simulate the dynamics of fire contours. Follow-up studies could be also focused on defining fire hazards, and fire parameters for other landscapes conditions in Russia and in the world; and on designing a system for routing monitoring for the entire Forest Fund. Great opportunities are offered by the use of remote sensing data.

Thus, a landscape map reflects the natural differentiation of the environment, and may become a good basis for a system of monitoring and information support for decision-making in the area of forest protection both to prevent fires through forest management planning and limiting the access to fire-prone areas, and to detect and fight fires through manoeuvring the fire fighting resources, planning the aerial patrolling routes, and managing the fire fighting operations. Landscapes as relatively homogeneous areas allow to develop and extrapolate data of pointed observations (field and laboratory phytomass analyses, assessments of amounts and characteristics of forest fuels), and to evaluate the consequences of fires and losses inflicted by them.

Literature

Korobeynikov, V.P., N.A. Marchenko, and G.S. Tsitsiashvili. 1992. On principles of database composition for prediction and computation of large forest fires. Vladivostok, Russian Academy of Science, Far East Branch, 18 p.

Marchenko, N.A. 1989. Geographical information system of Prymorskiy region. Its aims and possibility of creation. In: Modeling of safety from fires and burst, p.136-142. Vladivostok, Russian Academy of Science, Far East Branch <in Russian>.

Marchenko, N.A. 1991a. Vertical gradients of meteoelements in Primorsky region and possibility of meteodata extrapolation. Geography and Natural Resources No. 3, 138-143 <in Russian>.

Marchenko, N.A. 1991b. Methods of defining of moisture condition and degree of fire danger in nature. In: Mathematical physics and modeling in ecology, p.87-99. Russian Academy of Science, Far East Branch <in Russian>.

Marchenko, N.A. 1993a. Forest fires in the Sikhote-Alin' Mountains. Vestnik MSU (Moscow State University Herald), Geography, No. 2, 79-87 <in Russian>.

Marchenko, N.A. 1993b. Estimation of forest fire dangers as probability of fire with definite spreading speed. Geography and Natural Resources No. 4, 131-136 <in Russian>.