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The spatial and temporal distribution of fires on Sakhalin Island, Russia

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Abstract. In the 1990s, catastrophic fires affected ~8 million ha of forest lands in the Russian Far East, including forests of Sakhalin Island. A study that correlated the spatial distribution of burned area and topographic features (elevation, slope, aspect) was carried out for Sakhalin Island. Burned area information derived from forest inventory maps (1935 to 1990) and satellite imagery (1998) was digitised and entered into a Geographic Information System. The burned area locations were correlated with topographic information; the normalisation procedure allows for analysis of the dependence of the fire scars on landscape features. The analyses show that fires occur primarily on the eastern, south- and north-eastern facing areas; >90% of fires occur at elevations lower than 300 m, and >95% occur on slopes <10 degrees. For the period 1935 to 1998, ~54% of the Sakhalin Island forest land territory was burned. From the total area of fire scars, formed from 1935 to 1998, 90.5% occurred owing to single fires, 8.6% of fire scars were the result of burning by two fires, 0.9% of fire scars were from three fires, and 0.03% from four fires. A fire return interval for the study region is ~120 years.

Additional keywords: boreal forest, historical data.

Introduction

In the 1990s, there were catastrophic wildfires in the Russian Far East, including fires on Sakhalin Island, which resulted in an excess of 8 million ha being burned (Sukhinin *et al.* 2004). Satellite data showed that over 60% of the total burned area occurred in Eastern Siberia and the Russian Far East region (excluding the Kamchatka Peninsula; Table 1). These data show that on an annual basis, an average of 1.2% of the Russian Far East boreal forest burns each year, with higher fire activity being found in the southern parts of this region than in the north. During years with large fires in the southern regions (such as 1998 and 2003), fires can affect 5–10% of the total land area. During the same period, burned area in the North American boreal forest region, which has only a slightly larger area than the Russian Far East (some 600×10^6 ha) averaged only 2.2×10^6 ha year^{-1}. The Sakhalin Island forests, which are typical for the Russian Far East, experienced some 4500 fires during the 1945–98 period, which burned >20% of the forests. Catastrophic fires of 1989 and 1998 were concentrated mainly in the northern part of the island. In closed stands, fires were crown fires, with ground fires in sparse stands.

The purpose of the present study is to formalise the relationship of area burned to topographic features, including aspect, slope, and elevation. The Sakhalin island orography, which combines ridges with planes, is an important determinant of fire pattern, and allows us here to provide a landscape analysis of fire patterns in time and space. Compared with North America, where large fire databases have been developed in a digital format for the boreal regions of Alaska and Canada (Kasischke *et al.* 2002; Stocks *et al.* 2002), there is no similar database for the Russian boreal forests. Hence, we examined the decadal spatial and temporal patterns of fire dynamics based on forest inventory records, by examining maps of areas that burned (for the 'pre-satellite data' time period), in combination with satellite-derived data (after 1998).

Study area

Sakhalin Island lies off the eastern coast of Russia, located between 45–54°N and 142–145°E, and has a total area of 7.64×10^6 ha (Fig. 1). Three-quarters of this narrow ($948 \times \sim 100$ km) island is covered by a mountain range (oriented north–south) with a mean elevation of 600 to 700 m (maximum elevation = 1609 m). The north end of the island is dominated by the flat North Sakhalin plain. The soils of the island are acidic, with sandy podzols dominating the northern part of island, and clay podzols found on the rest of the island (Ivlev 1965).

The climate of this island is monsoonal in nature. Fogs and clouds are typical for spring and summer. Because of its considerable latitudinal length (948 km), there are considerable differences in climate between the northern and southern parts of the island. Thus, mean annual temperature ranges from −1.4°C in the north to +2.2°C in the south, with an average precipitation ranging from 400 mm year^{-1} in the north to 750–850 mm year^{-1} in the south; in the middle part of the island, the precipitation level is 500–750 mm year^{-1}, with 1000–1200 mm year^{-1} in the mountains. The majority of the growing season precipitation

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Table 1. Summary of average areas burned in different regions of Eastern Siberia and the Russian Far East between 1996 and 2003 based on estimates derived from analysis of satellite imagery by Sukhinin *et al.* (2004)
Percentage of area is given in parentheses

Region	Area (10^6 ha)	Average burned area (10^6 ha)	Year of largest area burned	Burned area (10^6 ha)
Republic of Yakutia	310.3	1.6 (0.5%)	2002	5.0 (1.6%)
Khabarovsk Krai	78.9	1.1 (1.5%)	1998	5.5 (6.9%)
Amur Oblast	36.4	1.3 (3.6%)	2000	3.1 (8.5%)
Chita Oblast	43.2	1.6 (3.8%)	2003	5.9 (13.7%)
Magadan Oblast	8.0	0.2 (2.2%)	2003	0.5 (6.1%)
Sakhalin Oblast	7.6	0.1 (0.7%)	1998	0.3 (4.0%)
Chutokota Autonomous Okrug	11.9	0.04 (0.4%)	2001	0.1 (1.0%)
Total	496.3	6.0 (1.2%)	–	–

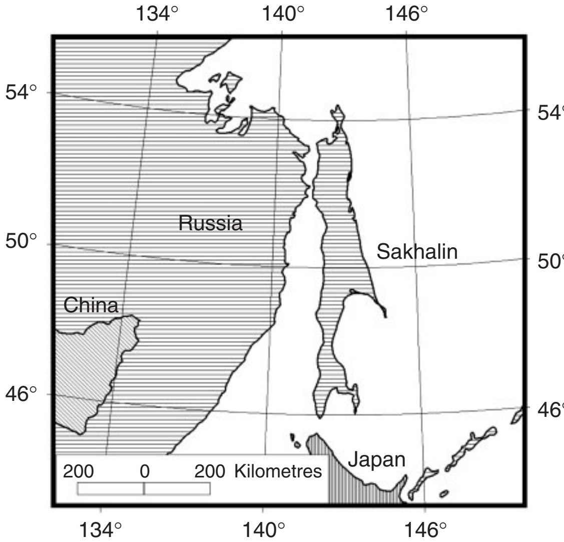

Fig. 1. Study area: the Sakhalin Island.

occurs between July and September, whereas most of the winter precipitation occurs in February and March. July is the warmest month (average of 15°C) and January the coldest (average of −13°C). Springs are typically cold and often experience late snowfalls. During most years, the early part of summer is cool and relatively dry, with increased levels of precipitation in the late summer and early fall. The remaining part of the fall season is relatively warm and sunny. Winter storms with heavy snowfalls are common. Snow cover lasts up to 200 days in the north and 150 days in the south. Typhoons (with wind speed $>30\,m\,s^{-1}$) may occur in late summer and fall; owing to this, wind-throw of trees is typical in the area. Those winds in periods experiencing high fire danger promote the rapid spread of fire, resulting in large burned areas. The period of high fire danger typically lasts from May through September; in extreme years, it includes the second part of April and early October (Zhukov 1969).

Forest lands cover 87% of the island area. Wildfires and logging have affected forest age structure: currently, the mean age is ~100 years with a mean timber volume $\sim 115\,m^3\,ha^{-1}$. The climax forests are fragmentary, and located only in remote and inaccessible areas. Sakhalin Island supports high plant diversity, with 1313 species being recorded, including 88 endemics. It has been divided into three major ecozones (Tolmachev 1955; Klintsov 1973): the northern ecozone (above 51.5°N) is dominated by larch (*Larix kurilensis*) forests. The middle ecozone (48.0–51.5°N) is dominated by dark-needled, coniferous forests, the overstorey canopies of which are dominated by spruce (*Picea ajanensis*) and fir (*Abies sachalinensis*). The southern ecozone (below 48.0°N) consists of mixed coniferous and deciduous forests, with several species of birch (*Betula alba* and *B. ermanii*) and spruce and fir being present. At local scales, forest composition is modified by climatic variations associated with changes in elevation or proximity to the coastline. As a result, the mountain ridges (up to ~900 m) are occupied primarily by dark-needled, coniferous forests, with birch forests in the elevation belt between 900 and 1000 m. The high-elevation areas are dominated by prostrate or half prostrate five-needle pine (*Pinus pumila*). This latter species is also found on the flatter regions of the northern part of Sakhalin Island, where it either forms a component of the larch forests, or forms pure stands (Richter 1961).

During the period 1905–45, the region south of latitude 50°N was occupied by Japan. According to forest inventory data, in 1908, forests covered ~90% of the south Sakhalin territory, with 3% of burns and clearcuts. In 1935, forested area had decreased two-fold, and fires had affected >20% of forest land. Before 1945, most of the merchantable forest was cut and removed in the southern part of the island (Newell and Wilson 1996).

The major years during which Sakhalin forests experienced fires during the period 1935–98 are presented in Fig. 2; the latest one, described in detail, occurred in 1998. In 1998, both the middle and northern parts of Sakhalin were abnormally dry: there was practically no precipitation from May to September. Fires began in May and stopped in October. The most dangerous situation was in September, when strong winds ($>30\,m\,s^{-1}$) co-occurred with dry weather. Officials reported ~350 forests fires, 64% of which were anthropogenic in origin; these figures are similar for southern Siberia (65%), based on satellite data (Kovacs *et al.* 2004). According to official reports, resulting

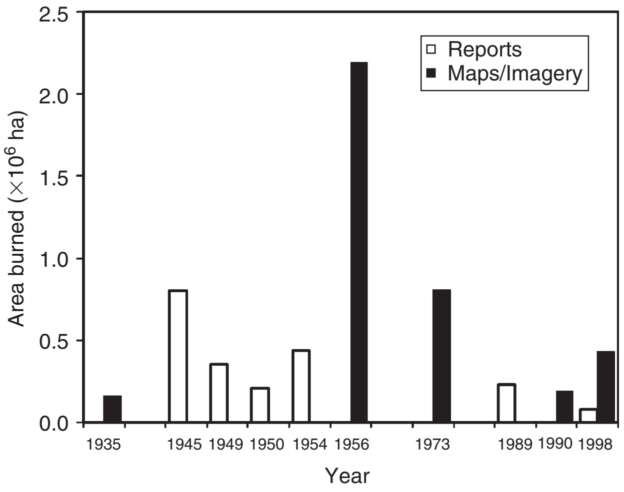

Fig. 2. Inter-annual variations in area burned for Sakhalin Island from (1) (open bars) official Russian reports of burned area database (Sabirov 1999), and (2) (shaded bars) based on information from forest inventory and satellite analyses data.

burned area was 80 800 ha, including 28 400 ha of turf and bog areas.

Methods

Burned area information

The analyses of the relationships between burned area, fire location and landscape features were carried out using information derived from several sources. Burned area information was obtained from forest inventory maps, Advanced Very High Resolution Radiometer (AVHRR) imagery, and forest management data taken at the regional and local forest enterprise (*leshoz*) levels. Landsat data were also used in the analysis; these images were used, together with on-ground data, for verification of the AVHRR data. Landscape features (slope, aspect, elevation, etc.) were obtained from topographic maps and field surveys.

We used AVHRR imagery to map the perimeters of large fires that occurred in 1998. Maps of fire locations and perimeters from earlier time periods were derived from forest inventory maps produced for Sakhalin Island. The earliest fire-perimeter information was obtained from a topographic map containing the boundaries of forest types and fires in 1935. This map (at a scale of 1 : 500 000) contained information for northern Sakhalin Island only (>50°N). Area of burns for the southern part of the island for that time, according to archive data, was 360 000 ha. Maps produced in 1956, 1973 and 1990 (on a 1 : 2 500 000 scale) were based on field surveys collected for Sakhalin Island. These field surveys were collected a few years before the publication of the maps, with the newest fires being 2 or 3 years before the map date and the oldest fires being 10 to 15 years before the map date.

Topographic information

The baseline topographic reference used for the study was a 1 : 1 000 000 scale digital elevation map (DEM) (http://www.ngdc.noaa.gov/seg/topo/globeget.shtml/, accessed 15 October 2006), which contained a matrix of height values with a 30-s resolution in latitude and longitude. The 30-s resolution of the topographic map corresponded to a distance between two points of the height values at the 54th parallel (north part of the study region) of 546 m in latitude and 928 m in longitude. For the 46th parallel (south part of the study region), it corresponded to 646 m and 926 m, respectively. The elevation absolute accuracy was ∼100 m. Despite this fairly coarse DEM resolution, it corresponded to the scales of other map data sources. Sakhalin Island relief is rather smooth, and linear interpolations of coarse DEM produce adequate results.

Surveys (by personnel from Sukachev Forest Institute, the Siberian Branch of the Russian Academy of Sciences) collected at 82 sites in the middle and northern parts of the island in September of 2000 were used to ground-truth the burn perimeter map that was generated from the AVHRR imagery. At each site visited, we determined whether the burn scar originated from the most recent fires in 1998 or from an earlier fire based on patterns of vegetation regrowth. For fires that we determined had occurred before 1998, we consulted with local forest officials, who informed us that the older burn scars occurred during fires in the late 1980s. For the older burn scar events, we also confirmed that the areas had burned earlier than 1992 by examining Landsat imagery collected in 1992. At each site, the following information was collected: topography (altitude, azimuth, slope); disturbance type (recent or old fires, degree of forest clearing or cutting); type of the vegetation cover; species type and diameter, height, and density of all canopy trees; description of regenerating vegetation and ground cover, and soil type. The coordinates of each site centre were determined using a Garmin Scientific Model 12 (Olathe, KS, USA) global positioning system (GPS) unit (estimated accuracy of ±15 m).

Analysis methods

The boundaries of all fire perimeters were digitised from AVHRR imagery and the forest survey maps using GeoDraw for Windows (Zamai and Yakubailik 1998), and exported for analysis into ArcView geographic information system (GIS) 3.1 (with the ArcView Spatial Analyst 1.1 and ArcView 3D, Analyst 1.0, and Grid Plus 1.0 extension modules, ESRI, Redlands, CA, USA). As the topographic maps and AVHRR imagery were in different coordinate systems, each data layer was transformed into a Transverse Mercator projection (Krasovsky ellipsoid, central meridian 141°, central parallel 53°). A further transformation of the data was performed on the layers with the isolines of relief and fire scar perimeters being transformed into a triangulated irregular network (TIN) model (Delone triangulation) in order to construct a raster model (GRID-theme) with 0.05-km resolution. As a result, it was then possible to use mapping algebra to determine aspect and slope using the combined data layers. To analyse the dependence of the fire location on landscape features, we carried out our three-dimensional (3-D) analyses using the 1 : 1 000 000 scale digital map.

As a result of these analyses, the following layers were formed:

1. a relief points layer;
2. an isolines altitude layer with a 50-m elevation step;
3. a 3-D relief model;
4. an azimuth points layer;
5. a slope steepness points layer.

We analysed fire occurrence for eight slope aspect categories ((1) north (338–23°); (2) north-east (23–68°); (3) east (68–113°); (4) south-east (113–158°); (5) south (158–203°); (6) south-west (203–248°); (7) west (248–293°); (8) north-west (293–338°)) and eight slope steepness categories ((0–1°), (2–5°), (6–10°), (11–15°), (16–20°), (21–25°), (26–30°), and (30–45°)). Higher steepness categories were not considered because continuous forests do not grow on slopes >∼40°. We analysed the dependence of fire on altitude using 100-m elevation increments between elevations of 0 to 1300 m (above upper tree line).

To assess the relative distribution of burned area between different landscape features, we developed a parameter κ, which was estimated as:

$$\kappa_{c(i)} = A_{c(i)\text{-f}}/A_{c(i)\text{-I}}$$

where the *c(i)* subscript represents the *i*th category of landscape feature *c*, $A_{c(i)\text{-f}}$ is the area of fire within the *i*th category of landscape feature *c*, and $A_{c(i)\text{-I}}$ is the area of the *i*th category of landscape feature *c* over the entire island. If area burned is not dependent on the different categories of the specific landscape feature, then $\kappa_{c(i)}$ will be equal for all categories.

Error assessment

An important consideration in our study was an estimation of accuracy. Our accuracy assessment included estimating the errors associated with the following categories (Gromov and Marchenko 2002; OST-68 1998):

1. Original data sources used for digitising. This error depended on the scale of the map and was determined by the physical characteristics being measured on a map, for example, the thickness of a line. The uncertainty on these maps is ∼0.4 mm (the thickness of a printed line).
2. Vectorisation. Errors occurred during creation of DEMs depending on the computer technologies employed. Scanning, digitising methods, and mathematical operations associated with data transference all contributed this error. To minimise this vectorisation error, we used high resolution of scanning (not less than 300 points per inch), specialised applied software of the type of EasyTrace/GeoDraw (Zamai and Yakubailik 1998) and digitising methods to create a vector within the pixels' limits of raster line. In this case, such vectorisation errors are much less than the original sources for the original sources described in point 1 above.
3. The mapping model associated with transformation of spatial data. The uncertainty in the DEM may be determined by the interval used for drawing horizontal lines and the uncertainty of GRID-theme construction associated with the methods of interpolation.

The scanning of the original paper maps (1935, 1956, 1973) was done using 300 points per inch resolution. Thus, for the 1 : 500 000 scale map (1935), a 0.4-mm thick line translates into an uncertainty of 64 m, whereas for the 1 : 2 500 000 scale maps (1956, 1973), an uncertainty of 320 m was possible. For the 1998 AVHRR map, the line thickness translates into an uncertainty of 500 m. The boundaries for the 1990 map were digitised by the Woodshole Research Center, Woods Hole, MA, USA with an unknown scanning resolution. For this map, we assumed the uncertainty of the above-mentioned digitised maps (320 m).

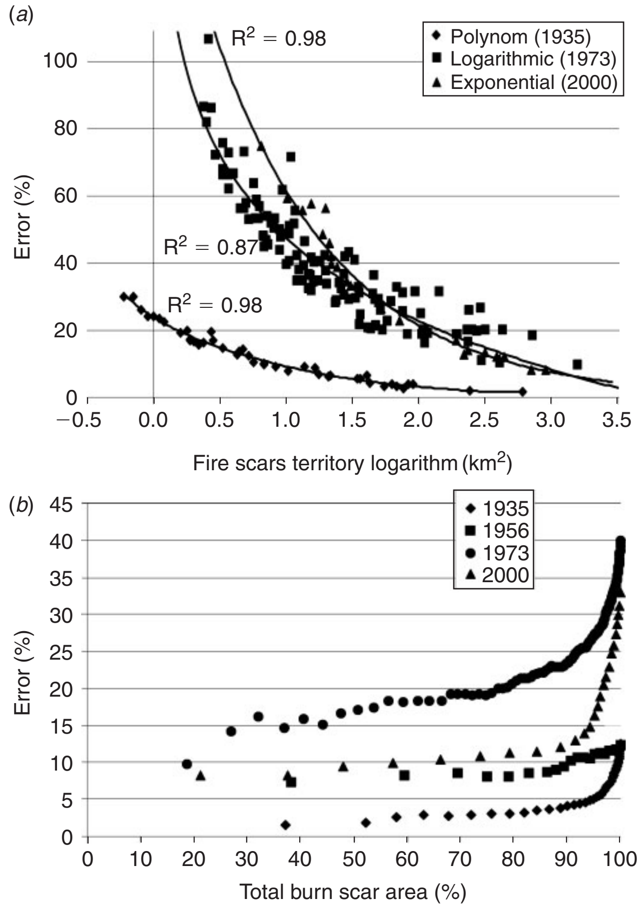

Fig. 3. (*a*) Dependence of the vectorisation uncertainties on the burned area estimates. (*b*) Dependence of average value of the inaccuracy on the percentage of the sorted testing plots total area.

The error (E) in percentage in the area of a fire boundary associated with the line thickness can be calculated as:

$$E = [(P \times L)/A] \times 100$$

where P is the perimeter of a specific fire, A is the area of the fire, and L is the line thickness.

In accordance with this formula, relative error decreases when fire area becomes larger. Another factor that has influence over the error is related to perimeter line form: error for the rounded area will be smaller than for an elongated area of the same perimeter value.

Fig. 3*a* illustrates the dependence of E as a function of A for the different map and imagery sources, and shows that as the area of the fire increases, the error of vectorisation decreases. Fig. 3*b* presents an estimate of error based on cumulative area burned, beginning with the largest fires and then adding in smaller fires. This figure shows there was a dramatic increase in cumulative errors when the smallest fires were considered. For the purposes of the present study, we used the error associated with 90% of the total area burned to represent the average error, which was 4%

for the fires of 1935, 10% for 1956, 23% for 1973, 17% for 1990, and 13% for 1998. To summarise, it must be noted that estimated error varied from year to year because of the different scales of original paper maps and the corresponding map resolution. Another factor that defines error is connected with distribution of fire scars in size: relative error is smaller for fires of large area. For example, if in a particular year there are a lot of small size fires, then an error for this year will be larger.

Results

Temporal dynamics of burned area

The inter-annual variations in burned area for Sakhalin Island over the period of 1935 to 1998 are presented in Fig. 2, which includes estimates of area burned for specific years from the official reports of fire management agencies as well as the areas generated from digitising fire perimeters from maps and imagery. Maps of the different burn perimeters for different time periods are presented in Fig. 4. Over the entire study period, fire scars were fairly evenly distributed over the entire island; however, fires were more frequent on the northern half of the island compared with the southern end. This could be attributed to lower precipitation levels in the north (400 *v.* 750–850 mm in south). Between 1945 and 1998, the official Russian statistics on fires included a total 2.10×10^6 ha of burned area (Fig. 2), whereas estimates derived from forest inventory maps and satellite imagery were 3.58×10^6 ha of burned area, or 1.7 times higher.

The availability of information on burned area that can be analysed within the framework of a GIS made it possible to analyse fire recurrence, e.g. how frequently did the same area burn over the course of the study period. The important issue in the fire-recurrence analysis is to estimate the extent to which the fire scars on the consequent maps are the same, i.e. to exclude duplication. To check that, we directly compared the fire scar contours on the consequent maps (i.e. 1956 *v.* 1935, etc.). The coincident contours (or parts thereof) of fire scars within existing fire scars where vegetation had regrown were identified. Calculations showed that the total area of these overlapping fire scars on the maps was 2.8% of the total burned area; therefore, these areas were excluded from the following analysis. We found that 90.5% of the burned areas were of a single-fire origin, 8.6% contained two fires, 0.9% three fires, and 0.03% four fires. There was a statistically significant log-linear correlation between the fire frequency (number of fires per burned area) and the proportion of the area burned (Fig. 5).

Relation of burned area to the topographic characteristics

Our analyses showed that the fires on Sakhalin Island largely occurred in the lower elevation forests. A little over 90% of the burned area occurred at elevations <300 m, and where 76% of the land surface of Sakhalin Island was at or below this elevation (Fig. 6). This result is due to higher precipitation in the mountains (1000–1200 mm); the second reason might be biomass decrease at higher elevations near the tree line (Kasischke *et al.* 2002). Fires occurred primarily on terrain with shallow slopes, with 95% of the burned area occurring on slopes <10° (Fig. 7), where 94% of all land area on Sakhalin island had slopes less than 10°. A local increase is observed at a slope steepness of >20°, which is attributed to an increase of the fire speed coefficient on the steep slopes (Fig. 7, data of 1956 and 1973). With respect to aspect, fires occurred mainly on the eastern-facing slopes of the terrain of Sakhalin Island, with local maxima on the north-eastern and south-eastern slopes (Fig. 8). This observation reflects the presence of two main ridges throughout the

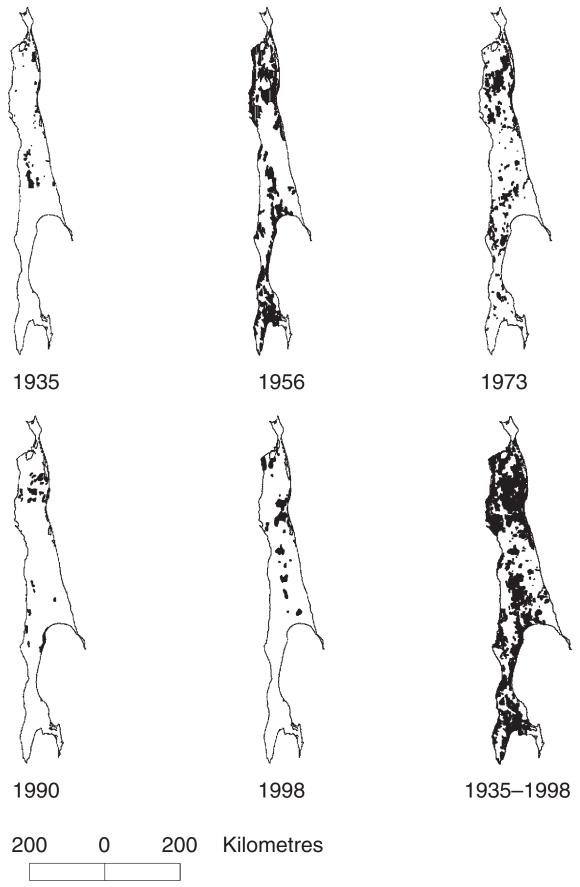

Fig. 4. Spatial distribution of burned area for Sakhalin Island from satellite imagery (1998) and forest inventory records (all other years).

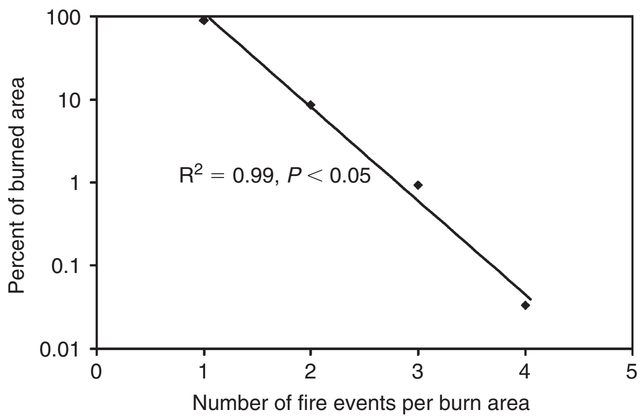

Fig. 5. Number of fire events per burn area.

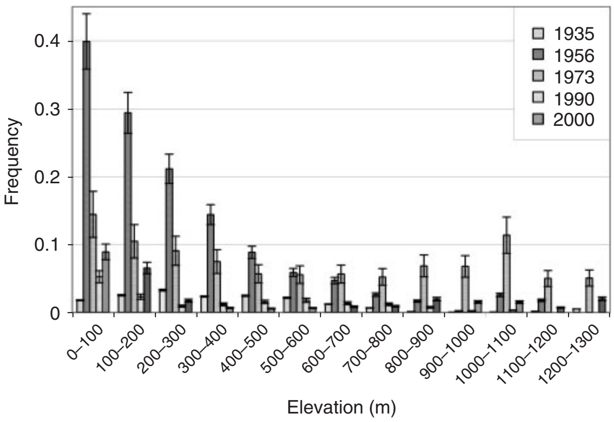

Fig. 6. Dependence of burned area on terrain elevation (normalised data).

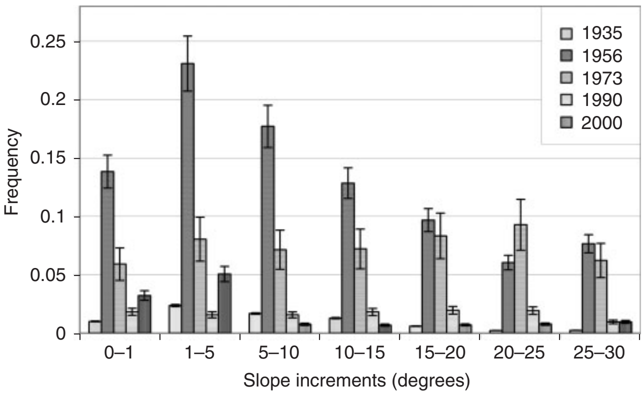

Fig. 7. Dependence of burned area on terrain slope (normalised data).

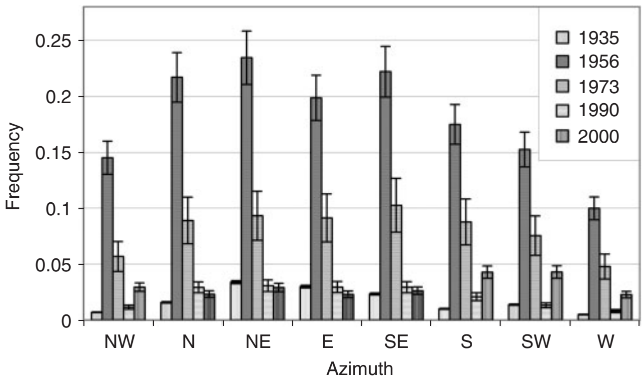

Fig. 8. Dependence of burned area on terrain aspect (normalised data).

island, which are oriented along the meridian and influence precipitation patterns.

Discussion

As study area for fire occurrence, Sakhalin Island is large enough (7.64×10^6 ha), and has the terrain orography, climate and forests that are typical for the Russian Far East; this allows us to detect some general regularities of the fire scar distribution

Fig. 9. Repeated fires (in this case 1989 and 1998) lead to substitution of larch stands by grass communities.

on the landscape. Topographic characteristics (aspect, steepness, and altitude) play an important role in wildfire occurrence and severity. Aspect and steepness considerably affect the level of fuel humidity, because windward slopes receive more precipitation, the water drains away more quickly from steep slopes, flowing down into the lower third of the slopes, and is accumulated in the local depressions. Drying of the forest fuel is also affected by aspect and slope steepness. The impact of altitude is connected with the climate vertical gradient, which in turn influences the fire danger. All landscape characteristics examined affect the type of forest combustible materials, distribution of precipitation, fuel humidity, and also wind direction (including fire-caused winds). In the continental part of Siberia, wildfires are observed mainly on the south-western slopes. On Sakhalin, fire scars occupy mainly eastern, south-eastern and north-eastern slopes owing to the orography of the island, and, more importantly, owing to the fact that eastern slopes are in the rain-shadow. The suggested procedure of normalisation allows analysing the dependence of the fire scars from landscape features, as the analysed element of the territory (with given landscape characteristics) correlates with the proportion of this relief's element on the whole studied territory. The analyses show that fires occur primarily on eastern, south- and north-eastern facing areas, with >90% of fires occurring at elevations lower than 300 m. With respect to steepness, >95% of fires occur on slopes <10 degrees; the presence of an additional maximum in fire scar distribution depending on slope steepness was also found (Fig. 7), which is consistent with a considerable increase of the fire speed coefficient on the slopes over 20 degrees. On the slopes of the mountains, stony screes and rocky outcrops form as a byproduct of fire. For the analysed time period (1935–98) ~54% of the forest land of the island forests was burned; over 90% of burns were caused by single fires. The stands suffer from fire and gradually break up, accumulating dead wood, supporting grass communities, and creating the conditions for the repetitive forest fires (responsible for ~10% of fire scars). These fires cause the greatest ecological impact by eliminating seed trees, destroying the regeneration, which may lead to deforestation of the territory for a long period (Fig. 9). For example, some fire scars that were mapped in 1935 were also present on the maps issued in 1956, 1973 and 1990.

Based on chronosequences of area burned taken from maps and satellite imagery (Fig. 2), we estimated that a total of 3.58×10^6 ha burned on Sakhalin Island between ~1935 and 1998, or 0.056×10^6 ha year^{-1}. As forested land occupied 87% of island territory, we estimated the fire return interval for Sakhalin Island to be ~120 years. This value, in the context of climate-induced increase of air temperature and extreme fire danger season frequency, will decrease, and lead to decrease of carbon sequestration capacity of Sakhalin Island forests, as well as the Russian Far East forest in general.

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