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VARIABILITY OF FIRE BEHAVIOR, FIRE EFFECTS, AND EMISSIONS IN SCOTCH PINE FORESTS OF CENTRAL SIBERIA

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Abstract. As part of the Russian FIRE BEAR (Fire Effects in the Boreal Eurasia Region) Project, replicated 4-ha experimental fires were conducted on a dry Scotch pine (Pinus sylvestris)/lichen (Cladonia sp.)/feathermoss (Pleurozeum schreberi) forest site in central Siberia. Observations from the initial seven surface fires (2000-2001) ignited under a range of burning conditions quantified the different fuel consumption and fire behavior characteristics (e.g., rate of spread, fireline intensity, etc.) possible in this particular forest fuel type. Experimental results and dendrochronological study of local fire history both support the dominance of local fire regimes by low to moderate-intensity surface fires. Carbon released by the experimental fires ranged from 4.8 to 15.4 t C ha^{-1} depending on fuel conditions and fire severity. Preliminary emission data show a strong correlation between carbon dioxide (CO_2) and carbon monoxide (CO) emissions, which should facilitate accurate estimates of fire impacts on atmospheric chemistry. Carbon concentration in smoke samples was related to fire severity. The short landscape-scale fire-return interval (50 years), combined with typically low fire severity, in pine ecosystems of central Siberia is often associated with low tree mortality and relatively rapid buildup of litter and understory fuels after a fire.

Keywords: aerosols, carbon, emissions, FIRE BEAR Project, fire regimes, forest fire behavior, Scotch pine, Siberia

1. Introduction

The Russian boreal forest zone contains about 21 percent of the global forest area and is a major reservoir containing 28 percent of the global forest carbon (Dixon et al. 1994), yet data on the extent and impacts of fire in these forests related to actual burning conditions are scarce and often contradictory. While past Russian records have tended to underestimate burned area (Cahoon et al. 1994; Conard et al. 2002; Kasischke et al. 1999), recent efforts in the field of remote sensing have produced improved estimates that suggest that wildfires in Russia can affect as much as 12–14 million ha per year (Cahoon et al. 1994; Conard and Ivanova 1997; Conard et al. 2002; Dixon and Krankina 1993; Kasischke et al. 1999). However, additional research is needed before remote sensing data can be used to accurately quantify fire severity or the impacts of wildfires on terrestrial carbon cycles. Furthermore, changes in land management and land-use practices, regional climate, and fire suppression capability will affect fire risk and ecosystem damage from fires in ways that are poorly understood. In changing environments, fire can be a key agent to accelerate changes toward new ecosystem conditions. Improved understanding of the landscape extent and severity of fires and of factors affecting fire behavior, effects of fire on carbon storage, air chemistry, vegetation dynamics and structure, and forest health and productivity is needed before such considerations can be adequately addressed in regional planning. The Russian FIRE BEAR (Fire Effects in the Boreal Eurasia Region) Project is a forest fire research study in central Siberia developed to provide answers to these basic questions on the management of fuels, fire, and fire regimes to enhance carbon storage and forest sustainability in ways that minimize negative impacts of fire on global environment, wood production, and ecosystem health. The purpose of this paper is to provide initial results from this ongoing project for the years 2000 and 2001.

2. Methodology

2.1. Description of study area

The research site is in a remote location along the Tugulan River on the west side of the Yenisey River (60°38′N, 89°41′E) in the Krasnoyarsk Region of central Siberia. The village of Yartsevo, the closest to the site, is 60 km to the southeast. The study site is situated on the Sym Plain, part of the eastern edge of the West Siberian Plain, which extends from the Yenisey River in the east to the Ural Mountains in the west. The Sym Plain is relatively flat (200–300 m above sea level). High-ground water levels and discontinuous permafrost have favored the creation of numerous small lakes and bogs. Alluvial sands and loamy sand are common in river valleys and ancient linear runoff depressions of the region (Gorozhankina and Konstantinov 1978; Zhukov et al. 1969; Parmuzin 1985).

Stands in the research area are representative of the central taiga pine forests (Parmuzin 1985) that occur across the Sym Plain landscape. The total forest area is less than 40 percent of the region due to the abundance of bogs. The particular site type represented on our study area is a Scotch pine (*Pinus sylvestris)*/lichen (*Cladonia* sp.)/feather moss (*Pleurozeum schreberi*) forest type located on a dry site. The soils are alluvial-ferrous podzols supported by small-grained carbonate-free sand with no underlying permafrost. The site quality is Class IV and Class V (Anuchin 1982).

The West Siberian Plain is in the transition zone between the Atlantic air mass of the west and the continental air mass of eastern Russia. There is a north-south increase in continental climate over the area (Alisov, 1956). The climate is cool and moist, with an average annual air temperature of −2.2 °C. Annual precipitation is 433 mm, with large year-to-year variations. The summer frost-free period is typically 86–107 days. Stable Siberian anticyclones dominate the area in winter, with temperatures often reaching −50 °C. In spring, increases in insolation lead to a decrease in relative humidity and drought periods are common.

In the summer, cyclone activity grows and promotes penetration of warm air from the south. While most precipitation occurs in the summer months, drought is also common here due to dry and warm air masses coming in from central Asia, Mongolia, and the central portions of eastern Siberia. During these droughts, the forest can become highly flammable. Most large fires occur from June to early August (Valendik 1990; Valendik and Ivanova 1996).

2.2. Plot design

Twenty-two plots measuring approximately 200 × 200 m (4 ha) were laid out at the experimental site. To help coordinate the various types of data being collected, a 25 × 25 m sampling grid was laid out on each plot using numbered metal pins (normally 49 pins). The grid location was tied into the corners of each plot to assist in geo-referencing of the grid. Since the lichen can become very fragile when dry, travel corridors were established within each plot to access the grid sample pins and to restrict the spatial impact of disturbance caused by researchers. Three plots were set aside as unburned controls.

A complete fire weather station was established and maintained once researchers arrived at the site for the season (usually for the June to July period). Daily observations of dry-bulb temperature, relative humidity, barometric pressure, 10 m open wind speed, wind direction, and precipitation were taken at 1300 hours Local Standard Time (LST) to assist in calculating different fire behavior danger rating systems. Weather data from the Yartsevo airbase were used for the early part of the fire season.

2.3. Fuel sampling

Ground fuel consisting of the organic forest floor (litter, fermentation, and humus layers) was sampled at 24 locations on each plot. Ground-fuel sample points were 1 m east of every other grid-sampling pin starting with Pin 1. At each point a 25 × 25 cm sample was cut from the forest floor (through the litter to mineral soil). After the litter layer was collected, the duff and humic horizons were sectioned horizontally into 2 cm thick layers. Samples were oven-dried to determine weights. Estimates of fuel weights of the surface vegetation (e.g., *Vaccinum* sp., *Ledum* sp., etc.) were also obtained from the ground sample plots. Postfire samples were taken immediately after each fire adjacent to the prefire sample locations to determine actual consumption.

Surface fuels representing dead and down woody fuels (DWF) were sampled prior to and immediately after each fire with a modified version of the line-intersect method used by McRae et al. (1979). Since we were dealing with a natural situation where the DWF should fall to the ground without any bias to orientation, a 5 m straight-line transect was set up in an east-west direction. The grid pin was used to delineate the transect beginning and a smaller metal pin was used to delineate the transect's end. The use of metal pins allowed transects to be accurately relocated for postfire sampling. Because of the apparent sparseness of DWF on the plots, all the slash size classes were tallied for the entire length of all sample lines (49 lines/plot). Two depth-of-burn pins (McRae et al. 1979) were placed one meter on either side of the end-sampling pin. Crown fuel weights were determined by destructive sampling of trees using standard fuel size classes of dead and green branch wood material (McRae et al. 1979) but are not reported here as no crown fires were experienced during the first two years of burning. Permanent photo points established at various sampling grid pins allowed the changes brought about by the fire and the postfire recovery to be documented.

2.4. Burning procedures

Fires were carried out in June and July, which corresponds to the main fire season for this region. Plots were burned under a wide range in fuel moisture and weather conditions to observe effects on fire behavior, fire severity, emissions, and other ecological factors. Construction of protective firelines (primarily consisting of a 30 cm plowline), ignition, and suppression were the responsibility of the Russian Aerial Forest Protection Service (Avialesookhrana) fire management personnel. All experimental plots were burned using line ignition along the windward side to quickly create equilibrium fire behavior that mimicked wildfires under similar burning conditions (Johansen 1987; Weber 1989). Ignition commenced in the middle of the windward plot side and was carried out by two people using Russian driptorches walking quickly to either plot corner to ensure rapid ignition of the entire side. The driptorches were also used to burn out each side as the fire spread down the plot to ensure containment of fire within the firelines. In more severe burning conditions, the firelines were widened on critical sides with a 5 m burnout strip prior to ignition of the main fire.

2.5. Fire behavior monitoring

To enable accurate measurement of fire spread, electronic timers similar to those of Blank and Simard (1983) were constructed. These timers were buried next to each sample grid pin (49 timers per plot) to record the time when the flaming front passed each pin. The basic principle for the timer use is that 3 time values are required as input into an algorithm developed to estimate direction and rate of spread of a fire across a triangular area (Eenigenburg 1983, 1987;

Simard et al. 1984). Visual observations with stopwatches supplemented the timer data.

Fuel moisture samples were taken of major types of ground and surface fuels just prior to burning in areas adjacent to the plot being burned. These were collected by depth or woody fuel size in metal soil tins that were sealed with tape to prevent any moisture losses. Tins were stored in a cool place until they could be transported to the laboratory, where they were dried and reweighed to determine moisture content. Recording anemometers made five-second observations at a 1.5 m height above the ground in the understory adjacent and upwind of the burn plot. Fire documentation using videotape recorders and still cameras allowed for further post-fire analysis.

2.6. Vegetation

Vegetation was sampled and described to provide a good description of the fuels present on a dry Scotch pine forest site. The vegetation on the experimental plots was described based on standard Russian inventory methods (Sukachev et al. 1957; Pobedinsky 1966). Description of the living ground cover included its structure, composition, abundance based on 7 categories (i.e., from single individuals to high density) using the Druhdeh's scale (Pobedinsky 1966), and projected cover.

To quantify tree seedling regeneration (<5 years old), we determined seedling density, age, height, and distribution of regeneration related to microenvironmental conditions across the plot site. Twenty-five sample plots were laid out tied to the sample grid points. Plot size was either 2 × 2 or 1 × 1 m, depending on the density and uniformity of distribution of the regeneration. Seedling age and height were recorded and regeneration vigor was categorized using Alexeyev's (1989) method, where seedlings are classified as healthy, weakened, dried-out, or dead. Saplings (>5 years old) were also tallied on these plots.

Shrubs were sampled using 2 × 2 m sample plots that were tied to the sampling grid. Within each sample plot, projected cover (%), number of shoots, average height, and average stem diameter at ground-level were determined for every shrub species. To facilitate interpretation of fire behavior and fire effects data, the living ground cover was mapped out for each plot. This consisted of identification of all vegetation associations and determining their boundaries based on differences in species composition and dominance. The classification used was derived from the surface vegetation plots described above. Mapping was accomplished by walking along the 25 × 25 m sampling gridlines and establishing sample points every 5–10 m, depending on ground cover diversity, to determine boundaries more exactly. Boundary locations for each vegetation association were mapped by stretching a measuring tape between the sampling grid points.

Stand structure of trees greater than 10 cm diameter at breast height (DBH) was measured using the point-centered quarter (PCQ) method (Cottam and Curtis 1956). The PCQ plots were centered on every other grid sampling point. Each tree was characterized by basic mensurational parameters (e.g., height, DBH, and height to live crown (HTC)) as well as by measures of char height after the fire. Stand density and tree basal area were also determined from these data.

2.7. Forest Fire Chronology and Fire Regime Reconstruction

Forest fire chronology for the project area was reconstructed from dendrochronological analysis of slabs cut from well-pronounced fire scars found on trees located throughout the experimental area. In addition, well-preserved snags and stumps were sampled to obtain longer fire chronologies. Estimated fire dates were determined from standard fire-scar analysis methodology (Madany et al. 1982; Dieterich and Swetnam 1984). All tree rings were cross-dated using the methodology of Shiatov (1986). Fire years identified on the slabs were then pooled into a number of general site chronologies (Madany et al.1982; Baisan and Swetnam 1990; Caprio and Swetnam 1993; Swetnam 1996). This enabled highly reliable determination of years with fires. Because a large percentage of fires in this ecosystem are small in area (<2 ha), mean fire intervals were estimated for our forest island from the fire chronologies in several ways. We determined ratios between the period covered by the series and the number of recorded fire dates for all cores (Arbatskaya and Vaganov 1997). We then determined similar ratios for fire dates that occurred on at least 30 percent and at least 50 percent of the cores in the sample at that date to gain better insight into the spatial scale of fires on the landscape. In addition, we determined average fire return intervals for the period 1550–1956 for 7 individual trees that recorded both the 1869 and 1956 fires. Slab samples were taken from 6 live trees and from 5 dead snags and stumps at our site. In addition, slabs were collected from 13 trees on two forested island sites immediately southeast but separated from our study site by bog.

2.8. Fire Emissions

Emissions of trace gases and aerosol particles were sampled only at ground level in 2000 to characterize emissions from specific fuels during smoldering combustion. For 2001, sampling also took place in the smoke plumes. The aerial samples were collected by a helicopter (Russian MI-8) to allow characterization of the integrated emission products from flaming and smoldering combustion of the fire above the canopy.

2.8.1. *Carbon Emissions*

The ground carbon emission sampling system consisted of a battery-powered pump mounted on a portable table that allowed the equipment to be quickly moved to new sampling areas. Samples were collected through a stainless steel sampling probe connected to a flexible stainless steel tube leading to the pump. The intake was held approximately 0.5 m above the emission source. Samples were collected in evacuated 250 ml glass bottles that were pressurized to approximately 1.9 atmospheres.

Aerial samples were taken after the flame front had advanced two thirds of the distance across the experimental plot. Samples were collected in the smoke plume about 150 m above the ground (120–200 m). Clean air samples were collected prior to all fires to establish background concentrations and to verify that there was no contamination from the helicopter exhaust in the sampling stream. Instrumentation on board (see below) enabled the determination of when emission concentrations were high enough to take samples. Although the smoke may have been diluted by the helicopter downwash, smoke concentration in samples was sufficient for accurate analysis of chemical components and for calculating emission factors for all compounds of interest. Aerial samples were collected through a 6.4 mm stainless steel line that extended out from a belly port of the helicopter. The instruments aboard the helicopter consisted of:

1) A LICOR LI-800 carbon dioxide (CO_2) instrument, with a flow rate of 1 l/min.
2) A Campbell Scientific data logger with a keypad/display to record and display real time CO_2 concentrations every second.
3) A canister sampling system consisting of a 12-volt KNF pump, with an adjustable pressure relief valve downstream set at 2.3 atmospheres to control the pressure in the canister. Electro-polished 850 ml evacuated stainless steel canisters were used for collection. Quick-connect fittings on the canisters and a flexible stainless steel line allowed fast changeover of canisters.

Carbon monoxide (CO), CO_2, and methane (CH_4) were analyzed for all samples with a Hewlett Packard 5890 gas chromatograph equipped with a methanizer and a flame ionization detector. The column used for CO and CO_2 was a 3.2 mm diameter Alltech Carbosphere carbon molecular sieve, with helium carrier gas (flow rate 18 ml/min). Calibration standards of CO, CO_2, and CH_4 (Air Liquide) were used, as well as National Institute of Standards and Technology (NIST) reference standards for CO, CH_4, and CO_2. The chromatograms were collected and analyzed using HP ChemStation II software. Low levels of carbon monoxide in the helicopter canister samples were analyzed using a Trace Analytical RGA3 reduction gas analyzer. The clean air samples taken from the helicopter prior to each fire had concentrations below 0.10 ppm for CO and below 360 ppm for CO_2.. This eliminated any concerns of contamination of our samples from the helicopter exhaust.

An emssion factor, defined as the amount of the compiound emitted per kilogram of dry biomass burned, was calculated for these carbon compounds. The modified combustion efficiency is the molar ratio of the emitted CO_2 to the sum of the emitted CO and CO_2 above ambient levels.

2.8.2. *Aerosol Emission*

On-ground particulate sampling was carried out at the edge of the burning experimental plot. Smoke was pumped through a circular 70 mm polymeric thin-fibrous aerosol Petrjanov (AFAChA-20) filter fixed in a filter holder with a pump flow rate of 20 l/min. Collection time ranged from 2-10 min per sample taken at a height of 0.5-1.0 m above the ground over the ignition source. Before use, all filters were dried to constant weight (5–7 days) in a hermetic glass desiccator filled with granules of fresh NaX zeolite (the 13X Molecular Sieves) that had been dried at 400 °C for several hours before being used. Weighing of filters post-fire used the same drying procedures. Sample weights on the AFAChA-20 filters ranged from approximately 1–10 mg dependent upon smoke characteristics and pumping time. These small-weight samples make the weighing procedure very important.

Aerial samples were taken using a filter probe extended out of one of the helicopter's side portholes a distance of 0.5 m from the body. A pump with a flow rate of 100 l/min was run 1–2 min per sample. A filter register was kept for each sample that included important parameters (e.g., the date of the sample, fire conditions, kinds of fuel being burned, sample location, pumping flow rates, times of pumping, etc.).

Quantitative determination of chemical elements in the aerosol particles sampled on the AFAChA-20 filters was performed by the synchrotron radiation X-ray fluorescence (SRXRF) method (Barashev et al. 1986, 1995). This method can only detect elements heavier than potassium. The sensitivity of the SRXRF method was studied earlier with reference to various mineral substances, and the detection limits were found to range from 0.05–0.1 g/cm^2 for calcium and potassium to 0.0004–0.001 g/cm^2 for strontium, zirconium, and molybdenum. Concentrations lower than the detection limits were recorded as zero.

Aerosols produced from soil erosion are always present on vegetation and in the atmosphere as dust, and this must be corrected for in the results. Since iron is not normally found in biomass smoke emissions, it can be used to correct filter sample results for ambient aerosol element concentrations produced from soil sources. Published reference data for the normal soil element contents of typical soils found in central Siberia (e.g., clay, sedimentary clays, shale, sand, etc.) from Kist (1987), Perelmann (1979), and Kovalskaja (2002) was used to differentiate between the two sources for emission microelements collected (burning of forest biomass versus soil emissions). To do this, we normalized the concentrations of the microelements relative to the concentration of iron found in the emission sample. The reference relative concentration (RRC) is the amount of a particular element in background soils relative to iron, based on published reference data (Table VII; data from Kist 1987; Perelmann 1979; Kovalskaja 2002). Experimental relative concentrations (ERC) are the element amounts measured in smoke samples on the aerosol filters relative to iron. The ratio ERC/RRC, referred to as experimental reference ratio (ERR), represents the relative increase of an element in the aerosol smoke sample compared to the soil reference value. A ratio near one indicates that soil is the primary source of the element; the greater the departure from one, the greater the contribution of biomass combustion to the aerosol concentration of a particular element.

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3. Results and Discussion

3.1. Forest fire chronology and fire regime reconstruction

The fire history for the study site was reconstructed to determine dates of past fires. Fourteen fires were dated from fire scars over a 450-yr period: 1599, 1661, 1701, 1722, 1737, 1744, 1779, 1808, 1813, 1860, 1869, 1912, 1919, and 1956 (Figure 1). The ages of the oldest trees on the site and dendrochronological methods based on tree ring width suggest that a widespread stand-replacement fire also occurred in 1550. A number of these fire dates were recorded on only a small percentage of sampled trees, indicating that they were quite local (small) in nature. A fire occurred somewhere on our forest island site an average of every 29.0 years between 1550 and 1956, the dates of the first and last recorded fires on the site. However, this does not consider the extensiveness of fires at different spatial scales (Swetnam and Baisan 1996). To filter this out, we noted that twelve fires were recorded on at least 30 percent of the trees (including the 1550 date). The average mean fire interval between these fires was 36.9 years. Larger, landscape-scale fires recorded on at least 50 percent of the sample trees occurred 8 times (every 58 years) over the same period. The largest fire events, which affected essentially all trees in the samples, occurred in 1550, 1661, 1722, 1813, 1869, 1912, and 1956 (every 67.7 years). Most of these events are recorded by fire scars, and were apparently not stand-replacement fires. Widespread stand-replacement fires (as evidenced by mortality

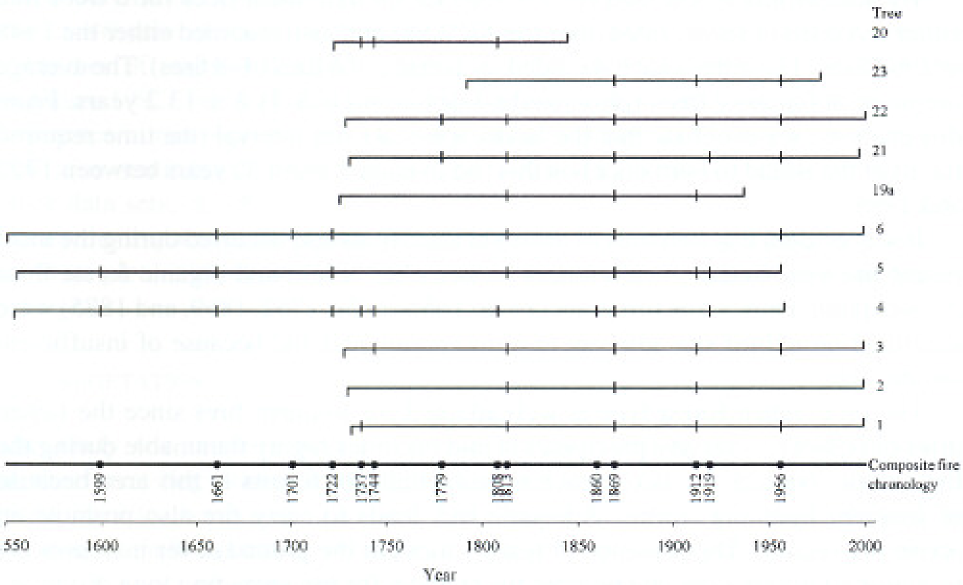

Figure 1. A fire chronology chart showing dates of fires based on fire scar and dendrochronological analysis of selected trees on and adjacent to the experimental site.

of sample trees and appearance of new regeneration) occurred only in 1550, 1722, 1813 and 1869. This gives an interval for stand-replacement fires of over 150 years for this site (1550–2000).

We also estimated the average fire interval on individual trees that either recorded or regenerated after the 1722 fire and also recorded the 1956 fire. Seven trees each recorded an average of 6 fires (4–8 fires). The average fire interval for these trees (plus one standard deviation) from 1722 to 1956 was 49.6 ± 13.6 years. From this analysis, we conclude that the landscape-scale fire interval (the time required for all of the island to burn once) on our study area averaged about 50 years between 1722 and 1956. With the small number of sample trees available for the earlier period, it is hard to make a reliable estimate, but the average interval for fires recorded on these three trees between 1550 and 1722 is 57.3 years.

Sixteen fire years were identified on a forest island sampled adjacent to our experimental fire site: 1668, 1696, 1722, 1738, 1754, 1769, 1781, 1822, 1869, 1879, 1898, 1912, 1926, 1948, 1966, and 1998. The oldest tree was 420 years old dating from 1578. Fires were recorded an average of every 20 years on this site between 1668 and 1998. A similar analysis to that conducted for the experimental site (above) indicated that 9 fires were recorded on at least 30 percent of the trees, with an average interval of 36.7 years. Fires recorded on at least 50 percent of the sample trees occurred 7 times (every 55.0 years) over the same period. The largest fire events, which affected essentially all trees in the samples, occurred in 1722, 1869, 1898, 1948, and 1998 (every 82.5 years). Widespread stand-replacement fires occurred only in 1722 and 1869 (an interval >140 years).

We also estimated the average fire interval on individual trees for 6 trees that either recorded or regenerated after the 1722 fire and also recorded either the 1948 or 1998 fires. These trees each recorded an average of 6 fires (4–8 fires). The average fire interval for these trees (plus standard deviation) was 51.8 ± 13.2 years. From this analysis, we conclude that the landscape-scale fire interval (the time required for all of the island to burn once) on this site averaged about 52 years between 1722 and 1998.

It was evident that two fires of different intensities had occurred during the most recent fire year based on differences in tree char height and organic forest floor consumption. Only a few fire years (1572, 1656, 1722, 1752, 1869, and 1885) were identified on a third site adjacent to our experimental site because of insufficient sample size.

The pine-lichen forest type is well adapted for frequent fires since the lichen dries out quickly after any precipitation and becomes highly flammable during the fire season. Natural fire occurrence remains high for forests in this area because of frequent lightning storms. Adequate fuel loads to carry fire also promote an active fire regime. The presence of feather moss in the ground cover increases the ground-fuel drying time and reduces the chances for fire spreading long distances.

The various fires on our sampled forest island sites appeared to have occurred often at different dates. However, 1722, 1869, and 1912 appear to be years when fires occurred on more than one site probably indicating dry years when extensive fires were prevalent here. Since the experimental site is remote and inaccessible to the local population during the summer, these fires were almost all primarily lightning-caused. The many tree individuals that have been clearly hit by past lightning and sustained damage on these sites confirm the frequency of lightning hits at our site. The abundance of fire-scarred trees that are still alive indicates that most of the fires identified were low- to moderate-intensity surface fires. Since signs of some fires occurred on just a few of our trees, this probably indicated that these fires were small and short-lived due to unfavorable weather and fuel conditions. In their fire chronology study for the Yeniseysk Region, Arbatskaya and Vaganov (1997) indicated that 1822 and 1898 were large-burned-area years.

The mean fire interval estimate of about 50 years for our site differs from that calculated for the pine/lichen stand of Bor Island located 30 km north-east of our project area. Although Bor Island is also an isolated inaccessible forested island with lightning being the sole ignition source, the mean fire interval is 95 years (FIRESCAN Science Team 1996). The forest island on which our site was located was much larger in area than Bor Island (50 ha), which would lead to a higher probability of ignition by lightning strikes. To explain this type of effect, Wirth et al. (1999) developed a fragmentation index that linked decreased fire frequency to increases in the degree of forest fragmentation by wetlands. Our current research site also has a groundcover diversity much greater than what was found on Bor Island. This can affect the spatial and temporal patterns of fire by breaking up continuity of fuels and locally inhibiting fire spread under less extreme conditions. The fire interval of about 50 years for our site is longer than the 25–40 year intervals described for other pine/lichen forests in the region by a number of other researchers (Furyaev 1996; Swetnam 1996; Arbatskaya and Vaganov 1997; Wirth et al. 1999). While this difference may represent an actual difference in fire regime related to the relative isolation of the site by wet bogs, it may also result from differences in approach to data analysis, in sample sizes of other data sets, or other factors. Careful comparisons among various data sets to clarify the impacts of these factors on fire interval estimates could provide a more accurate picture of landscape-scale fire regimes for dry Scotch pine sites in central Siberia.

3.2. Vegetation

The study site consists of a forest island surrounded by bogs, and is typical of the forest-bog matrix found in this region. The site is occupied by a pure pine/lichen/feathermoss forest stand. The stand typically has a single-canopy but is made up of multi-aged trees averaging 23–35 cm in diameter and 17–22 m in height (Table I). There are small patchy areas of sapling-size trees, which are usually in areas of more open canopy and appear to have been created by earlier disturbances. Fires have had a considerable impact on the age structure of the pine stands found

TABLE I

The prefire Scotch pine forest stand structure present at the experimental site near Yartsevo, Siberia

Fire No.	Average tree dbh* (cm)	Average tree height (m)	Stand density (stems/ha)	Stand basal area (m^2/ha)	Percent live trees (%)
1	30.5	20.6	441	34.3	100.0
2	30.6	20.0	216	17.8	100.0
3	29.1	19.2	324	24.2	100.0
4	35.2	17.9	219	23.1	88.5
5	25.4	16.8	376	22.0	91.4
6	31.1	19.4	200	16.5	89.0

*dbh represents diameter at breast-height.

on the experimental site. Although these are predominately single-canopy stands, several age groups were identified on various parts of the island (120–140, 180–190, 220–250, and 280 years old). These trees were established following the 1722, 1744, 1813, and 1869 fires (Figure 1). The oldest trees are 450-years old.

Regeneration consists of 0.5 m high pine seedlings evenly distributed across the site. Saplings, growing in small clumps in open areas, are 2–3.5 m high. The density of the seedling regeneration ranges from 5–30 thousand per hectare. Most seedlings do not survive due to stresses caused by shade intolerance and moisture deficiency; those that do survive are too short to contribute to any ladder fuel effects that would assist in the transition from a surface to a crown fire.

Understory vegetation, consisting of shrubs, grasses and forbs, is sparse due to the dry nature of the site. *Ledum palustre* is the dominant understory shrub with scattered individuals of *Rosa acicularia* and *Salix caprea*. The ground cover varies with micro-environmental conditions, but generally occurs in distinct plant microgroups. The *Ledum sp./Vaccinium vitis-idaea*/sphagnum (*Sphagnum* sp.) association dominates the moister parts of depressions within the forest. Coverage of the grass/small shrub layer ranges from 15–40 percent with heights ranging from 20–35 cm. Shrub species composition varies considerably with microsite conditions (*Vaccinium vitis-idae, Vaccinium myrtillus, Ledum palustre*). On better-drained mesotrophic sites, *Vaccinium vitis-idaea* and *Vaccinium myrtillus* are abundant. *Ledum* covers all moist sites, and excessively wet sites favor species typical of bogs (e.g., the *Ledum* sp./*Vaccinium vitis-idaea/sphagnum* sp. microgroup).

The diverse nature of the living groundcover across these dry Scotch pine sites is illustrated in Figure 2. Lichen (e.g., *Cladonia rangiferina, Cladonia arbuscula, Cladonia gracilis, Cladonia stellaris, Cladonia uncialis*, and others) is widely distributed on the site. Its coverage varies greatly ranging from 20% on sites without

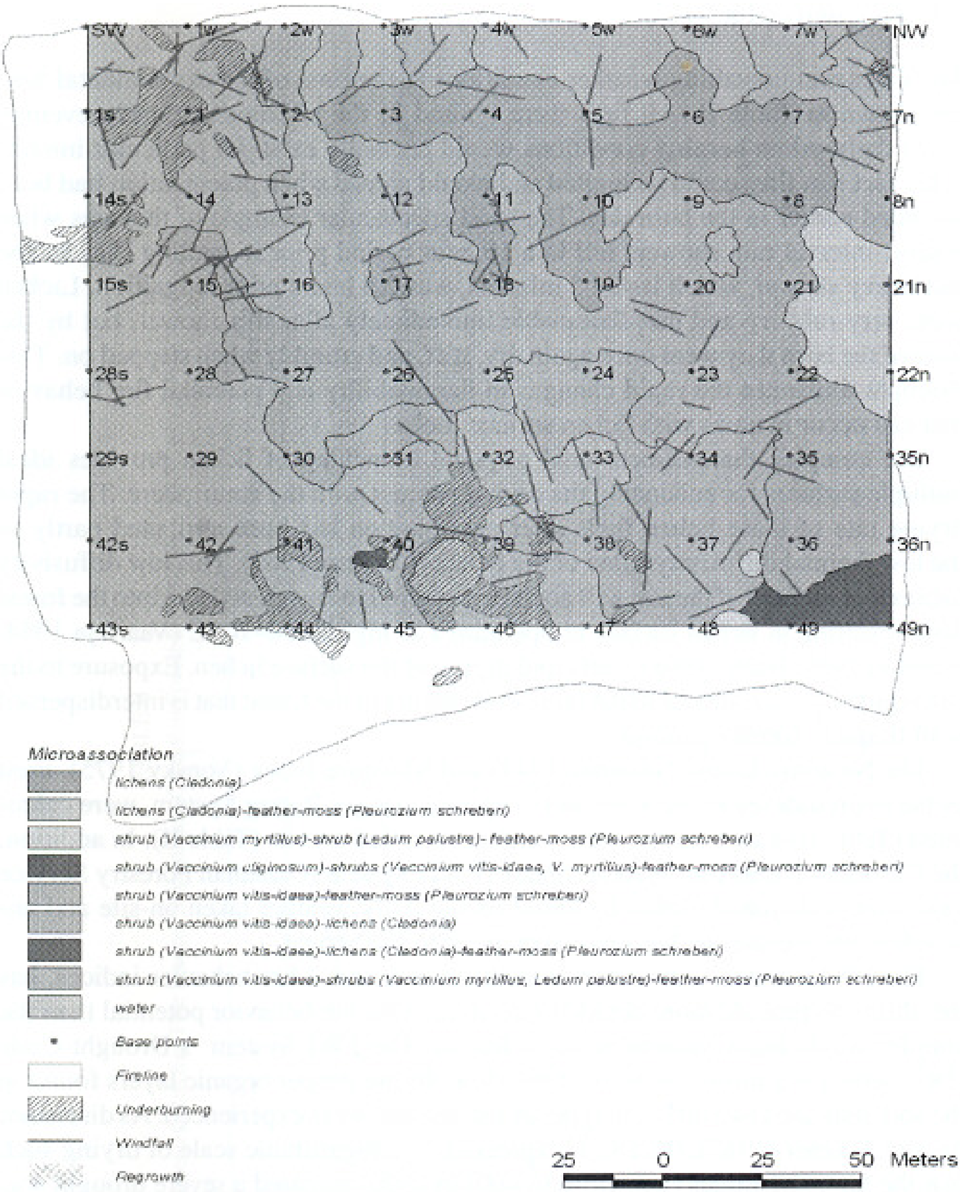

Figure 2. A prefire living-ground cover map for Fire 6 showing the diversity of ground types present at the experimental site.

recent burns to 100% on sites with more recent burns (i.e., 30–35 years ago). A moss layer dominated by *Pleurozeum schreberi* also covers 60-100% of the total area. Other mosses were also present (e.g., *Dicranum polysetum, Aulacomnium palustre, and others).*

3.3. Fire behavior

The dates and prevailing weather conditions at the time of the experimental fires are shown in Table II. All fires were ignited in the afternoon or early evening when daily prime burning conditions would normally exist. Of particular interest is the fact that fires could be ignited and would spread when precipitation had been recorded earlier in the burn day. The most spectacular example of this was when 6 short-interval rain showers fell in a 16 hour period prior to igniting Fire 3. The last heavy shower, which lasted 5 minutes, was 2.5 hours prior to ignition. Lichen were very rubbery and non-flammable immediately after this shower, but by the time of the burn they were once again dry, stiff, and crumbly when stepped on. This example illustrates the rapid changes in flammability and potential fire behavior that can occur in areas with lichen surface fuels.

The complex three-dimensional physical branching of lichen provides ideal multiple surfaces for enhancing the drying process with the atmosphere. The rapid drying rate of these lichen fuels after precipitation has been attributed partly to the low thermal diffusivity value of the lichen (Cochran 1969). This low diffusivity means that the heat of the sun will not be transferred to any great depth into the forest floor resulting in lichen surface temperatures as high as 50–70 °C (Vaartaja 1954, Beaufait 1959, Hallin 1968), and rapid drying of the surface lichen. Exposure to the sun is aided on our site due to the more open nature of the forest that is interdispersed with frequent forest openings.

The Nesterov Index (Nesterov 1949) and Moisture Index (Vonsky 1975), used as the main indexes in the Russian Forest Fire Danger Rating System, were calculated (Table II) based on the daily weather recorded on site (Table II). In addition, the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service 1987) was calculated (Table II) based on the daily weather taken on-site and antecedent fire weather at Yartsevo taken prior to our arrival.

The FWI System, with 3 fuel moisture codes and 3 fire behavior indices, has the ability to provide more detailed information on fire behavior potential than the simpler single index systems used in Russia. The FWI System 's Drought Code (DC), which is a moisture index of the slow-drying deeper organic layers found in the soil, indicated two different types of fire seasons were experienced. As discussed by Van Wagner (1987), the DC is expressed on a logarithmic scale of drying such that the high DC values (i.e., close to 400) in 2000 indicated a severe drought was occurring in the area that would indicate the potential for deeper burning of the organic forest floor, while the lower DC values (i.e., close to 200) of the July fires in 2001 indicated a much less severe fire season. The only early season fire (Fire 3), that took place in June rather than July, had a DC value of only 104 indicating that the deeper layers of the forest floor would have been too moist to be consumed by any spring fire. An extreme overall fire danger, based on the Fire Weather Index (FWI) value, was recorded for Fire 1.

TABLE II

Ambient fire weather parameters, Russian Fire Danger System and Canadian Forest Fire Weather Index (FWI) System component values associated with each experimental fire

			Weather parameters[a]				Russian Fire Danger System		Canadian Forest Fire Weather Index (FWI) System components[c]					
Fire No.	Date (dd/mm/yyyy)	Ignition time (LST)	Temperature (°C)	Relative humidity (%)	Wind (km/h)	Rain[b] (mm)	Nesterov index	Moisture index	FFMC	DMC	DC	BUI	ISI	FWI
1	18/07/2000	15:00	26.4	21	1.0	0.0	2093	2421	92.8	50.5	393	76.4	8.5	24.7
2	26/07/2000	16:30	24.2	50	3.6	0.0	1170	1273	87.7	34.8	399	57.1	3.2	10.0
3	19/06/2001	18:00	27.0	32	10.2	2.0	2045	1583	84.9	16.9	104	24.0	3.4	6.3
4a	24/07/2001	17:00	14.1	95	3.6	0.7	461	470	73.7	27.4	193	40.4	0.9	1.8
4b	26/07/2001	15:00	18.2	43	9.7	1.0	207	297	76.0	18.9	189	30.2	1.3	2.6
5	28/07/2001	15:00	21.2	40	0.8	0.0	1034	1124	86.9	23.4	202	36.4	2.8	6.8
6	30/07/2001	14:00	22.4	52	2.6	0.0	561	651	88.1	28.2	217	42.6	3.7	9.5

[a]Based on solar noon weather.

[b]Rainfall in previous 24-hr period.

[c]Based on weather at ignition (see Table I). Abbreviations are: FFMC-Fine Fuel Moisture Code, DMC-Duff Moisture Code, DC-Drought Code, ISI-Initial Spread Index, BUI-Buildup Index, and FWI-Fire Weather Index. Further component definitions of the FWI System may be found in Canadian Forestry Service (1987).

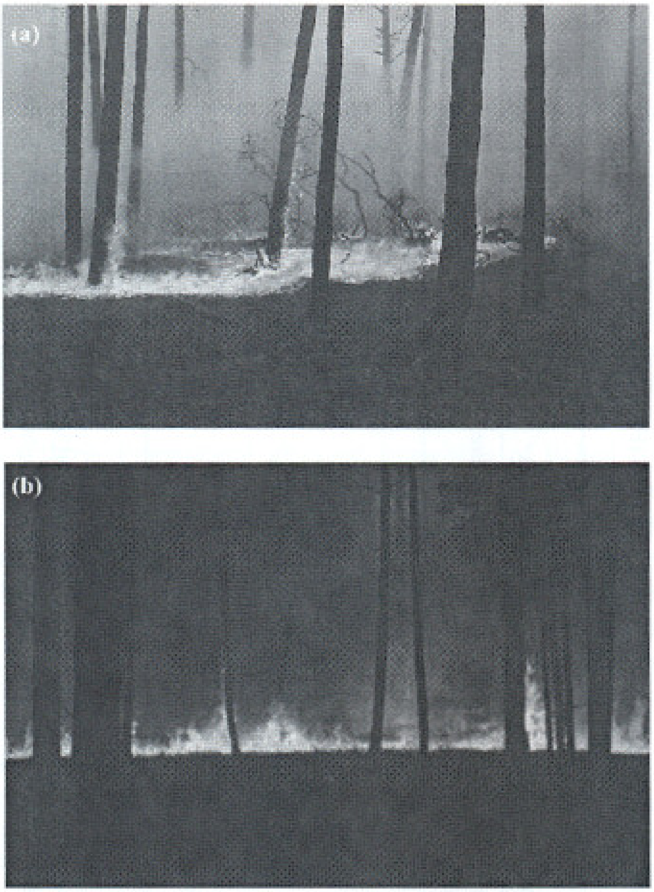

Figure 3. Pictures showing typical Scotch pine fire behavior on a dry site in central Siberia for (a) a low-intensity surface fire (Fire 3), and (b) a high-intensity surface fire (Fire 1). The second fire was severe enough to cause tree mortality of all trees on the site.

All fires conducted to date have been surface fires ranging from low intensity (Figure 3a) to very high intensity (Figure 3b). Given the park-like characteristics of the forest stand and the general lack of ladder fuels, a combination of extreme drought or high wind along with pockets of ladder fuels (e.g. patches of sapling-size trees) are necessary for a sustainable crown fire to develop in this type of forest stand. Such fuel characteristics help explain the dominance of surface fires in this forest type and support estimates that during normal fire years roughly 80% of the Siberian fires may burn as surface fires (Belov 1976, Furyaev 1996, Korovin 1996). Fuel consumption for different fuel categories on the site is given in Table III. Ground fuels, comprising of litter and the organic forest floor (fermentation and humus layers), contributed on average 87 percent of the fuels consumed by our

TABLE III

Fuel consumption values and equilibrium (steady-state) fire behavior characteristics observed during each experimental fire. Values in parenthesis are for the preburn fuel loads (No preburn crown data is currently available, but it is our plan to publish this at a late date) and for preburn forest floor depths (L, F, and H organic layers)

	Fuel consumption (dry weight) by category (kg/m^2)							Fire behavior characteristics		
Fire No.	Live vegetation[a]	Down woody debris	Litter	Forest floor	Tree Crown	Total	Total carbon release (t/ha)	Depth of burn (cm)	Rate of spread (m/min)[b]	Fireline intensity (kW/m)[c]
1	0.068 (0.068)	0.438(0.959)	0.255(0.255)	2.311(5.162)	0.000	3.072	15.360	6.4(10.1)	9.0	9018
2	0.065(0.065)	0.400(1.679)	0.294(0.294)	1.341(3.274)	0.000	2.100	10.500	4.7(7.8)	2.0	1067
3	0.027(0.027)	0.034(0.141)	0.098(0.098)	1.194(1.548)	0.000	1.353	6.765	4.4(5.1)	4.9	2140
4a[d]	–	–	–	–	–	–	–	–	0.6	183[e]
4b	0.023(0.023)	0.028(0.708)	0.185(0.185)	0.719(3.499)	0.000	0.955	4.775	3.3(8.1)	2.5	1156
5	0.047(0.047)	0.055(0.184)	0.178(0.178)	0.798(4.296)	0.000	1.078	5.390	3.5(9.1)	2.9	1016
6	0.040(0.040)	0.062(0.144)	0.181(0.181)	1.009(5.715)	0.000	1.292	6.460	4.0(10.7)	5.9	2473

[a] Herbaceous and shrub materials growing at ground level.

[b] Rate of spread values were obtained only from the rate-of-spread timers. Values represent average equilibrium spread rates.

[c] All low heat of combustion values have been adjusted to account for actual fuel moisture.

[d] Because Fire 3a was extinguished before any fuel sampling plots were consumed, there are no quantitative measurements of actual fuel consumption for this fire.

[e] Fireline intensity calculation for Fire 3a was based on fuel consumption estimated from Fire 3b.

fires. This percentage is higher than those observed in North American boreal forests, where tree density are higher, crown fires are more common, and crown fuels may constitute as much as 57% of the total fuels consumed (Stocks, 1987, 1989; Alexander et al. 1991).

Assuming that carbon comprises approximately 50 percent of the dry fuel consumed (Levine and Cofer 2000), the carbon released from these experimental fires varied from 4.8 to 15.4 t C ha^{-1} depending on burning conditions (Table III). This range of carbon release reflects the variability of actual burning conditions (e.g., fire behavior and fuel consumption) experienced throughout a normal fire season. Additional carbon could have been released if a crown fire had developed. Based on our crown structure sampling using fine fuels, dead fuel, and foliage component weights, an additional 3.0 to 7.1 t C ha^{-1} could have been released if a fully developed crown fire had occurred, depending upon the stand structure present. Our data indicates the considerable potential for error in estimates of regional or global carbon emissions from fire that do not incorporate methods for accurately estimating fire severity based on realistic fuel consumption values.

Table III shows the fire behavior characteristics quantified by the present study. Depths of burn into the organic forest floor (duff) ranged from 3.3 to 6.7 cm. The surface fire rates of spread varied from 0.6 to 9.0 m/min. Such spreads are a result of in-stand winds; whereas, if crowning were to occur the rate of spread would probably be faster given the strength of above-ground canopy-level winds. Crown fires would have involved larger areas because of higher expected spread rates but may not actually involve any drastic increases in direct carbon emissions on an area basis. Fireline intensities (Alexander 1982; Byram 1959) ranged from 183 kW/m on the lowest-intensity surface fire to 9018 kW/m on the highest-intensity surface fire. The latter fire (Fire 1), which scorched the foliage, resulted in the mortality of most of the overstory trees. This intensity was well below the crown fire intensity (28062 kW/m) estimated for the Bor Island experimental fire (FIRESCAN Science Team 1996) ignited just north of our present site. However, ignition patterns greatly influenced the initiation of a crown fire at Bor Island.

The use of a fire behavior chart or nomogram (Andrews and Rothermel 1982; Alexander and De Groot 1988) can be a useful way of interpretating expected fire behavior. Based on the intensity classes used in the Canadian Forest Fire Danger Rating System (Alexander and De Groot 1988; Alexander and Lanoville 1989; Taylor et al. 1996) these fires ranged from Class 1 to 5 (Table IV). The fire behavior description of the table describes our fires well. Our only fire to achieve a Class 5 rating (Fire 1) failed to torch or crown due to the absence of ladder fuels.

Initial results show that the FWI System works well in the Scotch pine forest type of the present study as indicated from the correlation matrix shown in Table V. This should not be surprising since the system was designed for boreal forest conditions in Canada. Of the two Russian Fire Danger Systems, the Moisture Index appears to perform better than the Nesterov Index for estimating fuel consumption, depth of burn, and fireline intensity (Table V). Based on the experimental fires conducted so

TABLE IV

Fireline intensity classes describing probable fire behavior and difficulty to control (adapted from Alexander and De Groot 1988; Alexander and Lanoville 1989; Taylor et al. 1996)

Fireline intensity class	Fireline intensity (kW/m)	Fire behavior description	Control ranking
1	<10	Firebrands are self-extinguishing. Fire fails to spread.	Very easy.
2	10–500	Creeping or gentle surface fire.	Fairly easy.
3	500–2000	Low to highly vigorous surface fire.	Moderately difficult.
4	2000–4000	Very vigorous or extremely intense surface fire.	Very difficult.
5	4000–10000	Intermittent to active crown fire.	Extremely difficult.
6	>10000	Extreme fire behavior	Virtually impossible.

TABLE V

A modified correlation matrix showing the correlation between values obtained from the two Fire Danger Systems and various fire parameters measured during the experimental fires

	Russian Fire Danger System		Canadian Forest Fire Weather Index System				
Fire parameter[a]	Nesterov Index	Moisture Index	DMC	DC	BUI	ISI	FWI
Fuel consumption	0.6537	0.8424[b]	0.9412[c]	0.8227[b]	0.9281[c]	0.9010[c]	0.9414[c]
Depth of burn	0.7633[b]	0.90007[c]	0.8773[b]	0.6806	0.8437[b]	0.9436[c]	0.9445[c]
Rate of spread	0.5702	0.6716	0.6385	0.2309	0.5566	0.8907[c]	0.8235[b]
Fireline intensity	0.6050	0.7819[b]	0.8204[b]	0.4997	0.7623[b]	0.9618[c]	0.9393[c]

[a]Fire No. 3 was eliminated from this table because of incomplete data.
[b]Significant at the 95% confidence level.
[c]Significant at the 99% confidence level.

far, the Moisture Index and the FWI System both appear to be good indicators of fire behavior parameters. Future plans are to develop models to assist in the prediction of carbon release (based on fuel consumption) and fire behavior characteristics. Such models will be useful in improving carbon emission estimates for this forest type.

3.4. Fire Emissions

3.4.1. *Carbon Emissions*

The ratios of CO to CO_2 for fires in 2000 and 2001, based on ground sampling, are shown in Figures 4 and 5, respectively. Modified combustion efficiencies (MCE) and average emission factors of CO_2 and CO of ground-level and aerial samples,

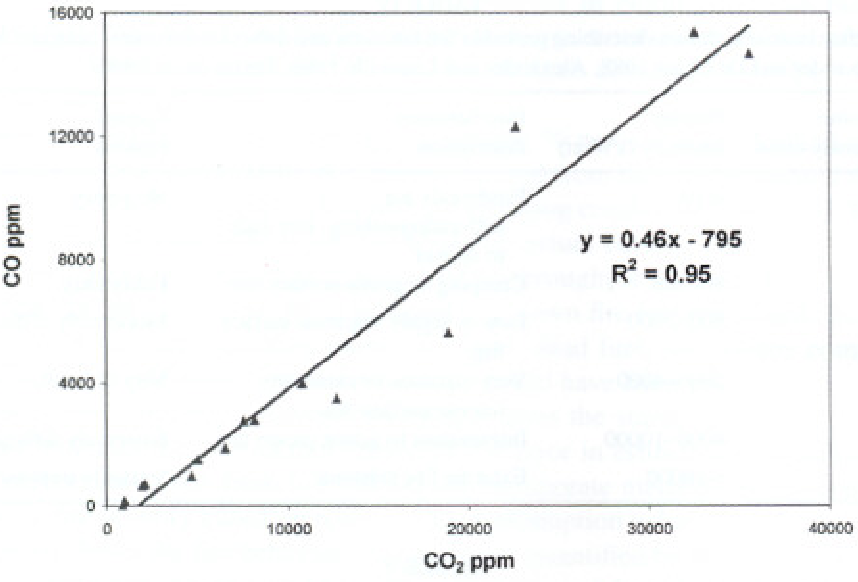

Figure 4. Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations based on all 2000 ground-based samples.

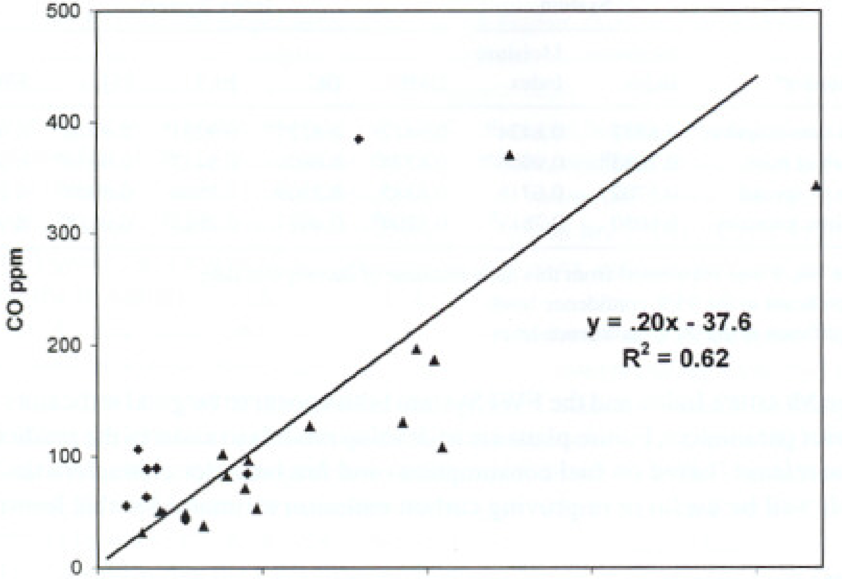

Figure 5. Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations based on all 2001 ground-based samples.

TABLE VI

Average emission factors and modified combustion efficiency (MCE) of ground-level samples, grouped by fuel type for 3 fires conducted in 2001

Fire	Fuel type	Modified combustion efficiency	Emission factor (g/kg)	
			CO	CO_2
4b	Lichen	0.83	196.6	1493
4b	Rotten wood	0.94	66.2	1717
4b	Stump	0.66	386.5	1161
5	Lichen	0.79	237.1	1428
5	Log on ground	0.80	224.5	1443
5	Understory vegetation	0.87	152.0	1577
6	Moss and lichen	0.59	458.9	1060

grouped by fuel types for the three fires in 2001, are shown in Table VI. Only ground-level emissions samples were collected for the 2000 fires. Concentrations of CO and CO_2 were high (Figure 4) for both fires (Fires 1 and 2) because samples were collected close to the fires. The concentrations of CO_2 and CO show a high degree of linear correlation ($r^2 = 0.95$) and the ratio of CO to CO_2 was 0.46, as these samples were collected during smoldering combustion (Ward and Hardy 1991).

The 2001 ground-level samples were collected primarily during smoldering combustion at a much lower concentration range (i.e., 350 to 2,500 ppm for CO_2, and 5 to 500 ppm for CO). Despite the large difference in intensity of the fires (Table III), the CO to CO_2 ratio was essentially the same for Fires 4b, 5, and 6 (Figure 5). Table VI shows the range of MCE values and the emission factors of CO_2 and CO for these fires. A low modified combustion efficiency (MCE = 0.66) and a high CO emission factor (EFCO = 387 g/kg) was measured for burning stumps on Fire 4b. This could be due to a low decomposition state of the stumps (i.e., still solid) and higher fuel moistures. Feathermoss/lichen on Fire 6 also had a very low MCE of 0.59 and a high EFCO (459 g/kg), probably as a result of the higher fuel moisture of the feathermoss. Burning of rotten wood on Fire 4b and understory vegetation on Fire 5 were more efficient with higher MCE values of 0.94 and 0.87, respectively, and relatively low emission factors of CO and high emission factors of CO_2 ($EFCO_2$). Typical smoldering MCE values of 0.79 and 0.83 with EFCO values of 197 g/kg and 237 g/kg were observed for burning lichen on Fires 4b and 5, respectively. These values are useful in characterizing the smoldering emissions of the most common fuels found on our plots. However, they do not provide the emission factors for flaming combustion or the total emissions from the fires.

The ratio for the aerial smoke plume sampling taken over the three 2001 experimental fires is shown in Figure 6. Sampling took place while the helicopter

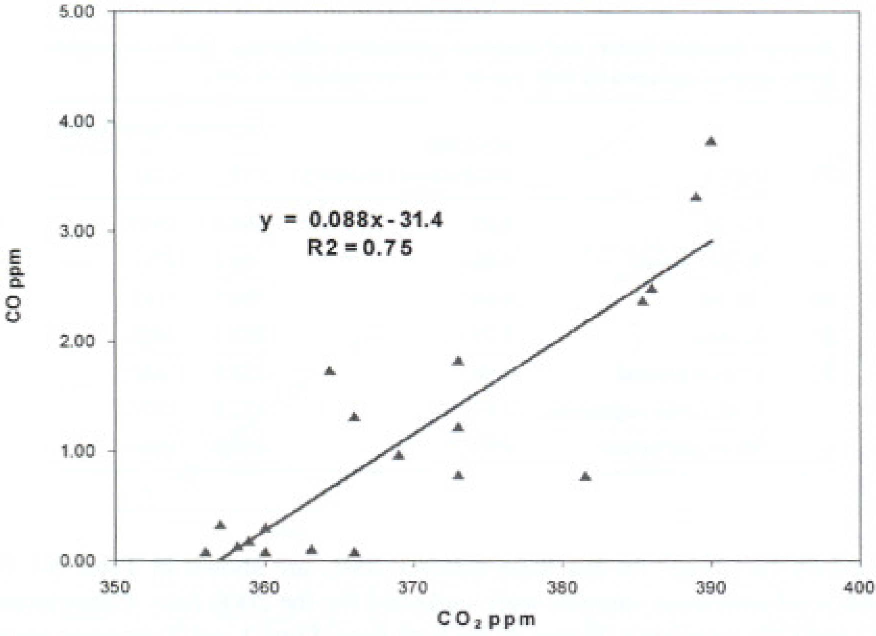

Figure 6. Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations based on all 2001 aerial samples.

hovered over the fire as the flame front was passing by directly underneath. This sampling represented a combined emission product for flaming and smoldering combustion. The CO and CO_2 emissions were linearly correlated ($r^2 = 0.76$) and the emission ratio of CO to CO_2 was 0.088 (Figure 6). The modified combustion efficiency ranged from 0.88 to 0.91, the emission factors of CO were between 98 g/kg and 135 g/kg. and the average emission factors of CO_2 values were approximately 1650 g/kg. These value ranges are similar to those found for wildfires burning in pine forests in the western United States (Babbit et al. 1994) and for North American boreal and temperate forests (Cofer et al. 1996a). However, the average CO_2 emission factor for the 2001 fires (1650 g/kg) is higher than those reported for Bor Island (1475 g/kg), located near our site, for a high intensity crown fire (Cofer et al. 1996b). Emission factors in the range of 52–70 g/kg for CO, and 1720–1750 g/kg for CO_2 were measured for grassland fires in Brazil in 1990 (Ward et al. 1992). These are typical values of tropical savanna fires, that generally burn more efficiently with higher CO_2 emission factors than boreal pine forests.

3.4.2. *Aerosol Emissions*

Sixteen microelements were detected in the aerosol emission samples analyzed by the synchrotron radiation X-ray fluorescence (SRXRF) method (Table VII).

TABLE VII

Total mass concentration (C_0) and partial concentration ($\mu g/m^3$) of microelements in aerosol emissions sampled from the 2001 experimental fires. Reference relative concentrations (RRC) refer to the amount of the element in background soils relative to iron. Experimental relative concentrations (ERC) are the element amounts on the aerosol filters relative to iron. The experimental reference ratio (ERC/RRC) represents the relative increase of an element in the aerosol smoke sample compared to the soil reference value

	Microelements																
Results	C_0	K	Ca	Ti	Cr	Mn	Fe	Co	Zn	As	Se	Br	Rb	Sr	Zr	Mo	Pb
Filter sample																	
Mean[a] ($\mu g/m^3$):	50300	268	86	4.6	2.4	5.9	18.3	0.18	3.3	0.16	0.06	2.3	1.1	0.13	0.04	0.09	1.1
Standard deviation:	42500	248	70	7.0	3.2	6.1	13.7	0.37	4.1	0.29	0.10	4.4	1.2	0.15	0.10	0.19	1.1
Standard error:	7800	45	13	1.3	0.6	1.1	2.5	0.07	0.8	0.06	0.02	0.8	0.2	0.03	0.02	0.03	0.20
Reference relative concentration (RRC):	–	0.58	0.55	0.11	0.0023	0.017	1	0.0005	0.002	0.00012	0.00002	0.0007	0.004	0.001	0.0045	0.0001	n/d
Experimental relative concentration (ERC):	–	14.6	4.6	0.25	0.13	0.32	1	0.01	0.18	0.0087	0.0033	0.13	0.06	0.007	0.0021	0.005	0.058
Experimental reference ratio (ERR):	–	25.2	8.4	2.3	56.5	18.8	1	20	90	72.5	165.0	185.7	15.0	7.0	0.5	50.0	–

[a]Sample size = 30.

Nickel and copper were not included in this analysis. For any microelement, sample concentrations ranged often by two or three orders of magnitude. Variations in microelement concentrations probably reflect the diverse concentrations of the different elements found naturally in forest biomass. By comparing the concentrations found on the filters with the RRCs, an estimate can be made of the source of each element found in the particulate emissions. Elements ERRs of 25 or greater, which indicates their presence is almost certainly primarily due to biomass combustion, included potassium, chromium, zinc, selenium, arsenic, bromine, and molybdenum. Manganese and cobalt, with ERR of about 20, also possibly result from biomass combustion, while other elements such as titanium, strontium, zirconium, and possibly calcium have lower ERR values and are likely derived primarily from soil sources. The natural element contents (whose average values are presented in Table VII) can vary greatly, depending on actual soil types and conditions. Therefore, only in the case where the experimental value of the relative concentration of a certain element substantially exceeds its reference elemental content RRC (e.g., for K, and Zn) can one conclude that this element actually originated primarily from the burning of biomass on the site.

The microelements measured in the aerosol emission sampling represented approximately 0.5-1 percent of the total mass concentration (Table VII). Previous research suggests that the combined weight of elements such as oxygen, nitrogen, sodium, magnesium, aluminum, silicon, chlorine, and sulfur, which cannot be detected by the SRXRF method, is 10–20 times that of elements shown in Table VII (Kist 1987; Perelmann 1979). Consequently, the total amount of mineral substances may be 5–10% of the total mass of the fire particulate emissions. The remaining material in our samples (roughly 90%) consists of carbonaceous substances (unpublished data). This is similar to results of Levine et al. (2000).

Although the average percentage of these mineral elements in the total aerosol emission is only 5–10%, the total amounts of mineral substances emitted to the atmosphere from forest fires are considerable. The total concentration (C_0) value of particulate emission from our forest fires was approximately 50 mg/m^3 (15–240 mg/m^3 (Table VII)). Such large fluctuations in average concentrations are mainly due to variability of fuel loads and combustion conditions, as well as errors inherent in aerosol sampling. A further reason for these fluctuations is that aerosol sampling was carried out only at the fire edges because of concern for personnel safety. These data are a good start for characterizing the smoke of Russian boreal forest fires. The average total concentration of ground-level smoke aerosol emissions of 50 mg/m^3 is 1000 times greater than the average concentration of particulate matter found in the free atmosphere (20–60 μg/m^3). Consequently, even for the relatively small weight fraction of the mineral components (5–10% of the 50 mg/m^3 average concentration), the total amounts of microelement emissions from forest fires are quite high compared to background quantities.

4. Conclusion

The mean landscape-scale fire interval for our experimental forest island site has been approximately 50 years for several centuries. While slightly longer than typical intervals reported in the literature, this may be less a reflection of real differences in fire regimes than of differences in factors such as number and spatial distribution of samples, or methods of data analysis and interpretation. As is typical for the Scotch pine/lichen forests of the taiga regions of central Siberia, the fire regime in our study area is characterized by frequent, low-intensity surface fires, with stand-replacement fires occurring only when burning conditions are severe. The prevalence of surface fires is due to the low tree density (i.e., the open-canopy nature of the forest) in combination with the absence of understory species that could provide ladder fuels to aid in the transition from a surface to a crown fire. This contrasts to the less frequent fire interval (100–200 years) of many northern boreal forest of North America (Heinselmann 1981; Rowe et al. 1974; Smith and Henderson 1970; Vierick 1983), where stand-replacement crown fires result in extensive tree mortality. A combination of low scorch heights (Van Wagner 1973), as a result of the generally low-intensity surface fires (<2500 kW/m), and the insulating effects of the thick Scotch pine bark results in a low tree mortality in all but the most severe fires. The only live trees suceptible to these low-intensity fires are the few that may have major fire scar damage from previous fires, as well as younger regeneration and pole-size trees. Mature fire-scarred trees tend to burn out at the base because of the amount of dead and dry wood in the scar area until they can no longer support the upper structure at which time they fall over.

Initial reactions may be that the crown fires of North America are more severe and therefore have the highest impact on carbon cycling. However, the less severe but more frequent fires of Scotch pine forest in Siberia may in fact cumulatively release more carbon over multiple fire intervals because recovery of surface fuels is relatively rapid after low-intensity surface fires in which the overstory trees are not killed by fire. Inherent in this understanding is that the ground fuels are the largest and most important component consumed by any fire type (surface or crown) and contributes significantly to carbon emission outputs. Furthermore, one of the most significant effects of changing climate is likely to be on fire severity, and consumption of surface fuels.

Emission factors of CO_2 values from the 2001 fires indicated a higher value of approximately 1650 g/kg compared to what was found at Bor Island (1475 g/kg), located just north of our site, during a high-intensity crown fire (Cofer et al. 1996b). Preliminary data also indicate significant emissions of a wide range of aerosols, which have the potential to significantly affect both regional air quality and atmospheric chemistry and radiation fluxes.

All experimental fires to date have been surface fires. The study has documented a high variability in fuel consumption and fire behavior characteristics for this particular fuel type. The carbon released by the 6 experimental surface fires reported here has ranged from 4.8 to 15.4 t C ha^{-1} depending upon the fire severity. With a 30-year fire interval, this would translate into annual fire emissions on a site basis of 0.16 to 0.51 t C ha^{-1}, not including the effects of fire on factors such as soil respiration. This contrasts with the estimates for annual carbon production (sink) for central taiga mature pine stands of 0.58 t C ha^{-1} and an annual loss due to decomposition (source) of 0.44 t C ha^{-1}, for a net sink of 0.14 t C ha^{-1}(Vedrova 2002), an estimate that does not include losses due to fire. We now have estimated CO_2 and CO emissions for a dry Scotch pine forest type in Siberia based on total fuel consumption over a wide range of fire intensities. This is an ongoing project with 6 additional fires completed in 2002. In addition, wildfire aerial monitoring and ground sampling has been completed on several wildfires in the Boguchany Region. This aerial data combined with our ground data will help to test and improve on current satellite-based approaches for estimating the spatial extent of fires, and to develop and validate methods to estimate spatial patterns of burn severity.

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