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Fire in Ecosystems of Boreal Eurasia: The Bor Forest Island Fire Experiment Fire Research Campaign Asia-North (FIRESCAN)

FIRESCAN Science Team*

Fire in Ecosystems of Boreal Eurasia

The world's boreal forests and other wooded land within the boreal zone cover 1.2×10^9 hectares (ha), of which 920×10^6 ha are closed forest. The latter number corresponds to ca. 29% of the world's total forest area and to 73% of its coniferous forest area (ECE/FAO 1985). About 800×10^6 ha of boreal forests with a total growing stock (over bark) of ca. 95 billion m^3 are exploitable (41% and 45% respectively of the world total). The export value of forest products from boreal forests is ca. 47% of the world total (Kuusela 1990, 1992).

The vast majority of the boreal forest lands (*taiga*) in Eurasia are included in the Russian Forest Fund, covering ca. 900×10^6 ha. Depending on the criteria used to define "boreal forest," the area of closed boreal forest in the Russian Federation varies from 400 to 600×10^6 ha (Pisarenko and Strakhov 1993). These numbers correspond to a 43 to 65% share of the world's closed boreal forest.

Disturbances in Transition: Natural to Anthropogenic

Among natural disturbances, fire (lightning fire) is the most important factor controlling forest age structure, species composition, and physiognomy, shaping landscape diversity, and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle, since prehistoric times (cf. monographs and synopses, e.g., by Sofronov 1967; Slaughter et al. 1971; Zackrisson 1977; Sherbakov 1979; Viereck and Schandelmeier 1980; Alexander and Euler 1981; Heinselman 1981; Wein and MacLean 1983; Kurbatsky 1985; Johnson 1992; Sannikov 1992; Furyaev 1994; Shugart et al. 1992; Goldammer and Furyaev 1996). Small and large fires of varying intensities have different effects on the ecosystem. High-intensity fires lead to replacement of forest stands by new successional sequences. Low-intensity surface fires favor selection of fire-tolerant trees such as pines (*Pinus* spp.) and larches (*Larix* spp.) and may repeatedly occur within the life span of a forest stand without eliminating it.

Large-scale forest disturbances connected with drought and fires are familiar in recent history. The Tunguska meteorite fall near Yenisseisk (ca. 60°54′N–101°57′E) on 30 June 1908, a cometary nucleus explosion at ca. 5-km altitude, was one of the more exceptional events, causing large-scale forest fires in the region of impact (see Grishin 1996).

Several years later, from June to August 1915, the largest fires ever recorded occurred as a consequence of an extended drought in Central and East Siberia (Tobolsk, Tomsk, Yeniseisk, NE Irkutsk, S Yakutsk regions). Shostakovich (1925) estimated that the fires were burning ca. 50 days in the region between 52 to 70°N and 69 to 112°E. The main center of fires was between Angara River and Nijnya Tunguska, and the area burned was estimated at 14.2×10^6 ha. However, the smoke from these fires covered the region between 64 to 72°N and 61 to 133°E, corresponding to ca. 680×10^6 ha. Shostakovich estimated continuous smoke (visibility ca. 100 m) on 284×10^6 ha, heavy smoke (visibility 25–100 m) on 215×10^6 ha, and thick smoke (visibility 5–20 m) on ca. 181×10^6 ha.

It is not clear, however, whether lightning, human beings, or a combination of the two were the primary cause of the extended fires in 1915. In Eurasia, fire for a long time has been an important tool for land clearing

*The Bor Forest Island Fire Experiment was a joint effort by the science team in the first phase of the Fire Research Campaign Asia–North (FIRESCAN). Coordinators of the experiment were J. G. Goldammer, B. J. Stocks, V. V. Furyaev, and E. N. Valendik. The introductory part of this manuscript was compiled by J. G. Goldammer. Lead author of Part II of the manuscript was S. G. Conard (with J. S. Clark, V. V. Furyaev, J. G. Goldammer, G. A. Ivanova, E. Mälkönen, and T. W. Swetnam), and lead author of Part III was B. J. Stocks (with J. S. Clark, W. R. Cofer, B. D. Lawson, and J. G. Goldammer). The participants actively involved in preparing, conducting, and evaluating the field research are listed here. Christopher H. Baisan, James S. Clark, Wesley R. Cofer III, Susan G. Conard, Valentin V. Furyaev, Johann G. Goldammer, Gary Hartley, Galina A. Ivanova, Yegor K. Kisilyakov, Bruce D. Lawson, Eino Mälkönen, Loyd W. Overbay, Jon C. Regelbrugge, Brian J. Stocks, Thomas W. Swetnam, Erik Valendik, Ross W. Wein, and Edward L. Winstead.

(conversion of boreal forest), silviculture (site preparation and improvement, species selection), and in maintaining agricultural systems, as in hunting societies, swidden agriculture, and pastoralism (Viro 1969; Pyne 1996). In addition to the natural fires, these old cultural practices brought a tremendous amount of fire into the boreal landscapes in Eurasia. Early in the twentieth century, the intensity of fire use in the agricultural sector began to decrease because most of the deforestation had been accomplished for agriculture, and traditional small fire systems (treatment of vegetation by free burning) was replaced by mechanized systems (fossil-fuel-driven mechanical equipment). Despite the loss of traditional burning practices, however, humans are still the major source of wildland fires; only 15 percent of the fires recorded in the Russian Federation are caused by lightning (Korovin 1996).

In recent years wildfires were more or less eliminated in western Eurasia. The average annual area affected by fire in Norway, Sweden, and Finland is fewer than 4000 ha. Thus, the major occurrence of Eurasian fires is in the territory of the Russian Federation and other countries in the Commonwealth of Independent States. Statistics compiled by the Russian Aerial Fire Protection Service (*Avialesookhrana*) show that 10 000 to more than 30 000 forest fires occur each year, affecting up to 2 to 3×10^6 ha of forest and other land (Korovin 1996). Since fires are monitored (and controlled) only on protected forest and pasture lands, it is estimated that the real area affected by fire in Eurasia's boreal vegetation is much higher. For instance, satellite-derived observations by Cahoon et al. (1994) indicate that during the 1987 fire season approximately 14.5×10^6 ha were burned. In the same fire season, ca. 1.3×10^6 ha of forests were affected by fire in the montane-boreal forests in Northeast China, south of the Amur (Heilongjiang) River (Goldammer and Di 1990; Cahoon et al. 1991). Fires in boreal North America in the past decade affected, on average, 1.5 to 5×10^6 ha/yr. An exceptional year was 1987, in which 7.4×10^6 ha of forests were burned in Canada (FIRESCAN Science Team 1994).

Concerns: Global Change and Fire

Expected global warming over the next 30 to 50 years, as predicted by Global Circulation Models, will be most evident in the northern circumpolar regions (Bolin et al. 1986; Maxwell 1992; Shugart and Smith 1992; Shugart et al. 1992). Wein and de Groot (1996), Fosberg (1996), Stocks (1993), and Stocks and Lynham (1996) emphasize that fire may be the most important (widespread) driving force in changing the taiga under climate warming conditions. The prediction of increasing occurrence of extreme droughts in a $2 \times CO_2$ climate indicates that fire regimes will undergo considerable changes. Increasing length of the fire season will lead to higher occurrence of large, high-intensity wildfires. Such fire scenarios may be restricted to a transition period until a new climate-vegetation-fire equilibrium is established.

Regional warming may also lead to the shift in vegetation zones, such as the boreal forest shifting north ca. 500 to 1000 km (Kauppi and Posch 1988). The shift in ecosystems will considerably affect the distribution of phytomass. Estimates of carbon (C) stored in above- and below-ground live and dead plant biomass (without soil organic matter) in the global boreal forest area range between 66 and 98 gigatons (Gt) (66–98×10^{15} g) (U.S. Department of Energy 1983; Apps et al. 1993). Additional large amounts of C are stored in boreal forest soils (ca. 200×10^{15} g) and boreal peatlands (ca. 420×10^{15} g) (Apps et al. 1993). There is concern that changing fire regimes due to climate change will affect the balance of the boreal C pool and lead to additional release of C into the atmosphere, thus acting as a temporary positive-feedback loop to global warming.

Changing forestry practices in boreal Eurasia, stimulated by increasing national and international demand for boreal forest products, have resulted in widespread use of heavy machinery, large-scale clearcuts, and, with this expansion, in altered fuel complexes. Opening formerly closed remote forests with roads, and subsequent human interferences, bring new risks of ignition. Additional fire hazards with little predictable environmental consequences are created on forest lands heavily damaged by industrial emissions (severe damages in the Russian Federation affect ca. 9×10^6 ha). Radioactive contamination on an area of ca. 7×10^6 ha creates considerable problems because it redistributes radionuclides through forest fires (Dusha-Gudym 1992). These direct effects on the ecosystem are added to the indirect effects of climate change, and both will almost certainly lead to an unprecedented era of fire.

Objectives of Cooperative Fire Research in Boreal Eurasia

Jointly with the first East–West conference, entitled "Fire in Ecosystems of Boreal Eurasia" (Goldammer and Furyaev 1996), the Fire Research Campaign Asia-North (FIRESCAN) was prepared under cosponsorship by the International Boreal Forest Research

Association (IBFRA) and the IGBP/IGAC subprogram, "Impact of Biomass Burning on the World Atmosphere" (Biomass Burning Experiment [BIBEX]; for details, see FIRESCAN Science Team (1994) and Goldammer and Furyaev (1996)).

In accordance with the hypotheses of the IBFRA Stand Replacement Fire Working Group (Fosberg 1992), the objectives of the experiment were:

- Set a high-intensity stand-replacement fire under controlled conditions, under conditions and with characteristics of an uncontrolled wildfire.
- Investigate all pre- and postfire characteristics of the site.
- Describe fire behavior and relate the findings to ecological and meteorological conditions before and during the fire.
- Analyze emissions of aerosols (characteristics and transport), the most important radiatively active trace gases, and trace gases with stratospheric ozone-depleting effects.
- Relate the fire experiment to the fire history of the site and the surrounding landscape.
- Set up an investigation area for long-term follow-up research on ecosystem response (e.g., collecting data on mortality and recovery, succession, biological diversity, nutrient cycling, soil respiration, and carbon accretion).
- Demonstrate and compare methodologies in fire research developed in the East and West.

To meet these objectives, the FIRESCAN Science Team, an international multidisciplinary research team, assembled in summer 1993 to investigate site characteristics, fire effects, fire emissions, and fire behavior on a 50-ha experimental stand-replacement fire in a typical boreal pine forest.

The experimental site is in the central part of the Krasnoyarsk Region in Siberia, about 28 km west of the Yenisey River and 28 km south of the Dubches River (60°45′N, 89°25′E) at an elevation of approximately 150 m above sea level (figure 81.1). The study site is a nearly level, slightly elevated, sandy island of about 50 ha, which is surrounded by bogs dominated by mixed grass, sphagnum, and tall sedge (figure 81.2). The site was referred to as Bor Forest Island, after the town of Bor, 90 km to the north, which served as the transportation base for research activities. The Bor Forest Island study site is on the Sym Plain, in the Western Siberian Lowland, a large block of the earth's crust characterized by past tectonic depression. The Sym Plain is an area of low relief, with sandy surface materials of glacial-outwash and alluvial origin. Very deep, unconsolidated deposits are present, and there are numerous lakes and oligotrophic and mesotrophic bogs. Forests are dominated by pure pine stands of the *Pinus sylvestris-Ledum-Vaccinium vitis idaea-Pleurozium schreberi, P. sylvestris-P. schreberi-Cladonia sylvatica* (40%), and *Pinus sylvestris-Polytrichum commune*-dwarf shrub-Sphagnum (20%) forest types. Oligotrophic bog ridges with pools covered by *P. sylvestris*-dwarf shrub-Sphagnum forest cover 40% of the landscape. The forest on the experimental fire site is a typical middle-taiga pine forest of the Sym Plain.

Because Atlantic air masses are transformed to continental over the Western Siberian Lowland, zones and subzones are clearly discernible across the landscape. The climate is cool and moist. Average annual air temperature ranges from 3.2 to 5.7°C. Total annual precipitation is 450 to 500 mm, with wide year-to-year variations. Although most precipitation occurs in summer, frequent dry periods are caused by dry cyclonic air masses coming from the south. In the past century, 26 droughts have occurred in the area (an average of 2 to 3 times per decade).

The fire season lasts from May to September, with most fires in June and July. In the *Pinus sylvestris*-lichen forest types, about 20% of the area is in even-aged stands that have regenerated from stand-replacement fires. Fire periodicity varies from 40 to 50 yr in the north to 25 to 29 yr in the central part of Krasnoyarsk Territory. For the *P. sylvestris-V. vitis idaea*-Sphagnum forest type characteristic of the central part of the area, forest-fire periodicity is 10 to 80 yr. As in the rest of Siberia, periodic extreme fire seasons are common. Those seasons are remarkable for long rainless periods (up to 38 d), with relative humidities down to 30%, and air temperatures up to 30 to 35°C. Until the end to the nineteenth century, extreme fire seasons in the central Krasnoyarsk Territory occurred from 3 to 4 to 7 times a century. This frequency has increased up to 20 to 25 events in the twentieth century. Most of these fires are human caused, as a result of intensive forest exploitation in the area. For the past fifty years, extreme fire seasons associated with massive forest fires have occurred at least twice a decade, sometimes two years in succession (for more details on geology, climate, and ecology of the region, cf. Goldammer and Furyaev (1996).

Results of the first two years of investigation from the Bor Forest Island Fire Experiment, including pre- and postfire studies, are given in the next two sections. We then report characteristics of the study site and its

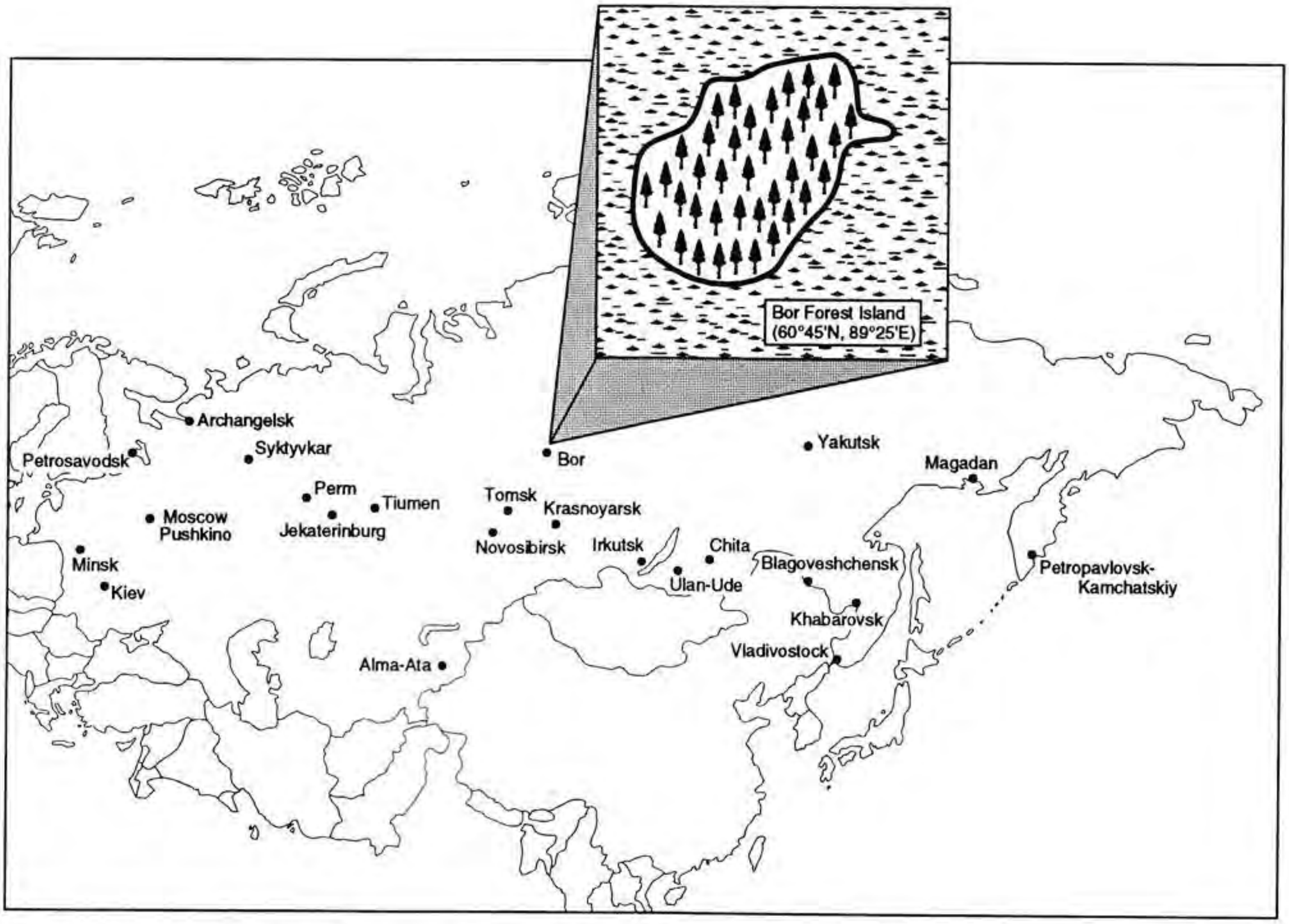


Figure 81.1 Location of Bor Forest Island near Bor, Krasnoyarsk Region, Russian Federation. All other names of locations are regional headquarters of the Russian Aerial Fire Protection Service *Avialesookhrana*, or relevant services in other countries in the Commonwealth of Independent States.

Figure 81.2 Bor Forest Island immediately prior to the experimental fire

vegetation, and present preliminary results on short-term fire effects. We then describe fuel characteristics, fire behavior, and emissions.

Fire History, Ecology, and Short-Term Fire Effects

Fire Ecology of *Pinus sylvestris* Forests on the Sym Plain

The Bor Forest Island experimental site is typical of pine-lichen forests in Western Siberia that have been described in the literature (Tkachenko 1952; Korchagin 1954; Shanin 1965; Komin 1967; Popov 1982; Furyaev and Zlobina 1985, and others). Generally, in the taiga zone, age of dominant pine stands depends on the time since the last intense fire. Pine stands on sands are represented primarily by pine-lichen forest types. Species composition of postfire woody-plant regeneration typically is similar to pre-fire composition. The time it takes for a young-stand canopy to become closed after fire depends on size of burned area, available sources of seed, and seed production in the years following the fire. Because of insufficient surface fuel loads, fires typically are patchy and cover relatively small areas. As a result, seed sources generally are available nearby. Only young and pole stands, and sometimes middle-aged stands, tend to burn out completely.

Popov (1982) described the regeneration processes in pine stands of the southern taiga zone in the Angara region in Central Siberia. These stands occurred on sandy and podzolic soils on high terraces and in river valleys, and experienced periodic fires. They were of the same forest type as the Bor Forest Island experimental site. Popov found that grass cover following burns in pine-lichen forests usually was extremely low and poorly developed; soil often remained bare in considerable parts of burned areas. Pine, either in pure stands or with a very small admixture of birch, typically began to regenerate in high densities (usually several hundred thousand pine seedlings/ha) after the first year of good seed crop. Popov describes these developmental stages for these stands:

1. young pine stands with red whortleberry (*Vaccinium vitis idaea*)-lichen surface cover, and birch as a minor component.
2. pole pine stands with litter and lichen surface cover.
3. middle-aged, pre-mature, mature, and old pine stands with surface cover dominated by red whortlebrerry.
4. pine-mixed grass-red whortleberry forest.

Popov found that forest regeneration typically occurred without major changes in composition of woody or herbaceous species. Some of the typical understory species for this type, along with their importance in the different regeneration stages, are listed in table 81.1. A continuous cover of lichens, *Pleurozium schreberi*, and *V. vitis idaea* develops under the canopy of dense young pine stands. An understory composed of alder (*Alnus fruticosa*) and dogrose (*Rosa acicularis*) is restricted to glades (clearings). Projected cover of the grass–low-shrub layer does not exceed 0.4. This layer is dominated by *V. vitis idaea*, *Majanthenum bifolium*, *Antennaria dioica*, *Festuca ovina*, and *Lycopodium annotinum*. Lichens and *Pleurozium schreberi* account for some 0.5 of the area. Several species not listed in the table occur primarily in the first stage of forest development, and are relatively uncommon even then. These include: *Chamaenerium angustifolium*, *Calamagrostis obtusata*, and *Polygala hybrida*. *Viola uniflora* is found throughout forest development, but typically only as scattered individuals.

Table 81.1 Understory vegetation typical of different forest development stages in pine stands on sandy podzolic soils (according to Popov 1982)

Species	Forest development stage a	b	c	d
Vascular plants				
Vaccinium vitis idaea	cop	cop	sol	sol
Antennaria dioica	cop	sp	sp	sp
Majanthenum bifolium	sp	sol	sp	sp
Festuca ovina	sp	sol	sol	sol
Rosa acicularis	sp	sol	sol	sol
Arctostaphylos uva-ursi	sol	sol	sol	—
Carex pediformis	sol	—	sol	sol
Geranium pseudosibiricum	sol	un	sol	sol
Melica nutans	sol	sol	sol	sol
Pyrola incarnata	—	sol	sol	sol
Rubus saxatilis	sol	—	sol	sol
Solidago virga-aurea	sol	—	sol	sol
Alnus fruticosa	—	un	sol	sol
Ledum palustre	—	un	sol	sol
Nonvascular plants				
Pleurozium schreberi	cop	sp	cop	cop
Cladonia silvatica	cop	sp	cop	cop
Cladonia rangiferina	sp	sol	sp	sp
Peltigera aphthosa	sol	sol	sp	sp
Dicranum	sol	—	sol	sol
Lycopodium complanatum	sol	sol	sol	sol
Dryopteris Linnaena	sol	un	sol	sol
Lycopodium annotinum	—	—	un	un

un = single individual; sol = up to 10% cover
sp = few individuals, 10 to 30% cover
cop = 30 to 90% cover

During pole stand formation, a fragmented understory of alder develops, dogrose begins to develop in places, and *Ledum* clusters are observed in clearings. Only isolated clusters of lichens and *V. vitis idaea* occur in extremely dense pole stands. Pole stands form with surface cover dominated by litter. If a surface fire occurs, it results in forming a lichen layer under the canopy of thinned pole stands. Rapid drying out of lichens promotes frequent low-intensity fires. Postfire changes in living-surface cover occur at a low rate. Lichens that cover fire-exposed soil are gradually replaced by *P. schreberi* and *V. vitis idaea*.

Density of pure pine stands decreases with time, and by age 80 to 100 they become rather open. Individuals of alder, dogrose, and *Ledum* are sparsely distributed in the understory. Pine regrowth occurs in groups and is viable only in clearings. The grass–low-shrub layer is composed of *V. vitis idaea* with *Majanthenum bifolium*, *Antennaria dioica*, *Festuca ovina*, and *Lycopodium* *annotinum*. Lichens and *P. schreberi* account for 0.6 of the area. In recently burned pine stands, regeneration is very abundant (more than 1 000 000/ha), but underdeveloped. Understory is represented by low-growing dogrose and young alder. The low-shrub layer is absent. The soil is partly bare and partly covered by lichens.

Thus, according to Popov (1982), regeneration patterns for pine stands on sandy and podzolic soils in the Angara region are very simple, with one forest type, which is characterized by four short-term regeneration stages.

Similar patterns have been described for postfire dynamics in pine forests of the southern taiga subzone in the West-Siberian Plain (Furyaev and Kireyev 1979; Furyaev and Zlobina 1985). They identified ecodynamic series based on descriptions of pine sites of differing ages following fire, and emphasized more the spatial dynamics and fire patterns typical of stands at different stages in development. Six regeneration (succession) stages differing in fire resistance were described for pine stands on fresh sands, which are mainly of the pine-lichen forest type similar to the forest on our experimental site.

Stage 1: recently burned areas with no signs of regeneration; partial or full tree mortality as a result of fire. Pine regrowth, understory and lichen layer completely removed by fire. Litter is the fuel type characteristic of burned sites in pine stands with lichen-dominated surface cover, and high fire danger is maintained because of downed wood and snags. Recurrent fires can hamper development of living surface cover and result in destruction of all recent seedlings. Postfire grass cover (before a new young pine stand is formed) is remarkably undeveloped and represented by sparsely distributed sedges and *Calamagrostis*.

Stage 2: young pine stands with surface cover composed of *V. vitis idaea* and lichens. Pine is mixed with birch, understory is absent, and the grass–low-shrub layer is poorly developed and represented by sedge and *V. vitis idaea*. Sixty percent of the area is covered by a lichen layer 2 cm deep.

Stage 3: pole pine stands with litter and lichens as surface cover. Pine stands are pure or mixed with birch. The fuel type is characterized by litter or lichens. The time when a young-stand canopy becomes closed after fire depends on specific site and environmental conditions. Repeated fires that promote stand thinning are common.

Stage 4: middle-aged and pre-mature (120–160 yr old) pine stands. These are uneven-aged pure pine stands. The fuel complex includes litter or lichens. The lichen layer continues to develop and grow in depth; it covers 0.6 to 0.7 of the ground.

Stage 5: pine-lichen or pine-whortleberry-lichen forests (120–160 yr old). These stands experience many repeated fires of low and moderate intensity. They are uneven-aged. Regrowth is sparse. Low shrubs account for up to 0.4 of the area. Living surface cover is dominated by lichens.

Stage 6: old pine stands with *V. vitis idaea* and lichens dominant in the surface cover. Age-class patches are easy to identify. These are subject to recurrent surface fires. Pine regrowth is sparse. Lichens account for 0.6 to 0.7 of the area.

To conclude, postfire regeneration stages for pine stands growing on recent sand deposits consist largely of uneven-aged pure pine stands with poorly developed pine regrowth, sparse woody understory, and a lichen layer that develops gradually in depth and cover after fire. The regeneration of pine-lichen forests does not include species replacement. After a year with abundant seed yield, one can expect abundant pine seedlings to occur. However, the great annual variability in seed production in taiga pine forests leads to considerable uncertainty about timing of postfire regeneration. Furthermore, because fire danger resulting from large amounts of downed wood, snags, and deteriorating trees remains high for several years in areas that have experienced stand-replacement fires, forest regeneration may be interrupted by repeat fires.

Mesoclimatic and hydrologic regimes characteristic of the sites studied by both Popov (1982) and Furyaev (Furyaev and Kireyev 1979; Furyaev and Zlobina 1985) undoubtedly differ somewhat from those of our experimental stand; nonetheless, we expect the processes of regeneration to be similar, with differences primarily in duration of regeneration stages or in exact patterns of understory development.

Postfire Insect Infestations Although it is clear from casual observation that severe insect infestation often occurs following fire in *P. sylvestris*, there have been no studies of insect complexes on burned areas in pine forests in the middle-taiga subzone on the Siberian plain. We speculate that there may be some similarities to insect populations in clearcut areas in neighboring regions. Fifty-eight species of stemwood insects have been recorded from pines in areas near the Bor Forest Island study site. These are mainly capricorn beetles, bark beetles, *Buprestidae*, snout beetles, and *Siricidae*. Population levels of these insects may increase greatly due to stress from disturbances such as drought, changing water tables, infestations by needle-eating insects, fungi, and fire. Some of those which may be most likely to invade following fire are:

Ips sexdentatus, the stenographer beetle, which is a widespread insect in pine stands. It is especially common in cut-over areas where pines have been damaged by slow-moving surface fires.

Phaenops cyanea F. is a widely distributed Buprestid species, and is one of the first beetles to attack trees that have been weakened by fire.

Ancyclochiera novemmaculata L. is less common than *P. cyanea*. However, it is well adapted to invading after fire, for it has been observed to fly great distances toward fires during the night by following smoke plumes.

Monochamus species. *M. galloprovincialis pistor* Germ. and *M. sutor* L. are both serious pests of pines. They cause large-scale drying of crowns, and larval damage to the wood causes serious loss in wood quality.

Although information from unburned and cut-over areas can provide some insights into possible insect pests following stand-replacement fires, we have little specific information from burned areas. Clearly, studies of insect populations following fires in this forest type are sorely needed.

The fire-effects research studies referred to in this chapter were conducted by comparing burned areas of different ages. Long-term observation of a permanent site burned by a high-intensity fire has never before been undertaken in Siberia.

Physical Characteristics of the Bor Forest Island Study Site

The study site is a nearly level, slightly elevated, sandy island of about 50 ha, which is surrounded by bogs dominated by mixed-grass/sphagnum and tall sedge. The central portion of Bor Forest Island is about 6 m above the bog surface. Soils are homogeneous across the island. The soil is a ferric podzol with a coarse sand texture. The A horizon, of mixed mineral and organic matter, is very thin. Occasional weakly cemented patches occur in the B horizon. Characteristics of the soil profile are described in table 81.2. The humus layer contained 34.6 t ha^{-1} of organic matter and 19.9 kg ha^{-1} of carbon, with 18.1 kg ha^{-1} of carbon in the mineral soil (0–70 cm).

Fire History

Fire records for the region are incomplete and cover only the last 20 years at best; therefore we must turn to records such as those in tree rings and lake deposits to obtain long-term records of fire history (Valendik and Ivanova 1990).

Long-Term Pollen and Sediment Records Sediment charcoal provides evidence of the long-term importance of fire. Unfortunately there have been no comparisons of particle accumulation rates in sediments with fluxes to the ground that occur during burns. During the Bor Forest Island experimental fire the spatial pattern of charcoal accumulation at ground level was determined using water traps (see page 862), and compared to a 4500-yr record of charcoal accumulation in sediments of a nearby lake. A core of lake sediment was obtained from Bor Lake, ca. 25 km east of Bor Forest Island, to reconstruct Holocene fire regimes. Soils are coarse alluvial sands of undetermined age. The lake is approximately 5 ha in area and 2 m deep. A 1-m-thick fringe of *Sphagnum* encircles the entire lake. The lake is a closed basin, possibly an ancient oxbow of the Yenisey River. The lake catchment is dominated by *P. silvestris*, but also includes scattered aspen groves. The catchment was clearcut one year prior to coring. A 1-m piston core was extracted and shipped to the laboratory for analysis. The core is largely organic, with sand at the base. The core has been sampled for ^{14}C dating, pollen analysis, and thermogravimetric analysis of sediment charcoal.

The pollen record shows a slight increase in *Pinus* relative to *Betula* since 4000 yr ago, with a concurrent decrease in *Picea* pollen (figure 81.3*a*, *b*), patterns typical of western Siberia (Peterson 1993). Although changes in the composition of vegetation may have been modest over the past 5000 yr, regional fire importance appears to have changed substantially, as evidenced by a dramatic decline in small charcoal particles in lake sediments between 4500 and 2500 B.P. (figure 81.3*c*). Such changes may reflect a combination of decreases in area burned or decreases in intensity of fires. In modern times, *Picea*-dominated forests are more likely to burn in high-intensity crown fires than are *Pinus*-dominated forests, where a higher percentage of area burns in low-intensity surface fires. The large particles that respond to more local fires indicate two periods, 5000 to 4200 B.P. and 3400 to 2800 B.P., when nearby fires appear to have occurred. Particle size distributions in these sections of the core were nearly identical to those observed in particle traps at the experimental burn, but core samples contained order-of-magnitude higher values than observed during our experimental burn. The sediment distribution of sieve samples is continuous with that from the smaller particles observed on pollen slides, suggest-

Table 81.2 Characteristics of the Bor Forest Island soil profile

Horizon	Thickness of horizon (cm)	pH	Organic matter (%)	Particle size composition (%)			
				Coarse sand	Fine sand	Silt	Clay
O	3.0	3.41	66.6				
E	12.0	4.00	0.67	73.3	24.8	0.5	1.4
Bs	7.0	4.11	1.47	73.4	19.2	3.0	4.4
BC	26.0	4.68	1.07	77.1	17.0	2.5	3.4
C		4.81	0.16	78.5	19.2	0.6	1.7

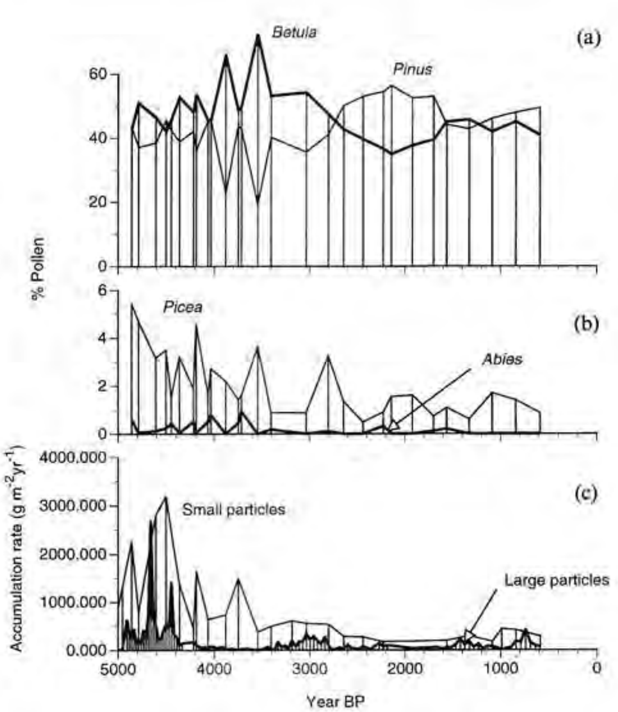


Figure 81.3 Pollen counts (% of total pollen) from Bor Lake core for *(a) Betula* and *Pinus*, *(b) Picea* and *Abies*, *(c)* Accumulation rates of carbon particles in sediment core. Period covered is 5000 to 600 yr B.P.

ing that distribution data are relatively unbiased by method. Sieve samples and airborne samples were analyzed by identical methods, and results were identical (figure 81.3*c*). The decline in fire importance over the past 5000 yr suggests that boreal fire regimes are sensitive to climate changes such as those which might occur with global warming. Before 4600 B.P., western Siberia was about 2°C warmer than today, a relatively small increase compared to the 5°C predicted for boreal regions in coming decades by some Global Circulation Models. Our data suggest cause for concern about the influence of such changes on fire regimes in the boreal zone.

Dendrochronology To reconstruct the fire history of Bor Forest island and compare it to surrounding areas, we sampled and analyzed scarred *Pinus sylvestris* trees. The goal was to determine frequency, seasonality, and size of past fires in the pine forests in this region. Ultimately, we plan to use the fire history of Bor Forest Island, combined with fire histories from many other stands in west-central Siberia, to investigate interactions among climate, human land-use practices, and fire regimes.

Cross-sections were obtained from eight trees on the island (trees EXB 03 to EXB 13) and from seven additional trees on a larger forested "mainland" northeast of the island (trees EXB 15 to EXB 101) with a chainsaw. The mainland was a short distance across a bog, and the maximum distance between sampled trees on the island and the mainland was about 2 km. Sampled trees on the island were primarily on the southern and western side of the island. Standard dendrochronology techniques (e.g., Graybill 1979; Swetnam and Dieterich 1983) were used to cross-date tree rings among the fire-scar specimens. The calendar-yr dates of fires and the approximate season in which the fires occurred were then determined by microscopically observing the position of the fire scars (lesions) within the exactly dated annual rings (Dieterich and Swetnam 1984). In addition to sampling fire-scarred trees, increment cores were taken from 20 dominant trees on Bor Forest Island to assess maximum ages of overstory trees. This was an informal sampling (not based on plots or transects), and so the ages of overstory trees and cohorts reported here are preliminary and should be confirmed by further sampling.

Before the experimental burn in 1993, at least six fires burned portions of the island during the past six centuries (A.D. 1481, 1638, 1753, 1796, 1867, and 1956). Intervals between these fires ranged from 43 to 157 yr, with a mean fire interval (MFI) of 95 yr. Fire-scarred samples in pine forests adjacent to the island, but separated by wet bog, recorded nearly three times

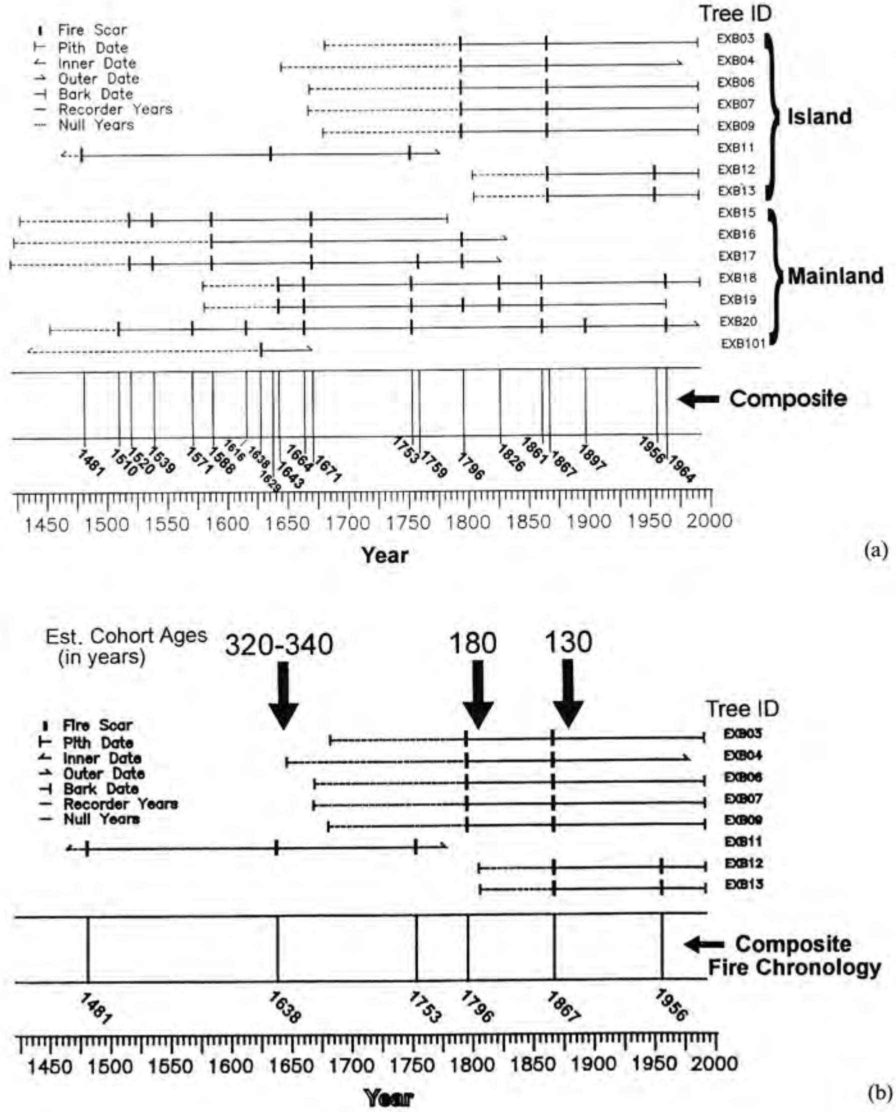


Figure 81.4 (*a*) Fire-scar chronology for Bor Forest Island and nearby areas. Site locations are described in the text. (*b*) Dates of major regeneration episodes on the island.

more fire dates during the same period (figure 81.4*a*). Only two of the six fire dates on the island coincided with fire dates on the mainland forest. As in other pine-forest sites on the Dubches Plain, mainland forest MFI ranged from about 25 to 40 yr. Preliminary stand-age structure estimates on Bor Island, derived from increment cores taken from mature trees (figure 81.4*b*), suggest that the overstory is composed of at least two major cohorts that became established approximately 180 and 130 yr ago. We speculate that these cohorts established following the fires in 1796 and 1867, respectively. An earlier cohort, about 320 to 340 yr old, was also suggested by the fire-scarred samples, although the number of trees sampled was too low to assign much confidence to this estimate. In addition to dating fires to the calendar yr, microscopic analysis enabled us to estimate relative seasons of past fires. The largest percentage of fire scars from Bor Island and the mainland appeared in the latewood portion of the tree ring, and the next largest percentage was within the first one third of earlywood. Although we lack specific knowledge about the cambial phenology of *P. sylvestris* from this area, it is likely that the latewood fire scars represent burns toward the end of the growing season (possibly August or September), and the earlywood scars probably represent fires that burned in June or July. Our findings suggest that relatively small stands of pine forest surrounded by bogs, such as Bor Forest Island, sustain lower fire frequencies because they are isolated from fires spreading across the larger, more continuous fuels of surrounding forests. Differences in fire sources and frequency suggest that significant differences in forest age structure and species composition might also be expected in landscape patches of different sizes and varying degrees of isolation within the matrix of bogs and river drainages on the Sym Plain.

Vegetation and Fuels

Prefire Vegetation Stand structure and vegetation composition were evaluated on a 10-m wide by 320-m long transect crossing Bor Forest Island in an east–west direction. Along the transect we determined stand composition, average tree height and diameter (DBH, 1.3 m), stem basal area, average tree age, and standing volume. DBH and tree condition (healthy, declining, dead) were determined for all 525 trees in the transect. Trees were categorized into 4-cm diameter classes (0–4 cm, >4–8 cm, >8–12 cm, >12–16 cm, >16–20 cm, >20–24 cm, >24–28 cm). We measured tree height and height to bottom of crown for five randomly selected trees in each diameter class (a total of 45 trees). Stand age was determined by increment cores taken from 20 trees. Downed-wood volume was determined by measuring diameters and lengths of fallen trees along a 100-m transect. Downed trees were classified by stage in wood decomposition as either intact or losing the shape of the tree. Living ground cover was described with regard to the vegetation structure and composition on 40 1-m^2 plots evenly distributed across the transect. Projected cover and abundance of species in the grass/low-brush layer were estimated visually according to the Drude Scale (Schenikov 1964):

Scale rating	Description
Soc (socialis)	Dominant plant species; coverage is more than 90%
Cop3 (coptosal)	Very abundant; 70–90% cover
Cop2 (coptosal)	Many individuals; 50–70% cover
Cop1 (coptosal)	30 to 50% cover
Sp (sporsal)	Individuals small in number; cover 10–30%
Sol (solitarie)	Very few individuals; up to 10% cover
Un (unicum)	A single individual

Vegetation was typical of central taiga forests in western Siberia. Before the experimental fire, Bor Forest Island supported a pure stand of Scots pine (*Pinus sylvestris* L.), well stocked and in even-aged patches (trees on most of the island were 130 yr old).

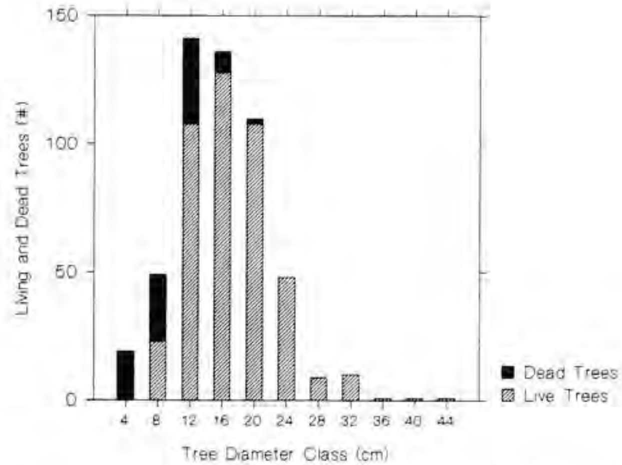


Figure 81.5 Diameter class distributions of dead and living trees in a 320 × 10-m sample plot, one year before the fire. Size classes indicated are upper limits of 4-cm-diameter classes.

The canopy cover was relatively high (0.6–0.7) and average density was 1470 trees ha^{-1}. Average diameter and height of living trees were 18 cm and 17 m, respectively. There were also about 170 stems ha^{-1} of standing dead trees, heavily concentrated in the smaller size classes (figure 81.5). The volumes of standing, living trees, snags, and downed wood were 248, 14.6, 17.3 m^3 ha^{-1}, respectively. Downed wood was in various stages of decomposition.

Advance regeneration was sparse, but included both *Pinus sibirica* Ledeb. and *Pinus sylvestris* L. The understory was of low density, with scattered patches of *Rosa acicularis* and *Salix caprea* dominating in some areas. The edge of the island and depressions were covered by *Spiraea salicifolia*. The ground cover was of mosaic character, but a dense mat of *Cladonia* lichens mixed with mosses dominated over much of the area. Lichens were represented by *Cladonia stellaris*, *C. sylvatica*, *C. rangiferina*, and *C. uncialis*. Green moss (*Pleurozium schreberi*) and low-shrub plants (*Vaccinium vitis-idaea*, *V. myrtillus*, *V. uliginosum*, and *Ledum palustre*) were found in shallow depressions (table 81.3). The heights of the lichen, moss, and low-shrub layers were 5 to 7, 3 to 5, and 12 to 35 cm respectively. The total biomass of living ground cover was 15.9 t ha^{-1}. Litter and forest-floor organic-layer load was 17.6 t ha^{-1}.

First-Year Vegetation Recovery and Stand Conditions

Photo Points Before the fire, ten permanent photo points were established on the island on sites selected to represent the range of prefire stand conditions in terms of tree-size distribution, occurrence of snags, re-

Table 81.3 Characteristics of prefire living ground cover in a pine-lichen forest, Bor Forest Island experimental site

Lichens and mosses	Abundance (Drude scale)	Shrubs	Abundance (Drude scale)
Cladina stellaris	cop3 soc	*Vaccinium vitis-idaea*	cop2
Cladonia sylvatica	sol	*Vaccinium myrtillus*	cop1 cop2
Cladonia rangiferina	sol	*Vaccinium uligunosum*	sp
Cladonia unciaeis	sol	*Ledum palustre*	cop1 cop2
Cetraria islandica	sol	*Carex*	sp
Pleurozium schreberi	cop3	*Calamagrostis langsdorfii*	sol
Hylocomium splendens	sp	Total shrub cover	10%
Dicranum undulatum	sp		
Ptilium cristacastrensis	sp		
Politrichum strictum	sol		
Sphagnum	sol		
Total moss and lichen cover	90%		

generation, and canopy closure. Both plot centers and base points for the camera were permanently marked. A standard 35-mm lens was used for photographs. Figures 81.6*a*, *b*, *c* illustrate typical stand conditions at one of these photo points before, immediately after, and one year after the fire. Notice the degree of crown drying between 1993 and 1994, the lack of obvious regeneration or herbaceous vegetation in the year following the fire, and the loss of bark from dead trees.

Postfire Vegetation Sampling When we returned to study forest regeneration on the experimental site, one year after the fire, we did not resample prefire plots to determine vegetation cover because living ground cover was virtually nonexistent. We observed only isolated individual pine seedlings in the interior of the island and newly emerged small sedge and wild rosemary (*Ledum*) sinusia where the fire burned into the edges of the bog. Otherwise there was no visible regeneration of either herbaceous or woody species. Plots were resampled in 1995 and showed first regeneration of *P. sylvestris*. The plots will be revisitated in following years to document development of vegetation.

Fuel Loading and Surface Fuel Consumption To determine ground fuel load and structure, the Russian team measured litter, forest-floor organic matter, and living ground cover, which was represented mainly by lichens. Along the east–west transect we established ten 1-m^2 plots (one every 10 m) for determining prefire lichen, litter, and small-branch loads. Forest-floor organic matter was measured in 0.5 × 0.5-m subplots. Samples were oven dried to constant weight and then weighted. Before sampling, we measured depths of lichens and litter and of the forest-floor organic layer. After the fire we established ten additional 20 × 25-cm plots next to the prefire plots to measure the organic matter remaining after fire. Twenty by 25-cm plots were also established next to these plots in the year after the fire to determine volume of postfire litter. The Canadian team also measured preburn and immediate postburn fuel loads at twelve sites throughout the burned area, primarily to quantify fuel consumption in the fire. Their methods are described on page 862.

Pine-lichen stands are remarkable for rapid development of flammability after a fire and high flammability over a long period during the fire season. A considerable load of ground fuels on the island (table 81.4) promoted high fire intensity, even in the absence of significant ladder fuels. The prefire surface fuel loads of 33.6 t ha^{-1} were decreased by 50% a year following the fire. The Canadian team estimated prefire ground and small (<3 cm) surface fuel loads of 44.9 t ha^{-1}, about 60% of which was consumed by the fire. We will continue to explore reasons for these differences. The prefire duff layer averaged 28.7 t ha^{-1}, with 13.9 t ha^{-1} of living lichens over the duff. A higher proportion of surface fuel than ground fuel (lichen and duff) was consumed. The Canadian group reported 48% reduction in the lichen and duff layer by weight and an 88% reduction in depth (all the lichen layer plus an average of 1.3 cm of duff). Ivanova (table 81.4) reported 79% reduction in loose surface litter and 21% reduction in the forest-floor (duff) layer one year after fire. Except around bases of trees, the fire burned to mineral soil in few places. Essentially all the loose

(a)

(b)

(c)

Figure 81.6 View from photo point 5 of typical stand condition on the island. (*a*) Before the fire. (*b*) Immediately after fire. (*c*) July 1994, one year after fire.

Table 81.4 Russian measurements of prefire and postfire (1 yr after fire) structure and load of fuels in a pine-lichen forest (dry weights) at Bor Forest Island. Miscellaneous litter includes lichens (prefire), needles, bark, etc. Small branches are up to 2 cm in diameter. Forest floor is the compacted forest-floor organic layer.

	Prefire		Postfire
Fuel type	Depth (cm)	Fuel load (g/m^2)	Fuel load (g/m^2)
Miscellaneous litter	—	1593	245
Cones	—	15	104
Small branches	—	81	6
Total loose surface litter	7.0	1689	355
Forest floor	3.5	1673	1314
Total	10.5	3362	1669

litter measured in 1994 had accumulated since the fire. This litter consisted primarily of needles (77.6%) and bark (8.6%) shed from injured and dying trees following the fire. The prefire research allowed us to estimate prefire fuel loads and biomass consumption, and to investigate postfire processes of forest restoration in this area.

To measure the effects of the fire on the carbon and nutrient contents of the soil organic layer, and to monitor postfire accumulation of soil organic matter, two 30 × 30-m plots were established. Prefire and postfire samples were collected on 5 and 7 July 1993. The chemistry of the humus layers before and after the fire is described in table 81.5. Fire intensity on Plot 2 was higher because of a greater amount of downed woody material.

Tree Mortality

Stand-Level Mortality The extent of crown fire was estimated from low-level aerial photographs by determining the percentage of the area of the island that experienced complete canopy removal (all foliage and small twigs were combusted). Because the fire burned the entire surface of the island, the remaining area was assumed to have burned in surface fire. Areas of crown scorch were determined by foliage color (light green or brown in areas where crowns were scorched, dark green where they were not). A 30 × 30-m plot was established in July 1994 to evaluate stand structure, tree mortality, and insect damage. The plot contained 203 trees 6 cm or greater in diameter. Tree diameter (DBH) was measured at 1.3 m from the ground surface. Maximum scorch height on the bole and percentage of crown with dried foliage were recorded for each tree. Trees were classified as alive, dead, or dying. The plot was on the northwest corner of the island in

Table 81.5 Element content and standard deviations (kg ha^{-1}) of the humus layer in Bor Forest Island before and after fire

Element	Plot 1		Plot 2		Mean	
	Before	After	Before	After	Before	After
			kg ha^{-1}			
C	19 710 ± 3890	20 030 ± 1300	20 040 ± 3010	15 170 ± 3260	19 870 ± 3290	17 600 ± 3470
N	380 ± 56	375 ± 20	402 ± 65	333 ± 66	391 ± 59	354 ± 51
P	24.8 ± 3.3	29.3 ± 4.1	26.9 ± 2.3	30.3 ± 6.8	25.9 ± 2.9	29.8 ± 5.3
K	24.4 ± 4.4	33.7 ± 5.0	26.1 ± 1.4	33.0 ± 10.5	25.3 ± 3.2	33.3 ± 7.7
Ca	58.5 ± 20.2	60.7 ± 13.3	57.8 ± 17.3	79.0 ± 16.1	58.2 ± 17.8	69.9 ± 17.0
Mg	8.3 ± 2.0	9.2 ± 1.7	8.3 ± 1.3	10.8 ± 1.8	8.3 ± 1.6	10.0 ± 1.8
Mn	5.6 ± 0.8	7.6 ± 1.9	15.5 ± 4.1	19.8 ± 4.0	10.5 ± 5.9	13.7 ± 7.1
Cu	0.21 ± 0.04	0.24 ± 0.03	0.22 ± 0.01	0.23 ± 0.06	0.22 ± 0.03	0.24 ± 0.04
Zn	1.98 ± 0.27	2.30 ± 0.20	2.05 ± 0.19	2.07 ± 0.39	2.01 ± 0.22	2.19 ± 0.31
Fe	68.8 ± 8.2	79.3 ± 21.3	68.2 ± 14.2	79.6 ± 28.8	68.5 ± 10.9	79.4 ± 23.9
Al	74.2 ± 12.7	92.3 ± 16.9	86.7 ± 25.4	90.0 ± 18.5	80.4 ± 20.0	91.1 ± 16.7

an area that had burned in surface fire only. It extended from the edge of the island up to the higher ground in the interior. In 1994 and 1995, mortality was also evaluated for the 525 trees on the vegetation transect described above.

Approximately 57% of the area of the island burned as a crown fire (see figure 81.15). All the trees in these parts of the stand died. In another 25% of the area, the surface fire was severe enough to scorch most of the crowns. Most of these trees were also dead within a year. In the plot established to evaluate mortality and insect infestation in the underburned area, trees had an average diameter of 15 cm. Of the 203 trees sampled, 17% were 6 to 11 cm in diameter, 53% were 12 to 17 cm DBH, and 30 were 18 to 23 cm DBH (figure 81.7). Fifty-five percent of the trees in the plot had maximum char heights of greater than 2 m (figure 81.8). Except for the smallest size class, there was generally a positive correlation between tree diameter and char height. A similar relationship is observed by Tsvetkov (1993) for *Larix*. Tree height was related to the proportion of dry foliage in the crowns, and nearly all trees less than 12 cm DBH were dead and had 100 percent dry foliage. At the time of sampling in July 1994, 75% of the trees were dead or dying (figure 81.7). Most trees 20 to 24 cm DBH are expected to survive. We anticipate additional mortality as insect damage increases and trees low in vigor continue to die. On the east–west vegetation transect, 94.5% of the 525 trees alive at the time of the fire were dead in 1994; this proportion had increased to 98.5% by July 1995, at which time the only living trees remaining were in scattered pockets on the slope along the margin of the island.

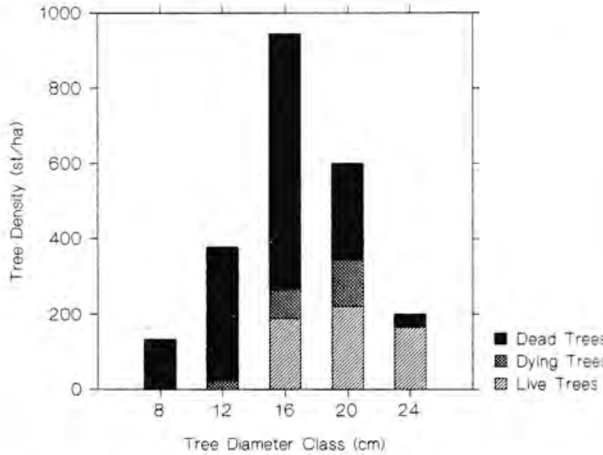


Figure 81.7 Diameter class distribution of live, dead, and dying trees one year after the fire on the 30 × 30-m sample plot

Modeling We also measured fire injury to individual trees so that we could begin to develop models for predicting mortality of *P. sylvestris* following wildfires. Immediately after the fire, we established five plots of 20 trees each. Plot locations were randomly selected but were linked to the transects established for fuel sampling. Twenty trees were tagged in an approximately circular pattern around the plot center. Plot radius varied with tree density, so that each plot included 20 trees. We attempted to distribute plots in areas of varying fire severity. This initial sampling, however, resulted in a very high proportion of sample

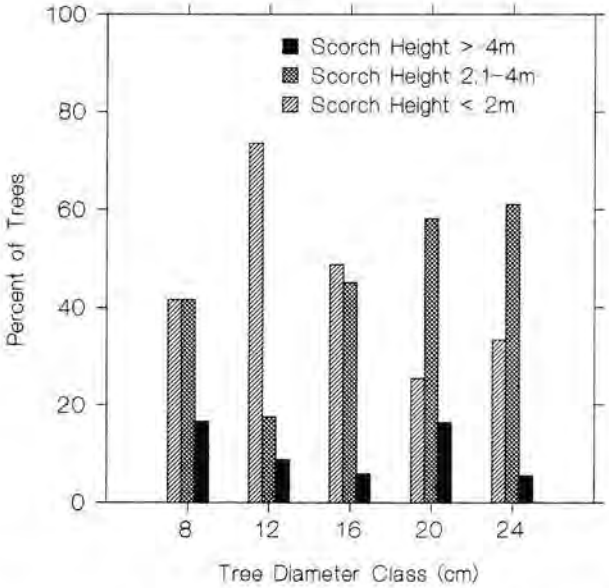


Figure 81.8 Distribution of scorch height by diameter class on the 30 × 30-m sample plot

trees in areas of medium to high fire severity, and most of these trees had died by 1994. In July 1994 we established five additional plots. Plot centers were again randomly located, but sampling was restricted to areas of low to moderate fire severity to ensure an adequate sample of surviving trees for modeling. In both years, all trees in the plots were tagged and numbered. Measurements included maximum and minimum scorch height on the bole, tree diameter, tree height, height to bottom of crown, and depth of residual forest-floor organic matter at base of tree (as a possible indication of effects of fire on shallow roots). In 1993, we also visually estimated percentage of crown scorch. This survey was not possible in 1994 because dead needles resulting from postfire insect damage and decreases in tree vigor could not be distinguished from scorch, and many needles had already been shed. In 1994 we also recorded whether trees had visible evidence of insect infestation on the boles (as indicated by exit holes in the bark and by visible insect frass).

Data were analyzed following procedures described in Regelbrugge and Conard (1993). Logistic regression analysis (Walker and Duncan 1967) was used to model the probability of postfire tree mortality as a function of tree-size and fire-damage variables. The model used is of the form:

$$P(m) = 1/\left(1 + e^{-(\beta_0+\beta_1 X_1+\cdots+\beta_k X_k)}\right)$$

where $P(m)$ is the probability of postfire mortality, X_1 through X_k are independent variables, and β_1 through β_k are model coefficients estimated from the data. We used DBH, maximum and average ((maximum − minimum)/2) stem-bark char height, relative char height (height of bark char/tree height), depth of forest-floor organic matter, and percentage of canopy volume scorched as independent variables to predict fire-induced mortality. The SAS LOGISTIC procedure was used to obtain maximum likelihood estimates of the model coefficients, and model fit was evaluated with the Homer and Lemeshow goodness-of-fit statistic (SAS Institute 1989; Saveland and Neuenschwander 1990).

Of the 201 trees sampled to develop mortality models, 57% were dead by a year after the fire. Ninety-nine percent of dead trees sampled, as well as 85% of the living trees, were infested with bark beetles. Although infestation tended to be low in living trees, at least another year will be required to ensure that all mortality has occurred before developing final models. Only 14 of 100 trees were intermediate in canopy-scorch estimates. Forty-three percent had no crown scorch and 43% had 90 to 100% crown scorch. Of those with no crown scorch, 56% were dead a year after the fire. Of those with 90 to 100% scorch, 97.6% had died.

General population characteristics for trees used to develop mortality models are listed in table 81.6. These trees were selected to provide a well-distributed set of characteristics for model development, and not to describe the stand in general. Diameters were slightly larger than those measured in the 30 × 30-m plot and in the vegetation transect, primarily because sampling focused on areas of incomplete mortality along the fringes of the island, where average tree size tended to be larger than in the interior.

Preliminary mortality models were developed both for the trees measured only in 1993 (where we could incorporate canopy scorch) and for all trees. For 1993 trees, a model incorporating canopy scorch, DBH, and crown length seemed to provide an excellent fit, with 97% concordant pairs, and a Hosmer and Lemeshow goodness-of-fit statistic with $p = 0.9937$ (table 81.7). We also attained good fit with a model incorporating crown scorch and DBH (94.7% concordant pairs, goodness of fit $p = 0.9518$; table 81.7). The best model for all trees together incorporated relative average char height and DBH^2. This model had 83.3% concordant pairs, with $p = 0.7702$ for the goodness-of-fit statistic (table 81.7). Any of these models might be sufficient for estimating stand-level mortality, but the ones based on crown scorch will be more reliable for predicting mortality of specific trees. Unfortunately, models based on crown scorch have the problem that

Table 81.6 Population characteristics of trees used in developing mortality models

Variable (units)	Sample size	Mean	Minimum	Maximum	Standard deviation
DBH (cm)	201	23.3	9.9	52.4	7.69
Height (m)	201	15.6	9.6	20.4	2.36
Crown length (m)	100	5.6	2.0	9.7	1.50
Crown scorch (%)	100	49.0	0	100	46.15
Maximum char height (m)	201	4.3	1.5	15.0	2.13
Minimum char height (m)	201	2.3	0.35	10.0	1.70
Average char height (m)	201	3.3	1.1	11.0	1.83

Table 81.7 Parameter estimates for the best-fitting mortality models for 1993 and 1994 data sets

	Model parameter estimates					
Sampling date (*n*)	INTERCEPT	DBH	DBH^2	SCORCH	CROWN L	REL AV CH
1993 (101)	10.587	−0.4899	—	0.0593	—	—
1993 (101)	14.717	−0.4312	—	0.0731	−0.9358	—
1994 (201)	−2.529	—	−0.0015	—	—	19.9466

model parameter estimates are very dependent on how soon after the fire the measurements are made. If these measurements are not made immediately, increasing crown drying in stressed trees may cause browning of needles not directly related to crown scorch. This problem was evident in data from the mortality plot (not shown), where crown drying was not nearly as reliable a predictor of mortality as was the crown scorch we measured immediately after fire. All models presented here are preliminary, however, because we expect continuing mortality.

Insect Damage In the year following the fire, insect damage was evaluated early in July on trees in the 30 × 30-m plot established for characterizing forest structure. All trees in the plot were visually inspected for signs of insect damage (emergence holes in bark and insect frass). In addition, a representative test area was established in the northeastern corner of the experimental plot. Trees were categorized as living, dying, or dead. A bark pallet (sample) of approximately 0.2 m^2 was removed from each of five trees, and counts were made of living larvae under the bark, mother passages in the bark, and larval passages in the wood. We also recorded the percentage of the crown that had dried needles. Living larvae were brought back to the laboratory for identification.

Visual inspection showed that all trees in the 30 × 30-m plot were infested with bark insects. The bark of many trees had already begun to peel off even a year after the fire, and piles of bark at the foot of the trunks were common. Insect activity was so intense that throughout the forest one could hear the sounds of bark insects in the tree stems. All five sample trees showed evidence of heavy insect infestation in the bark plates sampled (table 81.8).

Although variation in insect infestation from tree to tree was considerable, in general the levels were quite high, both in dead trees and in those still living. All the living larvae taken from the sample trees were in the genus *Monochamus*, but species identification was not attempted. The adult beetles observed were mainly gray capricorn beetles (*Acanthocinus edulis* L.), brown capricorn beetles (*Criocephalus vresticees* L.), and big pine weevils (*Hylobius abietis* L.). The small plot area makes it likely that important species were not observed.

Bor Forest Island Fire Behavior and Atmospheric Emissions

Preburn Fuel Sampling

For documentation of fuel sampling and fire behavior, Bor Forest Island was gridded with a three-by-four array of 12 grid points, each 250 m apart in a SW–NE direction, and 150 m apart in a NW–SE direction. At each of these locations a 15-m transect was established, and downed woody fuels were inventoried by the line-intersect method (McRae et al. 1979). Mean preburn oven-dry fuel weights were determined to be 0.198 kg m^{-2} for fuels 0 to 3 cm in diameter, 0.417 kg m^{-2} for

Table 81.8 Insect populations in the sample trees, in July 1994 at Bor Forest Island

Tree no.	Diameter (cm)	Bark sample (cm^2)	Living larvae (no./m^2)	Mother passages (no./m^2)	Larval passages (no./m^2)	Dried crown (%)	Vigor class
1	20	2512	8.0	39.8	8.0	25	dying
2	21	1978	5.1	70.8	70.8	100	dead
3	21	1978	15.2	40.4	30.3	100	dead
4	22	2148	23.2	46.6	4.7	50	dying
5	24	2713	0	29.5	40.5	100	dead
x			10.3	45.4	30.9	75	
(s.e.)			(4.05)	(6.9)	(13.8)		

fuels 0 to 7 cm in diameter, and 1.088 kg m^{-2} for fuels >7 cm in diameter. The total preburn downed woody fuel load was therefore 1.505 kg m^{-2}.

A total of 5 pins were located at fixed intervals along each line-intersect transect to determine an average depth of burn. A horizontal bar of each pin was placed flush with the top of the lichen layer. Following the fire, the distance between the bottom of this bar and the remaining organic layer would constitute the depth-of-burn measurement at each location.

To determine the bulk density of the forest floor, three randomly located 0.25 m^2 (0.5 × 0.5 m) sections of forest floor were removed and sectioned into lichen and duff layers. All materials were then oven dried and weighed. The lichen layer had an average depth of 6.9 cm (ODW 1.390 kg m^{-2}) and the duff layer averaged 4.0 cm in depth (ODW of 2.879 kg m^{-2}). The forest floor therefore averaged a depth of 10.9 cm, with an oven-dry weight of 4.269 kg m^{-2}.

At each of the 12 grid points a thermocouple/datelogger system was installed to determine the spread rate and residence time of the fire. The thermologgers are designed to measure and record flame-zone temperatures and their duration, above and below the top of the forest-floor litter (lichen) layer. Three thermocouple probes were mounted at +5 cm, −1 cm, and −3 cm with respect to the top of the lichen layer, and connected to a buried datalogger.

Fire Weather

Daily fire-weather data, recorded at the Avialesookhrana (Aerial Fire Protection Service) Base at the Bor airport, was used to track development of fire-danger conditions in the region of Bor Forest Island from the beginning of the 1993 fire season through the conducting of the Bor Forest Island Experimental Fire. Component codes and indexes of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), a subsystem of the Canadian Forest Fire Danger Rating System (Stocks et al. 1989), were calculated daily based on noon local standard time (LST) measurements of dry-bulb temperature, relative humidity, wind speed, and 24-hour precipitation. The Russian Nesterov Index (Nesterov 1949), based on noon LST measurements of dry-bulb and dewpoint temperature and precipitation, was also calculated during this period.

The 1993 forest-fire season in the central portion of Krasnoyarsk Region began in typical fashion. Following the usual cold and dry winter, snow cover disappeared early in May, although the month of May remained quite cool with low fire-danger conditions. June was a much warmer and drier period, with temperatures consistently above 20°C, wind speeds generally above 10 km h^{-1}, and very scant precipitation. Fire-danger conditions were generally extreme by late in June, but moderated substantially after more than 25 mm of rain fell during the 28 June to 1 July period. However, no further precipitation occurred prior to the Bor Forest Island Experimental Fire on 6 July, and fire danger steadily increased as temperatures rose and humidity decreased. By 6 July in Bor, fire-danger conditions were high to extreme. The Duff Moisture Content (DMC) and Buildup Index (BUI) of the Canadian FWI System were at levels indicating moderate to high fuel consumption, and the Fine Fuel Moisture Content (FFMC) and Initial Spread Index (ISI) levels also indicated moderate to high spread rates. Bor fireweather data for the 1 June to 6 July period are listed in table 81.9. Weather measurements taken on Bor Forest Island on 5 and 6 July were generally consistent with observations in Bor, except for slightly lower wind speeds.

Fuel Moisture

Because the moisture content of ground, surface, and aerial fuels is critically related to fuel consumption and fire behavior, a large number of fuel samples were

Table 81.9 Canadian FWI System codes and indexes for Bor Airport[a]

Month	Day	Temp.	RH	WS	Rain	FFMC	DMC	DC	ISI	BUI	FWI
June	1	16.4	24	7	0.0	93.3	26.6	80.0	9.7	29.0	16.5
	2	17.9	22	7	0.0	93.3	30.5	86.7	9.8	32.4	17.6
	3	20.7	31	7	0.0	92.8	34.4	93.8	9.1	35.9	17.5
	4	23.2	27	7	0.0	92.9	39.1	101.4	9.1	39.8	18.6
	5	18.7	29	7	0.0	92.7	42.8	108.1	8.9	43.0	19.0
	6	23.0	29	22	0.5	92.7	47.3	115.7	19.2	47.3	33.8
	7	23.8	32	7	0.0	92.8	51.8	123.4	9.1	51.7	21.1
	8	23.0	34	7	2.3	82.8	48.8	130.9	2.2	50.5	6.7
	9	21.9	34	7	0.0	89.0	52.8	138.3	5.3	54.0	14.5
	10	21.3	36	7	0.0	89.9	56.6	145.5	6.0	57.4	16.5
	11	23.9	34	7	0.0	90.8	60.9	153.2	6.8	61.1	18.8
	12	26.0	30	7	0.0	92.0	65.9	161.3	8.1	65.9	22.0
	13	24.7	25	14	0.0	92.9	71.0	169.1	13.1	71.0	31.9
	14	16.4	53	11	0.0	89.2	73.2	175.5	6.6	73.2	20.2
	15	18.1	40	7	0.0	89.2	76.2	182.2	5.5	76.2	17.9
	16	18.8	43	14	0.0	89.3	79.2	188.9	7.8	79.2	23.7
	17	8.0	43	18	0.0	88.6	80.6	193.8	8.7	80.5	25.6
	18	6.5	83	11	0.9	78.9	80.9	198.4	1.8	80.9	7.5
	19	12.3	62	11	0.6	81.2	82.3	204.0	2.3	82.3	9.4
	20	13.8	45	11	1.0	81.8	84.4	209.9	2.4	84.4	10.1
	21	16.3	52	11	0.0	85.1	86.6	216.2	3.7	86.6	14.4
	22	14.0	88	14	0.0	81.1	87.1	222.1	2.6	88.0	10.9
	23	19.8	36	7	0.0	87.8	90.6	229.1	4.4	91.1	16.9
	24	26.1	37	11	0.0	90.4	95.1	237.2	7.9	95.1	26.1
	25	26.8	36	11	0.0	91.0	99.8	245.4	8.6	99.8	28.4
	26	23.2	51	14	0.0	89.6	103.0	253.0	8.2	102.9	27.9
	27	19.1	77	11	0.3	84.9	104.2	259.9	3.6	104.2	15.6
	28	21.2	56	11	8.0	63.5	58.9	247.3	0.9	73.9	3.3
	29	17.1	94	7	10.0	23.5	30.5	228.9	0.0	45.8	0.0
	30	24.0	61	4	2.4	53.9	28.3	236.6	0.3	43.6	0.5
July	1	24.8	29	7	8.0	70.2	19.3	226.2	0.9	31.8	1.4
	2	26.8	35	4	0.0	87.1	23.6	234.7	3.5	37.7	8.4
	3	26.0	39	11	0.0	89.9	27.5	243.1	7.4	42.8	16.4
	4	26.7	37	7	0.0	90.7	31.6	251.6	6.8	48.1	16.4
	5	30.3	38	7	0.0	91.2	36.2	260.7	7.3	53.7	18.3
	6	30.2	36	7	0.0	91.6	40.8	269.9	7.7	59.3	20.1

a. Temperature in °C; wind speed in km h^{-1}, rain in mm, FFMC = Fine Fuel Moisture Code, DMC =Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Buildup Index, and FWI = Fire Weather Index.

collected immediately prior to igniting the Bor Forest Island fire. These samples were subsequently oven dried, and the average moisture contents of selected fuel strata were determined as a function of oven-dry weight. Moisture contents of fine downed and dead woody fuel were consistent at about 7.5% for material less than 3 cm in diameter. Forest-floor fuel moisture content showed strong demarcation between lichen and duff materials, with lichen values of 8.9% (0–4 cm) and 11.2% (4+ cm) contrasting with duff values of 50.2% (0–2 cm) and 104.1% (2–4 cm). The moisture content of one-year-old *Pinus sylvestris* needles averaged 74.7%. In general, these fuel moisture values agree closely with those forecast by the Canadian FWI System codes and indexes, and indicate that high fuel consumption could be expected during the experimental burn.

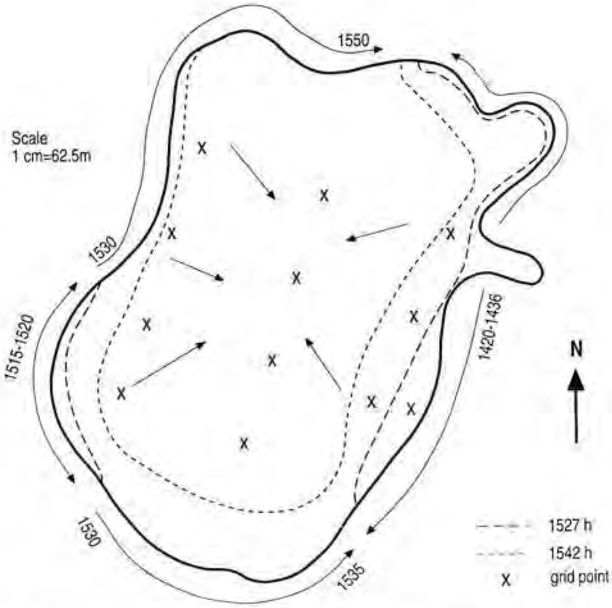


Figure 81.9 Ignition sequence for Bor Forest Island Experimental Fire, 6 July 1993

Figure 81.10 Ignition along west side of Bor Forest Island (1522 h)

Fire Behavior

Ignition Procedure Because the primary purpose of the Bor Forest Island Fire Experiment was to create a high-intensity, stand-replacement fire, ignition along the windward side of the island, with subsequent headfire development, was considered essential. Winds were light and variable on 6 July, and weather conditions measured on-site at 1300 h were similar to those observed at the Bor airport weather station. With light winds (~ 7 km h^{-1}) from the SE, ignition began along the E side of Bor Forest Island at 1420 h, using hand-held torches (figure 81.9). By the time this ignition line was complete (1436 h), however, winds had shifted 90° to the SW. This sudden wind change turned the original ignition line into a backing fire, and it was necessary to begin a second ignition line along the W side of the island to obtain a headfire effect. This line (approximately 500 m) was ignited between 1515 and 1520 h, and the two ignition lines began slowly moving together. Winds were still light and variable in direction, however, and it was decided to complete ignition along the southern and northern edges of the island, effectively creating a perimeter-ignited, convection-driven fire. This phase of the ignition began at 1530 h, being completed along the southern edge at 1535 h, and along the northern edge at 1550 h (see figure 81.9). The complete ignition phase was monitored and documented by helicopter-mounted cameras.

Rate of Spread In the early phases of the fire, spread rates were slow, with surface fire predominating, although some isolated torching took place (figures 81.10, 11), particularly when the fire reached the crest of the island's sloped sides. As the fire progressed, however, an increasingly stronger convective influence took place as the fire lines accelerated inward.

Crowning became more continuous, with a firestorm developing in the final phase of the burn. Although it was impossible to observe visually, thermologger measurements indicated that the active phase of the burn was complete by approximately 1550 h. That the Bor Forest Island Fire did not burn as a running headfire complicated use of thermologger data as an aid in quantifying spread rate. However, an average spread rate was determined from points

Figure 81.11 Typical high-intensity surface/intermittent crown-fire behavior on north side of Bor Forest Island (1545 h)

along the windward edge, where crowning became continuous to the fire-convergence zone. Over this distance the fire spread at an average rate of 25 m min^{-1} to 0.42 m s^{-1}.

Residence Times The thermologger data provided a clear picture of the combustion rate and residence time of the Bor Forest Island Fire, for usable data were retrieved from 11 of the 12 loggers. Figure 81.12 illustrates temperature versus time recorded at a typical grid point exposed to crown fire, near the center of the burned area where convection-influenced firelines converged. At this point the +5-cm thermocouple recorded a peak temperature of 850°C at 1548 h, remaining above 500°C for 1.17 min., and above 100°C for 3.84 min. The mean residence times above 500°C (at 11 locations) for the +5-cm, −1-cm, and −3-cm thermocouples were 1.07, 1.18, and 1.18 min. respectively. Corresponding mean residence times above 100°C were 5.64, 4.72, and 5.63 min. respectively.

The thermologger data represent primarily crown fire, originating from a deep but low bulk-density surface lichen layer. It can be inferred from figure 81.12, which shows very little time delay in temperature peaks reached by the −1 cm and −3 cm thermocouples, that the lichen layer burned very quickly, probably almost entirely by flaming combustion. No firm estimate of smoldering combustion's duration can be inferred from the thermologger data, under the assumption that the 5.64-min. mean residence time above 100°C for the +5-cm thermocouple represents flaming combustion. Smoldering in the forest floor

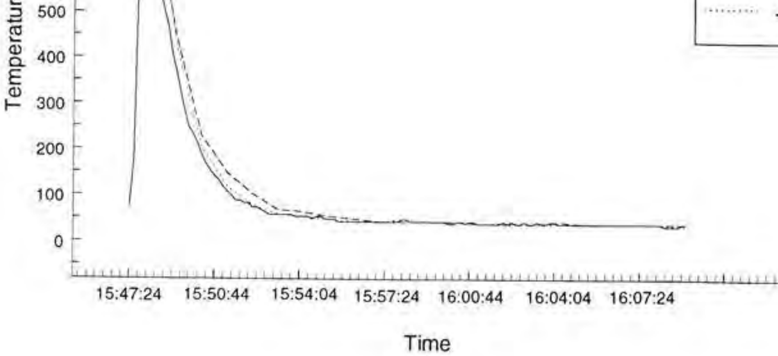


Figure 81.12 Typical temperature–time profile for Bor Forest Island Experimental Fire

behind the passage of the flaming front was observed to be minimal, however, with little residual smoke.

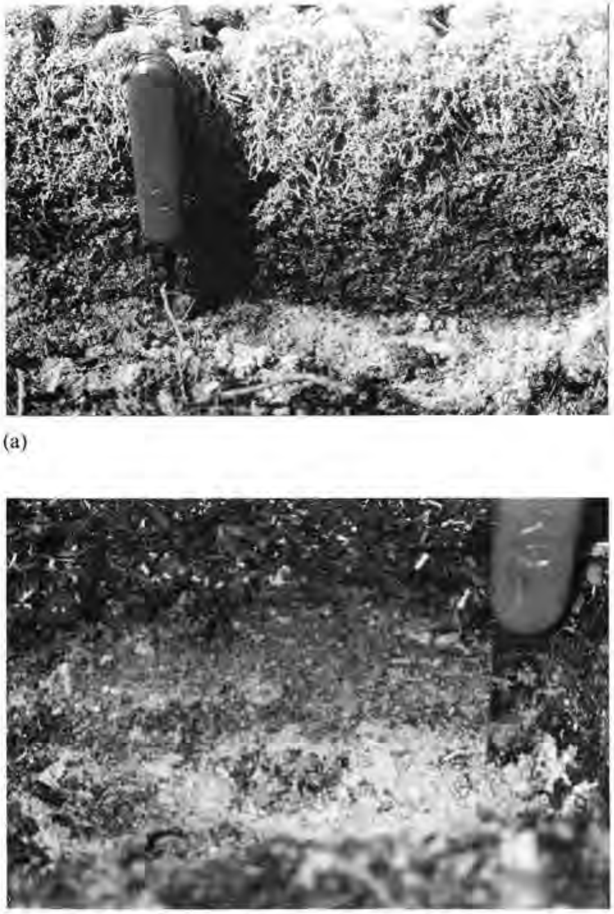
Fuel Consumption Following the fire, line-intersect transects were reinventoried to determine the quantity of downed woody fuel remaining on-site, and therefore the amount of surface fuel consumed. Fuel consumption averaged 0.194 kg m^{-2} for 0–3 cm size-class fuels, 0.270 kg m^{-2} for 0–7-cm size-class fuels, and 0.541 kg m^{-2} for fuels >7 cm in diameter, translating into surface fuel consumption rates of 98%, 65%, and 50% for these three size classes. Overall downed woody fuel consumed was therefore 0.811 kg m^{-2} (~54%).

Depth-of-burn pins along each transect were also measured immediately following the fire. Depth of burn was slightly variable, but averaged 8.36 cm, with a standard deviation of 2.23 cm. This result translates into consumption of all the surface lichen layer (1.390 kg m^{-2}) and an additional 1.46 cm (1.051 kg m^{-2}) of the underlying duff (organic) layer. Total ground fuel consumption was therefore 2.441 kg m^{-2} (figure 81.13*a*, *b*).

The brevity of the Bor Forest Island Fire Experiment did not permit sampling of aerial (crown) fuels. However, an aerial estimate of the portion of the island where crown fire consumed crown fuels determined that approximately 57% of the island fell into this category (figure 81.16). Using the diameter distribution of the island stand, along with crown fuel weights measured in jack pine (*Pinus banksiana*) in Canada (Stocks and Walker 1975), and assuming that aerial fuel consumption included needles and fine dead twigs (<1-cm diameter), a figure of 0.460 kg m^{-2} was estimated for crown fuel consumption. Total fuel consumption (ground, surface, and aerial) during the Bor Island fire was therefore determined to be 3.712 kg m^{-2} (38.12 t ha^{-1}).

Intensity The frontal fire intensity concept of Byram (1959) was used to approximate the intensity, or energy-release rate, of the Bor Forest Island fire. The formula $I = Hwr$, where H represents the low heat of combustion (~18 000 kJ kg^{-1}), w is the amount of fuel consumed (in kg m^{-2}), r is the forward rate of spread in m s^{-1}, and I is the frontal fire intensity in kW m^{-1}. Using the spread-rate and fuel-consumption values determined earlier, a frontal fire-intensity level of 28 062 kW m^{-1} was estimated for the fire.

This level of energy release represents an extremely intense fire within the boreal ecosystem, and is the result of high fuel-consumption levels in the flaming stage of combustion, combined with the strong convective fire activity generated by the ignition pattern of the fire. This extreme intensity was reflected in the strong vertical development of the convection column above the fire, which was estimated to have reached 5000 m during the most intense stage of the fire (figure 81.14). The development of this most intense phase of the fire is evident from the high levels of crown fuel consumption in the center portion of the island (figures 81.15, 81.16).



(a)

(b)

Figure 81.13 Prefire ground fuel profile, showing well-developed lichen layer (~7 cm) and underlying organic material (~4 cm) over mineral soil; (*b*) postfire ground fuel profile showing remaining organic material (~2.6 cm) over mineral soil.

Atmospheric Emissions

Radiatively Active Trace Gases A high-volume sampling system developed by NASA Langley atmospheric scientists was installed on an Aeroflot MI-8 helicopter and used to collect smoke samples immediately above the fire. Particle-filtered samples were drawn through a probe mounted on the nose of the

Figure 81.14 Well-developed convection column (5 km) above Bor Forest Island (1555 h)

Figure 81.15 Postfire ground-level view within high-intensity portion of Bor Forest Island fire

Figure 81.16 Bor Forest Island one day after the fire. Notice the heavily crowned-out center portion of the island, where convection-driven firelines converged.

Table 81.10 Mean CO_2-normalized emission ratios and standard deviations (in %) determined for the Bor Forest Island Fire

Type and stage of fire, no. of samples[a]	Mean CO_2-normalized emission ratios and standard deviations (%)		
	CO	H_2	CH_4
F 1 (4)	8.8 ± 2.7	1.2 ± 0.2	0.5 ± 0.1
F 2 (5)	11.3 ± 2.7	1.6 ± 0.1	0.4 ± 0.1
S 3 (4)	33.5 ± 4.5	2.2 ± 0.2	1.3 ± 0.2

a. Combustion phase (F = Flaming; S = smoldering), Stage of fire (1, 2, 3), and number of samples ( )

helicopter. This probe was coupled to a high-volume pump inside the helicopter by flexible hose. Each smoke sample was collected in a gas sampling bag, and then transferred into a stainless-steel bottle for subsequent laboratory analysis to determine levels of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). Smoke sampling was conducted at altitudes as low as safety would permit, as determined by fire intensity and smoke turbulence. Flight paths chosen during smoke-plume and column sampling were based on visual keys such as smoke color, flame characteristics, apparent turbulence, and combustion stage. Samples from the high-intensity flaming phase and low-intensity smoldering phase of combustion were targeted and collected during the fire.

The results from 13 smoke-sampling runs are presented in table 81.10 for three fire stages: flaming combustion during the surface-fire phase (F1), flaming combustion during the high-intensity crowning phase (F2), and smoldering combustion when no flames were visible (S3). Emission ratios in this table were determined by measuring excess (above-background) trace-gas concentrations in the smoke plume and normalizing these values against CO_2 levels. This relationship can be used to define combustion efficiency and to develop emission factors (g product/g fuel burned) if fuel-consumption levels are known.

A fact of major interest in table 81.10 is that samples collected during the high-intensity phase (F2) of the Bor Island fire revealed elevated CO emission ratios, suggesting lower combustion efficiency than inferred from results obtained from Canadian boreal logging slash fires during flaming combustion (Cofer et al. 1990). Methane and H_2 emission ratios, however, were similar to measurements obtained in the Canadian fires. During the smoldering-combustion phase (S3), CO emission ratios were almost three times higher than on Canadian logging slash fires.

It had been suggested that very-high-intensity flaming combustion may significantly change the emissions chemistry associated with the flaming stage in combustion, leading to less complete combustion and correspondingly higher proportions of incompletely oxidized combustion products such as CO (Cofer et al. 1989). The enhanced proportion of CO emissions during the vigorous flaming stage in the Bor Forest Island fire seems to support this thesis, although additional data will be required for verification. Trace-gas emissions from this fire are analyzed in greater detail in chapter 79.

Compounds Affecting Stratospheric Ozone To complement the NASA trace-gas emission measurements, both helicopter and ground-based grab sampling (using stainless-steel vacuum canisters) of emissions for specific analysis of methyl bromide (CH_3Br) and methyl chloride (CH_3Cl) was also carried out during the Bor Forest Island fire. Decay products of these compounds are known, like the longer-lived chlorofluorocarbons (CFCs), to induce depletion of stratospheric ozone. Bromine, we emphasize, is much more efficient on a per atom basis than chlorine in breaking down ozone (by a factor of about 40) (WMO 1992).

The emission ratios of CH_3Br and CH_3Cl measured in the Bor fire were in the range of 0.11 to 3.1×10^{-6} and 8 to 140×10^{-6} respectively. This reading was considerably higher than those found in savanna and chaparral fires or in laboratory experiments (cf. Manö and Andreae 1994). Highest values were found over smoldering surface fuels. This relation can be explained by the lower combustion efficiency of smoldering compared to the prevailing flaming combustion of grass type fuels.

Estimates of global pyrogenic emissions of CH_3Br from vegetation fires and other plant-biomass burning is in the range of 10 to 50 Gg yr^{-1}, or 10 to 50% of the total source strength (Manö and Andreae 1994). Accurately determining the contribution by boreal fires to the atmospheric budget of CH_3Br requires further analysis of boreal fire emissions.

Aerosols Along with the investigation of lake-sediment coring discussed earlier, a study of dispersion of particles emitted from the Bor Island fire was undertaken. Twenty-one 400-cm^2 traps were arrayed along three transects radiating away from the burn into the surrounding fen, to estimate the production and transport of "large" (10° micron) particles. Traps were located at 5- to 10-m intervals, beginning slightly within the burn edge and extending to >60 m from the burn. Traps were placed on the fen surface prior to ignition, filled with deionized water, and collected next day when smoldering emissions had ceased. Total particle fluxes and particle size distributions were determined by microscopy and image analysis (Clark and Hussey 1996).

The emission factor based on particle flux at the ground surface within the burn (72.9 g m^2) and average fuel consumption (3.712 kg m^{-2}) is 0.212 kg kg^{-1}, substantially higher than is typical for aerosols within a buoyant plume. This high value can be attributed to its being obtained for large particles trapped at the ground surface. Settling is an important removal mechanism for these large particles, and so they are rapidly depleted within a plume and generally not considered in aerosol measurements. The ground-level traps collected particles just slightly above the ground surface.

Particle deposition declines sharply within 5 m of the burn edge (figure 81.17*a*). Although scatter appears in the data, there is no trend over the interval from 10 to 70 m, indicating that depletion of particles is minimal. It is clear from figure 81.17*a* that traps are required at greater distances from the burn to adequately characterize the pattern of deposition. The high intensity level and well-developed convection column in the Bor Island fire probably lofted particles high enough that the gradient in particle deposition spans a much larger distance than was sampled here.

The interpretation that deposition is rather uniform within 100 m of the burn is supported by particle size distributions (figure 81.17*b*). The largest ($>10^1$ mm) particles are restricted to traps from within the burn. Maximum particle size was lowest ($10^{0.8}$ mm) for the most distant (> 20 m) traps. This relationship between maximum particle size and distance is consistent with removal of the largest particles by settling. But the distributions are nonetheless highly similar over most

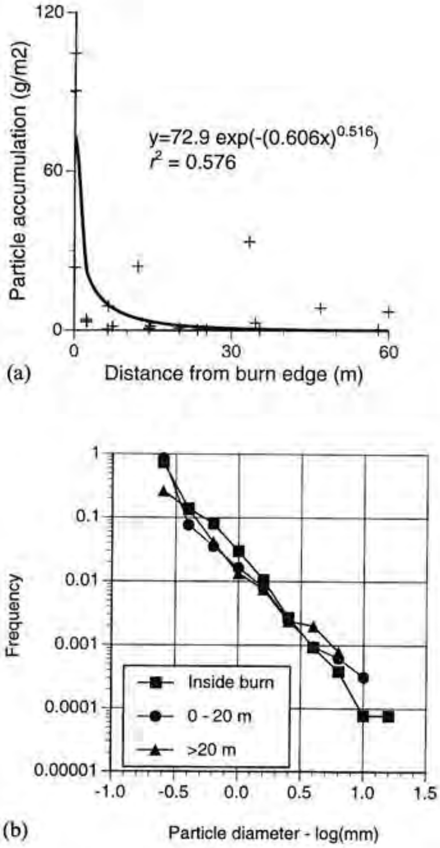


Figure 81.17 (*a*) Particle accumulation in traps/distance from edge of Bor Forest Island fire. (*b*) Particle size distributions for all Bor Forest Island traps.

of the particle size range (figure 81.17*b*). If settling was an important influence on deposition, we would expect to see the slope steepen with distance as large particles are preferentially depleted. We expect that traps at greater distances from the burn would have diameter distributions with much steeper slopes than those close to the burn.

Summary

The major objective in the Bor Forest Island Fire Experiment was to conduct a high-intensity, stand-replacement fire that would permit documentation of fire behavior and effects in a manner that would allow comparison of eastern and western fire-research methodologies. A narrow burning window and low wind speeds on the day of the burn meant that the required high-intensity fire could not be achieved without a convection style, perimeter ignition. However, this requirement was accomplished, and fire behavior was

Figure 81.18 Aerial view of a coniferous forest affected by a high-intensity fire in Yakutsk Region, August 1991

well documented, establishing a base upon which further fire-effects studies will be developed. In addition, this experimental fire effectively simulated many critical aspects of boreal wildfires, including variation in fire intensity and effects across the landscape. For comparison, figure 81.18 shows a 1991 Siberian wildfire near Yakutsk, which exhibits patterns in fire intensity similar to those in the Bor Forest Island fire.

This experiment also demonstrated that it is possible to accommodate a number of experimental approaches in one experimental fire, including combining fire-research methodologies from Russia and Western countries. Integrated research was successfully carried out on climatology, meteorology, fire behavior, fire emissions/atmospheric chemistry, fire history, and the fire ecology of the natural landscape and vegetation in this region of Siberia.

Additional new research is underway at present through contributions of the University of Bayreuth, Plant Ecology, in cooperation with the Severtsov Institute of Ecology and Evolution of the Russian Academy of Sciences. The program aims to investigate the carbon and nitrogen budget of *Pinus sylvestris* succession after fire. The experiment site is located about 20 km west of Bor Island. The fire experiment was used as reference for recent and dated burning events.

In various post-fire stand ages (3, 6, 30, 50, 80, 135, 200, 380 yr after fire) the following parameters are measured, (1) stand biomass and nitrogen distribution, (2) humus accumulation, (3) tree growth (tree ring analysis), (4) stand structure (number, diameter, height), and (5) xylem flux of water in sample trees. At Bor Island an automatic weather station installed in

August 1995 is logging the following parameters (Data logging: every 5 minutes, storage every 2 hours, start 10 August 1995 at 18:00. The capacity of the DL-2 logger will allow data storage until March 1997):

- Xylem sap flux in three healthy trees growing on the Appendix.
- Temperatures at +100, lichen surface, −10, −100, −250, −500 mm from surface in the unburned area of the Appendix.
- Temperatures at +100, litter, −100, −250, −500 mm from surface in the burned area.
- Relative humidity, temperature, and photon flux density 15 m above surface.

The Bor Forest Island site is an ideal location for long-term investigations on fire ecology. The site is well protected from human influences, being isolated from population centers and protected by surrounding bogs and marshland. However, many more long-term sites are required, covering a broad range of fuel types and ecosystems burned under varied conditions, to fully understand boreal fire regimes. This aim is particularly important at a time when global warming is expected to dramatically accelerate the role of fire as the major disturbance regime in boreal forests, with resultant impacts on the global carbon budget.

Acknowledgments

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