



Prescribed Burning in Russia and Neighbouring Temperate-Boreal Eurasia

A Publication of the Global Fire Monitoring Center (GFMC)
Edited by Johann Georg Goldammer

Contributing Authors: E. N. Valendik, J. G. Goldammer, Ye. K. Kisilyakhov,
G. A. Ivanova, S. V. Verkhovets, A. V. Bryukhanov, I. V. Kosov, Oyunsanaa
Byambasuren and the FIRESCAN Science Team

Prescribed Burning in Russia and Neighbouring Temperate-Boreal Eurasia
A Publication of the Global Fire Monitoring Center (GFMC)

Prescribed Burning in Russia and Neighbouring Temperate-Boreal Eurasia



A Publication of the Global Fire Monitoring Center (GFMC)

Edited by
Johann Georg Goldammer

Contributing Authors:

E. N. Valendik, J. G. Goldammer, Ye. K. Kisilyakhov, G. A. Ivanova,
S. V. Verkhovets, A. V. Bryukhanov, I. V. Kosov, Oyunsanaa Byambasuren, and the
FIRESKAN Science Team

www.forestrybooks.com

Supported by:



Federal Ministry of
Food, Agriculture
and Consumer Protection

based on a decision of the Parliament
of the Federal Republic of Germany

© 2013 Kessel Publishing House
Eifelweg 37
53424 Remagen-Oberwinter
Germany

Tel.: 0049 - 2228 - 493
Fax: 0049 - 3212 - 1024877
email: webmaster@forstbuch.de

Internet:
www.forestrybooks.com
www.forstbuch.de

Printed in Germany
www.business-copy.com

Preface

In the landscapes of temperate-boreal Europe – the western part of the Euro-Siberian region of the Holarctic Floral Kingdom – the prevailing fire regimes are shaped by human-ignited fires. Direct fire application in land-use systems – agricultural burning and burning of pastures – and human-caused wildfires, ignited accidentally, by negligence or otherwise deliberately set, have influenced cultural and natural landscapes since the beginning of land cultivation.

However, in the Central Euro-Siberian region there are large tracts of forest ecosystems that have been shaped by natural fire, e.g. the forests dominated by pine (*Pinus* spp.) and larch (*Larix* spp.) that constitute the “light taiga” in Siberia and adjacent regions.

Starting with the first East-West international conference “Fire in Ecosystems of Boreal Eurasia” and the Fire Research Campaign Asia-North (FIRESCAN) and its “Bor Forest Island Fire Experiment”, organized in Krasnoyarsk, Russian Federation, in 1993, the dialogue between scientists and forestry authorities from Europe, North America and the Russian Federation revealed the rich knowledge of the fire ecology of temperate-boreal Eurasia (Goldammer and Furyaev 1996)¹. The results of the following two decades of joint scientific research, mirrored by numerous publications by the international wildland fire science community, encouraged forest authorities to participate in the dialogue, devise new concepts in fire management and replace fire exclusion policies by integrated fire management approaches, which would include the use of natural fire and prescribed burning (prescribed management fires).

In Part I of this volume fire scientists of the Sukachev Institute for Forest, Russian Academy of Sciences, Siberian Branch, Krasnoyarsk, and the Fire Ecology Research Group at the Global Fire Monitoring Center (GFMC), Freiburg University / United Nations University, Germany, have now summarized experience and provide targeted advice in the application of prescribed fire in advanced fire management.

Part II constitutes a summary of results of the first 19 years of the “Bor Forest Island Fire Experiment” of 1993, a long-term, 200-years experiment designed for the period 1993 to 2192. The participating scientists are large in number, and more will join in future when this project will be handed over to the next generation of fire scientists.

1 Goldammer, J.G., and V.V. Furyaev (eds.). 1996. Fire in ecosystems of boreal Eurasia. Kluwer Academic Publishers, Dordrecht, 528 pp.

Part III summarizes the knowledge of the history and ecology of forest and steppe fires in Mongolia, as well as the first experiences of prescribed burning research and practices in pine forest ecosystems initiated in 2008.

The results of the work published in the first three parts of this volume had considerable impact on the objectives and formulation of the “White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia”, which was developed by scientists who work together within the Eurasian Fire in Nature Conservation Network (EFNCN), and released in 2010. The White Paper provides rationale and recommendations for the future use of prescribed fire and is published as Part IV of this volume.

Finally, steps are required to convincing forestry and land-use policy makers to consider the scientific evidence and the first achievements in application of prescribed natural and management fires, and to inform the public accordingly. The First International Fire Management Week”, held in Krasnoyarsk, Russia, in September 2012, came up with a number recommendations that point into the direction for integrating the recommendations of the fire science community in policy and practice, including capacity building.

These efforts of advancing fire science and policies have received substantial financial and institutional support by the Max Planck Institute for Chemistry, Germany, the Sukachev Institute for Forest, Krasnoyarsk, the Federal Forest Agency of Russia *Rosleskhoz*, the Aerial Forest Fire Center of Russia *Avialesookhrana*, the German Agency for International Cooperation *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) and the Federal Ministry for Food, Agriculture and Consumer Protection of the Federal Republic of Germany in the frame of the work of the bilateral Russian-German Cooperation in Sustainable Forest Management. Furthermore the contribution of members of the UNECE Team of Specialists of Forest Fire is acknowledged. The continuing scientific and technical support of Yegor K. Kisilyakhov, Sukachev Institute for Forest, in a number of wildland fire expeditions and field experiments in the Russian Federation and Mongolia, including the preparation of this book volume, has been crucial for the success of international cooperation in wildland fire research.

Most important for the success of the research and the policy dialogue was the contribution of Eduard Pavlovich Davidenko, former Chief of the Science and Technology Department of *Avialesookhrana*. At the stage of finalizing the edition of this book he passed away on 2 April 2013. In recognition of his professional and personal contribution to build a culture of cooperation between fire scientists and fire managers from Russia and other countries this book volume is dedicated to his memory.

Freiburg, Krasnoyarsk, Ulaanbaatar

6 May 2013

Contents

Preface	5
----------------------	----------

Part I: Prescribed Burning in Russia 13

E.N. Valendik, J.G. Goldammer, Ye.K. Kisilyakhov,
G.A. Ivanova, S.V. Verkhovets, A.V. Bryukhanov, I.V. Kosov

Introduction	15
---------------------------	-----------

1. Prescribed Burning Background in Russia: A Historical Overview.....	16
---	-----------

2. Fire Regimes of Siberian Forest Regions Covered by Prescribed Burning	19
---	-----------

2.1. Research Methods	20
-----------------------------	----

2.2. Forest Fire Activity in Central Siberia	21
--	----

2.3. Past Fire Chronology Reconstruction for Scots Pine Stands of the Southern Taiga Subzone	22
---	----

2.4. Reconstruction of Past Fire Periodicity in Forest-Steppe Scots Pine Stands	23
--	----

2.5. Reconstruction of Fire Chronologies in Mountain Scots Pine Stands .	24
--	----

3. Prescribed Burning of Logging Sites in Plain and Low-Mountain Dark Coniferous Forests.....	28
--	-----------

3.1. The Region of Interest	28
-----------------------------------	----

3.2. Vegetation	29
-----------------------	----

3.3. Logging Site Characteristics.....	31
--	----

3.4. Logging Site Fire Hazard	33
-------------------------------------	----

3.5. Logging Site Prescribed Burning Technologies.....	38
--	----

4. Prescribed Burning of Mountain Dark Conifer Logging Sites.....	54
--	-----------

4.1. Study Area.....	54
----------------------	----

4.1.1. Topography, Climate and Soils.....	55
---	----

4.1.2. Vegetation.....	56
------------------------	----

4.1.3. Fire Activity	56
----------------------------	----

4.2. Dark Conifer Logging Site Types in Eastern Sayan Mountains	61
---	----

4.3. Forest and Logging Site Descriptions	64
---	----

4.4. Burning Methods	66
----------------------------	----

4.5.	Fire Spread	68
4.6.	Prescribed Burned Logging Site Characteristics	71
5.	Prescribed Burning of Scots Pine Forest Logging Sites in the Lower Angara Region	75
5.1.	Environmental Characteristics of the Lower Angara Region	75
5.2.	Logging Sites	78
5.3.	Scots Pine Logging Site Prescribed Burning Methodologies.....	81
5.4.	Prescribed Fire Spread and Effects	81
6.	Prescribed Burning of Dark Conifer Forest Areas Defoliated by Siberian Moth.....	86
6.1.	Siberian Moth Site Fire Hazard	87
6.2.	Study Area.....	88
6.3.	Fuel Loading in Siberian Moth Stands	89
6.4.	Preburning Activities	92
6.5.	Prescribed Burning Methodology	93
6.6.	Fuel Loads Following Prescribed Burning.....	93
7.	Prescribed Burning in the Forest-Steppe Zone.....	99
7.1.	Prescribed Burning of Scots Pine Stands in the Wildland/Settlement Interface	99
7.1.1.	Krasnoyarsk Forest-Steppe	101
7.1.2.	Forest Fire Frequency	102
7.1.3.	Forest Fire Danger in the Forest-Steppe Zone	104
7.1.4.	Prescribed Burning Impacts on the Forest-Steppe Scots Pine Stands	105
7.2.	Prescribed Forest Burning in the Forest-Steppe Zone of the Trans-Baikal Region	108
7.2.1.	The Regional Characteristics	109
7.2.2.	Steppe Areas.....	113
7.2.3.	Prescribed Burning Technologies.....	113
7.2.4.	Optimal Prescribed Burning Weather.....	115
8.	Prescribed Fire Effects	117
8.1.	Prescribed Fire Influence on Soil	117
8.2.	Living Ground Vegetation Recovery	126
8.3.	Forest Regeneration on Logging Sites	130
Conclusions		137
References		139

Part II: The Bor Forest Island Fire Experiment ... 149

FIRESCAN Science Team

1. Fire in Ecosystems of Boreal Eurasia.....	153
1.1. Disturbances in Transition: Natural to Anthropogenic	153
1.2. Concerns: Global Change and Fire.....	155
1.3. Objectives of Cooperative Fire Research in Boreal Eurasia.....	155
2. Fire History, Ecology, and Short-term Fire Effects	159
2.1. Fire Ecology of <i>Pinus sylvestris</i> Forests of the Sym Plain	159
2.2. Physical Characteristics of Bor Forest Island Study Site	164
2.3. Fire History	164
3. Vegetation and Fuels.....	167
3.1. Pre-fire Vegetation	167
3.2. First-year Vegetation Recovery and Stand Conditions.....	169
3.3. Fuel Loading and Surface Fuel Consumption.....	172
3.4. Tree Mortality	174
4. Fuel Assessment, Fire Weather and Fire Behavior	180
4.1. Pre-burn Fuel Sampling.....	180
4.2. Fire Weather.....	181
4.3. Fuel Moisture.....	183
4.4. Fire Behavior	183
5. Atmospheric Emissions	191
5.1. Radiatively Active Trace Gases	191
5.2. Compounds Affecting Stratospheric Ozone.....	192
5.3. Aerosols.....	194
6. Summary	196
References.....	198
Annex I	203
Annex II.....	226
Annex III	228

Part III: Forest and Steppe Fires in Mongolia 233

Oyunsanaa Byambasuren and Johann Georg Goldammer

1. Introduction	235
2. Physical and geographical characteristics of Mongolia impacting the fire risk	237
2.1. Climate and climate change	238
2.2. Forest and other vegetation resources.....	239
2.3. Socio-economic development and forest utilization	241
3. Fire situation in Mongolia.....	244
3.1. Fire occurrence	246
3.2. Fire causes	247
3.3. Fire environment, fire regimes and the ecological role of fire.....	248
3.4. Fire history of different type of forest stands in West Khentii Mountains, Mongolia.....	248
3.5. Fire influence on vegetation cover.....	257
4. Demonstration Experiment Using Prescribed Fire for Wildfire Hazard Reduction.....	261
4.1. The Experimental Site	261
4.2. Objectives of the Demonstration Experiment Using Controlled Fire for Wildfire Hazard Reduction	264
4.3. Procedures of the Demonstration Experiment Using Prescribed Fire in Tunkhel Soum	265
Annex I: Photographic documentation and satellite images of the experimental site	267
References.....	274

Part IV: White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia 279

Johann G. Goldammer (ed.)

White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia	281
1. Natural Fire Regimes	282
2. Cultural Fire Regimes	284
2.1 Restoration of traditional practices of swidden agriculture.....	284
2.2 Maintenance of grazing lands	287
2.3 Nature conservation and biodiversity management.....	288
3. Substitutional Fire Use	293
3.1 Fallow management on small-scale and extreme habitats	293
3.2 Landscape management.....	295
4. Waste Disposal	298
5. Wildfire Hazard Reduction Burning.....	299
6. Limitations for Prescribed Burning: Contaminated Terrains	303
7. Conclusions and Recommendations.....	305
8. References.....	309

Part V: The Krasnoyarsk 10-Point Programme on the Future of Fire Management in Russia 315

Part I: Prescribed Burning in Russia

E.N. Valendik, J.G. Goldammer, Ye.K. Kisilyakhov,
G.A. Ivanova, S.V. Verkhovets, A.V. Bryukhanov, I.V. Kosov

Introduction

The term “prescribed burning” refers to the use of fire in natural environments for different objectives, such as forest and logging site fire hazard reduction, forest regeneration enhancement and elimination of undesired vegetation species and forest pests. Prescribed fires are conducted under environmental conditions that allow to meet fire intensity and rate of spread. As prescribed burning has not been permitted in Russia until recently, there are very little prescribed fire data in the Russian scientific literature. The USA, Canada, and Australia, where prescribed burning has been a common practice since as far back as the early 20th century, provide most scientific insight and experience in prescribed burning. There is an increasing use of prescribed fire in Western Eurasia, notably in nature conservation and management of cultural landscapes (GFMC 2010).

At present, opponents of use of fire in the forest still outnumber its supporters in Russia due to a long-term prescribed forest fire ban and perception of fire as a “disaster” by common people. However, “controlled fire” was recognized as an effective forest management tool by well-known Russian forestry specialists Tkachenko (1931) and Melekhov (1983). A number of foresters share their opinion nowadays. Studying negative and positive fire influences on forest ecosystem components and developing guidelines for the use of prescribed forest fire are the two major fire science priorities (Artsybashev 1984).

Prescribed fire was first used in Russia in 1952 through 1957, in western Siberian dark conifer forests killed by Siberian moth, in an effort to enhance forest regeneration.

Today, prescribed fire is permitted to be used for burning piled logging slash and creating fuel breaks by burning cured grass in treeless sites of the Russian forest fund in non-fire-season time (Anonymous 2007).

The V.N. Sukachev Institute of Forest, in cooperation with the Federal Forestry Committee of Krasnoyarsk Region, tested controlled broadcast burning of logging sites and forest sites damaged by insects or situated close to settlements to reduce fire hazard and stimulate forest regeneration. These fires were conducted in several forest districts as a part of a joint Russian-American project on forest management improvement in Siberia. These experimental prescribed burnings have grown to become a practical forest treatment since 1999. Mobile prescribed fire crews established in five Forest Management Areas (FMA) of Krasnoyarsk Region began to conduct prescribed burning.

The authors of this book tried to analyze the experience gained in prescribed burning so far and they are sure forest research scientists and forestry practitioners will find it useful.

1. Prescribed Burning Background in Russia: A Historical Overview

Cured grass burning was practiced for increasing grazing land productivity in forest-steppe and steppe landscapes of southern Urals, Kazakhstan, Trans-Baikal region, Yakutia, Khakassia, and Tuva as early as in the 5th and 6th Century. Cattle breeders noted that spring burning of cured grass resulted in proliferation of new grass, extended its growing season, and, hence, improved grazing conditions. As uncontrolled grass burning grew in scale and increasingly resulted in forest fires, this practice countrywide became a big problem in the 17th century. To cope with this situation, legal fines were imposed for arsons in the forest and the so-called “agricultural fires”. In the 18th century, Peter the Great promulgated a law that prohibited cured grass burning near forest and in forest glades. People conducting grass burns in areas adjacent to forests and disregarding fire safety rules were fined by penalties (Gaikovsky 1885; Shilov 1889).

Although the agricultural fire ban was extended to cover the entire snow-free period in the early 20th century (Nazarov and Sabinin 1913), agricultural burning still is practiced large scale.

Forest fires drastically grew in extent in Siberia and the Russian Far East in the early 18th century, as peasants from the European Russia began to move to these parts of the country, where they were given free non-forest and forest plots. Peasants burned forest to clear land for building settlements, sowing crops, and grazing cattle. Residents of settlements situated in taiga forest conducted burns in Scots pine (*Pinus sylvestris* L.) stands to increase productivity of red whortleberry (*Vaccinium vitis-idaea* L.) sites and in deciduous stands to improve conditions for bee keeping. Importantly, burning was done under control of peasant communities. This was actually when prescribed fire was started to be used for agricultural purposes.

In Russia, use of prescribed fire has always raised contradictory attitudes, from its full support to absolute aversion. Positive forest fire influence, namely, fire-caused increase in Scots pine stand regeneration rate, was noted as long ago as the beginning of the last century (Tkachenko 1911; Turin 1925). Therefore, it was concluded that fire could be used as a forest management tool (Tkachenko 1931) and first steps were taken in using fire as a tool to enhance forest regeneration (Kazansky 1931).

Clearing logging site from slash by fire was first approached scientifically in Karelia, European Russia, with burning methodologies and effective use manpower being the two

priorities. As a result, logging slash was burned on logging sites accounting 8% of the total Karelia's logging area. Prescribed fire tests showed that logging site clearance methods, such as post-logging burning of piled logging slash, piling logging slash and leaving the piles stay without burning, and burning of logging slash in the course of forest harvesting, failed to meet forest management requirements. Broadcast burning of logging slash and its burning on plots where logging slash occurs were introduced later. With broadcast burning, logging sites and remaining in-site seed tree pockets were recommended to be surrounded by 30-meter wide fire lines prior to burning. With the later method, firelines were established around logging sites and the plots were earthed up (Davydov 1934).

Pobedinsky (1955) reported that mineral soil can account for up to 40% of the total logging site area as a result of logging slash burning as compared to 5-10% resulting from logging itself. Mineral soil surface stimulates both natural forest regeneration and planted woody species growth. Logging slash burning should be conducted in summer, on calm days, at high slash moisture content on clearcuts having no healthy regrowth.

Belov (1973) proposed controlled burning in mature Scots pine and larch stands, as well as in those approaching maturity (5-10 years before logging) in order to ensure pre-logging forest regeneration. Also, he believed that burning of deep forest floor organic layer and feather moss layer can result in decreasing forest fire hazard for as long as 20-30 years, which decrease is beneficial for future forest generations. Burning of natural vegetation on permafrost increases soil thaw depth. Fires of moderate intensity were found to favor Scots pine stand development, provided that the mean fire interval (MFI) is 40-50 years (Belov 1973).

Melekhov (1983) considered prescribed fire as an important tool to achieve forestry objectives. He recommended to conduct fire-hazard-reduction controlled fires in Scots pine and larch stands aging 40-50 and older, when trees become fire resistant.

In Siberia, particularly in Krasnoyarsk Region, controlled fire was used by Prozorov (1956) to eliminate pine looper (*Bupalus piniaria* L.) pupae from the forest floor and reduce thereby the population of this forest pest. In this effort, litter and forest floor organic matter were broadcast burned or piled and then burned.

About four million hectares of dark conifer forests were damaged by Siberian moth (*Dendrolimus superans sibiricus* Tschetw.) in western Siberia in 1952-1957; thereof 40,000 hectares were completely killed forest (Furyaev 1966). This area was annually subjected to large forest fires that disturbed economical activities. Not one of all the costly efforts made to suppress these fires ever succeeded. Furyaev proposed to treat the Siberian moth-damaged conifer forest area with controlled fire in attempt to enhance forest regeneration. The USSR Ministry of Forestry approved the recommendation of Sukachev Institute of Forest not to suppress but contain wildfires in this area in order to prevent their spread into adjacent forest stands for 20 years. These activities led to forest regeneration resumption through woody species conversion only 18 year following the Siberian moth outbreak. This damaged area was colonized by deciduous species, such as birch and aspen, with fir, spruce, and Siberian pine seedlings occurring under their canopy.

Prohibition of prescribed burning on logging sites had negative consequences for forest protection and hampered forest regeneration drastically. As a result, thousands of hectares of treeless logging sites have high loads of logging slash and are covered by tall grasses. Windfall and infestation by Siberian moth and over-stocked light coniferous stands are commonly found. Fires occurring on these types of sites are particularly destructive, and post-fire forest regeneration is hampered for decades due to extreme severities.

Up to 70% of all wildfires begin on logging sites from where they are spreading to adjacent forests. In this situation, any forest restoration efforts are often jeopardized. Logging sites remain highly flammable during 3-4 months due to fuel overloading. Even prolific new green grass and shrubs fail to reduce high fire hazard on logging sites (Valendik et al. 2000).

Experience gained by other countries show that prescribed burning can be effective in reforesting logging sites and reducing their fire hazard levels. Fire burns logging slash and, hence, adds nutrients to soil that are available for plant growth. As a result, woody seedling vigor and competitive ability increases. Additionally, logging slash burning reduces the risk of invasion of xylophagous insects to neighboring stands.

It should be noted that wildfire suppression is very expensive, whereas controlled vegetation residue burning is nowadays the only effective and economical method to clear logging sites, stimulate forest regeneration, and prevent high-intensity fires.

The V.N. Sukachev Institute of Forest has conducted test underburning and prescribed fires on logging sites (Valendik et al. 1997; Valendik 1998; Valendik et al. 2000, 2001) and sites defoliated by Siberian moth (Valendik et al. 2006, 2007) in cooperation with Krasnoyarsk Regional Forest Committee since 1996.

These prescribed burning tests should be replicated in a range of natural environments to gain experience sufficient for developing prescribed fire use legislation.

2. Fire Regimes of Siberian Forest Regions Covered by Prescribed Burning

The current boreal forests of Eurasia have been shaped, among other factors, by fire (Goldammer and Furyaev 1996). At present, every Siberian forest stand has signs of at least one wildfire (Buzykin 1975). Since Siberia is a vast area containing several vegetation zones, it encompasses a wide diversity of climatic conditions and forest growing environments. Therefore, forest fires occur annually in different parts of this region. The general atmospheric circulation characteristic of this region, its great extension, remoteness from oceans, and complex orography are the main factors controlling Siberian climate. This is extremely continental climate, with continentality increasing west-eastward (Shumilova 1962).

Two types of fire regimes can be identified in Siberia (Valendik and Ivanova 2001). A fire regime characterized by a long MFI is common in western Siberian boggy dark conifer forests, and a short-MFI fire regime is dominating in low-mountain light conifer forests of eastern Siberia.

Severe droughts initiate exceptional fire seasons, when numerous fires occur simultaneously and produce large fires (Valendik 1990; Valendik and Ivanova 1996; Ivanova 1996; Furyaev 1996). As a result, extended wildfires occur. Fire seasons characterized by numerous forest fires have become frequent in certain parts of Siberia (the 2003 fire season in Irkutsk and Trans-Baikal regions, the 2006 fire season in Yakutia and Krasnoyarsk region). Extreme, largely climatically-driven fire situations are usually uncontrollable. These situations cover big areas, cause great economic losses, and threaten people's lives and property.

A fire regime is characterized by fire frequency, size, seasonality, and intensity (Crutzen and Goldammer 1993). Fire frequency expressed by fire interval is the number of fires that occurred in a given forest stand or area within a given period of time. The MFI has both direct and indirect influence on plant species life cycle, vegetation structure and species composition, and forest fuel accumulation rate.

Information on past fire regimes can be obtained from dendrochronological analysis. Fire scars, i.e. signs of surface fires visible in the lower parts of tree stems, provide past fire data. Past fire chronologies can be obtained by cross-dating series of fire scars (Melekhov 1947; Molchanov 1976; Madany et al. 1982). Fire scars are indisputably useful because they

allow us to reconstruct fire chronologies as far back as 300-500 years (Swetnam 1993) and date them to year and even to season.

Expected climate change is presumed to result in changing forest fire frequency (Kasischke et al. 1995; Goldammer and Price 1998). Fires are predicted to increase in frequency and extent and, hence, in their impact on vegetation in boreal forest ecosystems (Weber and Flannigan 1997). However, regional- and local-scale prediction of future fire regimes is problematic, as they will depend on probable changes of fire suppression methods and ignition sources, such as increasing lightning activity (Flannigan and Wotton 1990).

Human activities have marked impacts on fire regimes. Fire statistics for several recent years shows that human-caused fires account for over 85% of all forest fires in Russia. Although efforts are made to control fires, no noticeable reduction of Russia's annual area burned has been achieved (Korovin 1996). While there is much evidence that increasing fire frequency is a result of human activities, this frequency trend can also be attributed to changing weather conditions and forest fire management strategies. Burned area is dependent on changes of mean fire interval (MFI), which changes have a profound effect on boreal forest fuel accumulation (Kasischke et al. 1995). This dependence allows to conclude that fire regimes are greatly influenced by both human and climatic factors and that knowledge of fire regimes is critical for estimating ecosystem ecological state and predicting fire occurrence.

2.1. Research Methods

Central Siberian forest fire activity was evaluated using fire records and area burned data provided by the Aerial Forest Protection Service *Avialesookhrana*. Spatial and temporal patterns of fire seasons were analyzed in terms of indicators of the regional forest fire activity and extreme fire situation development. To do this analysis, the data on large forest fires from 1947 through 2003 were used. Dendrochronological analysis helped to reveal fire periodicity and MFIs for Siberian larch and Scots pine, the two major woody species of central Siberia that have distinct tree rings and well-pronounced early and latewood. Also, these species enjoy long life cycles, although larch trees older than 150 years often suffer from butt rot.

Full tree cross sections were taken to date past fires using a conventional methodology (Madany et al. 1982) that enables fire dating by cross dating of the dendrochronological data obtained. Fire dates identified on the collected tree slabs were united to build past fire composites (Madany et al. 1982; Baisan and Swetnam 1990; Caprio and Swetnam 1993), which allowed us to obtain highly accurate fire dates for the forest sites of interest. The fire chronologies obtained were used to determine characteristics of the regional temporal fire activity variability, such as MFI, MFI standard deviation, and fire periodicity. MFI was calculated as a ratio between the length of the composite chronology obtained and the number of fires recorded over the period of time covered by the chronology.

2.2. Forest Fire Activity in Central Siberia

Forest fires occur annually in Siberia. Three types of fire seasons are characteristic of central Siberian forests: (1) a short and continuous fire season with very high fire activity during 1-3 months common in northern and central taiga forests; (2) a long fire season with fires periodically occurring during 4 to 6 months in the southern taiga; and (3) a fire season with two fire activity peaks, a spring and fall, prevailing in southern mountain regions (Valendik 1990).

Our analysis of the forest fire distribution by vegetation zone between 1986 and 2000 showed that the biggest number of fires and area burned occurred in southern taiga (Figure 1), where most Scots pine stands and logging sites rapidly becoming highly flammable are found.

Number of fires reaches its maximum in June-July and July in the northern and central taiga subzones, respectively, whereas two fire activity peaks (in May and July) are observed for southern taiga. In the subtaiga and forest-steppe zones, the biggest number of fires occurs in May, after snowmelt, in forest stands with grass-dominated ground vegetation. However, fires can occur in these zones throughout the growing season in dry years.

Periodical extreme fire seasons are common in Siberia. Their onset is usually indicated by large forest fires occurrence following long droughts. In this case, vegetation characteristics become unimportant, because forest fire can spread over any forest site type under drought.

A 10-day rainless spell is the critical period of time in spring. Large forest fires can occur across Siberia's entire forest area. These fires occur in different parts of Siberia after 30 days of drought and 66 to 100% of all fires occur following 40-50 dry days. Large fires are few in fall (Valendik 1990).

Forest fire periodicity refers to their temporal distribution within a given area depending on periodical climatic changes, such as alternation of dry and wet periods of time. Time needed for forest fuel to build up to a critical level and its occurrence across a given area also control fire temporal pattern (Kurbatsky 1964).

Past fire dating provides a possibility to determine natural fire regimes in certain forest stands or landscapes. Comparison of fire occurrence data with tree-ring chronologies obtained for Scots pine stands of central Siberia revealed that responses of fire regimes to climate has changed since 1880. Fire occurrence closely correlated with dry years before, whereas human activity became an important fire regime control after 1880 due to building of the Trans-Siberian main line followed by active settlement of the area (Swetnam 1996). Increasing human influences have resulted in decreasing fire interval in southern taiga Scots pine stands (Vaganov et al. 1996).

We reconstructed past fires for southern taiga and forest-steppe Scots pine stands found where prescribed burns were conducted. Slabs of trees with fires scars taken on forest sites in Lower Angara region, Krasnoyarsk forest-steppe zone, and eastern Sayan Mountains (the sample site locations are shown in Table 1) allowed us to reconstruct fire chronologies as far as over 400 years back.

2.3. Past Fire Chronology Reconstruction for Scots Pine Stands of the Southern Taiga Subzone

Current forest age structure is largely a result of fire in Angara region (Buzykin 1975). While even-aged light coniferous stands usually occur after catastrophic (crown) fires, surface fires account for uneven-aged forest stand establishment.

To study forest fire periodicity in Lower Angara Scots pine stands, southern taiga, Scots pine stands with feather moss- and grass-dominated ground vegetation were chosen, as these stands represent the two major forest types in this region. Fires were reconstructed for a Scots pine/feather moss/red whortleberry stand found on the right bank of Angara river for the past 420 years (Table 1, Site 1, Figure 2).

Several sample trees recorded 10 to 12 fires. The past fires reconstructed for this site totaled twenty. MFI was calculated to be 21.1 years. Seven fires were recorded by 30% of all trees on the site, with an MFI of 39.4 years, and five fires scarred 50% of trees (MFI was 55 years) between 1672 and 1951. Most of sample trees recorded the 1774, 1798, 1832, and 1948 fires, indicating thereby that fires occur here every 58 years on average. It can thus be concluded that the landscape MFI was 39 years on Site 1 during the above period of time.

Twenty three past fires were found in a Scots pine/feather moss/small shrub stand (Sites 2 and 2a) situated on the right Angara bank for the period between 1537 and 1998. MFI appeared to be 20.0 years here. Scars of six fires were observed in 30% of all trees (an MFI of 31.8 years), and four fires left scars in 50% of all trees (once every 48 years on the average). The landscape-scale MFI was found to be about 32 years here over the past 300 years. Before Angara region began to be settled (i.e. before 1750), MFI was 71 years, whereas it decreased 3-4-fold after this area had been settled. Although forest fuel has accumulated to large amounts, MFI has shown a trend to increase over recent decades. This increase might be a result of timely fire detection and suppression.

Past fire reconstruction period and number of fires varied considerably among four sites (Sites 3-6) established in Scots pine stands with herbs in ground vegetation found at the southern taiga boundary with the forest-steppe zone, the left bank of Angara river. The biggest number of fires identified on these sites was 30 and MFI was calculated to range 12.3 to 20.7 years. As these Scots pine stands experience severe human impacts, they are subject to fire much more often as compared to southern taiga.

MFI decreases proceeding from north to south in the southern taiga subzone. MFI appeared to be 18.0-28.0 years near Boguchany village, the right bank of Angara river, whereas it was found to range 12.3 to 20.7 years near the village of Taseyevo, about 200 km south of Boguchany. These short MFIs are attributable to almost continuous forest cover and intensive human activities, which contribute to the amount on ignition agents. A study conducted in Angara region (Vaganov et al. 1996) revealed a human-caused decrease in fire intervals.

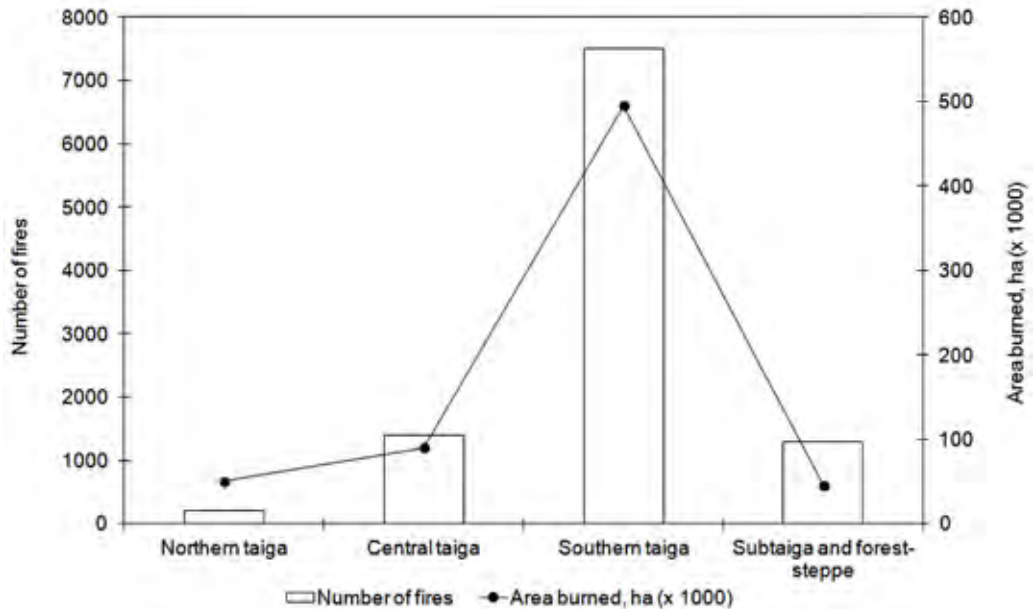


Figure 1. Distribution of fires and area burned by vegetation zone in central Siberia (1986-2000)

2.4. Reconstruction of Past Fire Periodicity in Forest-Steppe Scots Pine Stands

Forest fire periodicity was studied in Yukseyevo Scots pine stand located in the north of Krasnoyarsk forest-steppe. This stand includes several forest types, such as Scots pine/herb/red whortleberry, Scots pine/sedge/herb, and Scots pine/feather moss/herb types.

Full tree stem cross-sections containing fire scars were taken in two parts of the stand (Site 7). Several trees appeared to record up to 11 fires between 1845 and 1997, with the oldest fire scar in 1880. While a number of fires scarred all sample trees, other fires were recorded by only one of our sample trees. A possible explanation of the latter is that fire intensity varied due to variability of fuel loading and weather conditions and, as a result, fire damaged trees to different levels. Moreover, fire is known to be able to spread in a part or across a forest stand depending on living ground vegetation species distribution and moisture content. MFI was found to be 10.1 years for the stand of interest. The fires that left their signs on trees were recorded here before 1983. Although fires did occur here after 1983, they did not burn deep into the forest floor organic layer or were suppressed by forest protection service when small. For example, the last fire that occurred in 1995 was small in size and left no scars in trees.

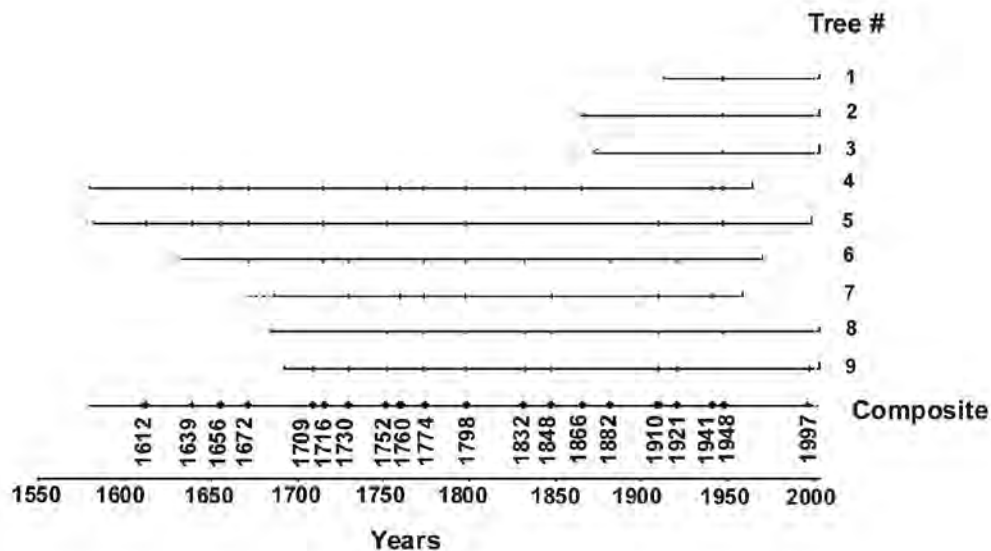


Figure 2. Forest fire chronology obtained for a Scots pine/feather moss/red whortleberry stand, Lower Angara region (Site 1 in Table 1)

A fire scar analysis done for a Scots pine/feather moss/herb/ stand adjacent to Masleyevo lake (Site 8), Kansk forest-steppe, revealed 23 fires from 1705 to 1994. MFI was calculated to be 12.1 years. Masleyevo lake has long been a recreation and, hence, a high-fire-risk area.

Fourteen fires were identified based on fire scar analysis for a Scots pine/feather moss/red whortleberry stand (Site 9) situated in Krasnoyarsk forest-steppe, 50 km south of Yukseyevo stand, over the period between 1880 and 1998. MFI was calculated to be 8.4 years here.

MFI ranges 8 to 12 years in forest-steppe Scots pine stands close to villages, fires occurring mainly in spring and early summer. Only 5% of all fires occur in mid- and late summer and fall. High fire frequency characteristic of these stands is attributed to both dry spells and strong human impacts.

2.5. Reconstruction of Fire Chronologies in Mountain Scots Pine Stands

We built a past fire chronology for two Scots pine stands found in Mana river basin, eastern Sayan Mountains. One is a Scots pine/sedge/spiraea (*P. sylvestris*, / *Carex* spp. / *Spiraea alba*) stand growing on a 20-degree southeast-facing slope (Site 10) and the other is a Scots pine

stand with herb-dominated ground vegetation located on a 30-degree south-facing slope (Site 11). Rock outcrops are common on both slopes. The sample sites are moist, as they receive much precipitation.

The Scots pine/herb stand site conditions are more xerophytic. Eleven fires (1782, 1800, 1819, 1834, 1851, 1871, 1884, 1902, 1921, 1931, and 1954) were identified for this stand using fire scars between 1748 and 1998. MFI appeared to be 22.7 years, which interval is typical under these conditions.

A fire scar analysis done for the moister Scots pine/sedge/spiraea stand allowed to identify fires in 1808, 1819, 1826, 1838, 1846, 1853, 1857, 1871, 1883, 1902, 1911, 1919, 1933, 1947, and 1982 for the period from 1782 to 1998, with MFI being 14.4 years. MFI has decreased here twice over the past two centuries due to the close proximity of this site to a settlement.

As is evident from fire scar examination, fires occur usually in late May-early June under these conditions. A particular feature of Scots pine stands growing on south-facing mountain slopes is that they rapidly become highly flammable and stay in this condition both under drought and throughout the entire fire season. Well-pronounced mountain relief and considerable ground fuel amounts favor high-intensity forest fire development. However, many fires spread as spot fires and scar very few trees. This is presumably due to the presence of rock outcrops that serve as fire barriers.

The sample stand structure was determined to have been influenced by fire. The Scots pine/herb stand consists of trees of several age groups, which resulted from fires that occurred here in different years. Trees of 180 years of age established after the 1819 fire make up the major tree age group in this stand. The oldest trees dying nowadays are 215 years old. The presence of old trees might be attributed to fire characteristics. High-intensity surface fires usually spread upslope and they become crown fires only where the forest canopy is vertically closed and woody regrowth is present, i.e. there exists a fuel ladder. Stone outcrops often prevent crown fire occurrence.

The MFI depends on conditions of forest growing and ranges between 15 and 24 years in eastern Sayan and southern taiga Scots pine stands. This period of time is sufficiently long for forest fuel accumulation to the critical level. In dark coniferous forests the MFI is 90-120 years. These MFI values have presumably been characteristic in mountain forests over the past five or six centuries.

MFI varies depending on latitude, topography, site conditions, and human influence in central Siberian Scots pine stands and decreases north-southward.

MFI is determined by fire season duration. For example, MFI is 47.2 years at the northern Scots pine range boundary, central taiga, where fire season lasts for 65 days. Further south, MFI decreases to 35 years, with fire season increasing to 100 days. It should be noted that MFI is shorter (20-40 years) on non-isolated sites, where fire can come from adjacent areas, as compared to isolated sites (up to 97 years) (Ivanova et al. 2007).

Fire season increases to 110 days and MFI ranges 18.0 to 28.0 years in Scots pine stands with ground vegetation dominated by feather moss or small shrubs found at the northern

boundary of the southern taiga subzone. Further south, fire season is 120 days long, human impact increases, and MFI decreases to 12.3-20.7 years.

Forest type also controls MFI. Fires occur most frequently in Scots pine/lichen stands found on sandy soil and loamy sand. Here, MFI is twice less than in Scots pine stands with ground vegetation dominated by herbs and red whortleberry or feather moss.

Fires occur annually in central Siberia. The fire regime of this region is characterized by frequent low-intensity surface fires, while high-intensity fires occur only in exceptional fire seasons. The data we obtained and other research scientists' data allow us to conclude the identified spatial fire dynamics, including MFI and fire season, has prevailed in this region over the past five centuries.

Table 1. Characteristics of the forest fire chronologies obtained for central Siberian Scots pine stands

Site #	Site location	Forest type	Study period, years	Fire years	MFI, years
The southern taiga subzone					
1	Angara river basin, Lower Angara region, 58°42' N, 98°25' E	Scots pine/feather moss/red whortleberry stand	1580-2003	1612, 1639, 1656, 1672, 1709, 1716, 1730, 1752, 1760, 1774, 1798, 1832, 1848, 1866, 1882, 1910, 1921, 1941, 1948, 1997	21.1
2	Irkineyevo river basin, Lower Angara region, 58°41' N, 98°18' E	Scots pine/feather moss/small shrub stand	1602-1999	1617, 1678, 1744, 1760, 1771, 1779, 1798, 1812, 1823, 1840, 1848, 1860, 1864, 1878, 1885, 1888, 1905, 1915, 1927, 1951, 1959, 1987	18.0
2a	Irkineyevo river basin, Lower Angara region, 58°41' N, 98°18' E.	Scots pine/feather moss/small shrub stand	1691-1999	1744, 1798, 1812, 1823, 1848, 1860, 1878, 1888, 1905, 1915, 1951	28.0
3	Bakchet river flood-plain, Lower Angara region, 57°05' N, 94°56' E	Scots pine/herb/sedge stand	1808-1994	1819, 1883, 1899, 1908, 1925, 1946, 1954, 1978, 1990	20.7

4	Bakchet river flood-plain, Lower Angara region, 57°01' N, 95°05' E	Scots pine/red whortleberry/herb stand	1713-1994	1750, 1788, 1798, 1818, 1838, 1842, 1854, 1864, 1875, 1882, 1893, 1901, 1909, 1916, 1925, 1967, 1974, 1981	15.6
5	Bakchet river flood-plain, Lower Angara region, 57°02' N, 95°10' E	Scots pine/tall grass/herb stand	1725-1994	1752, 1800, 1828, 1848, 1861, 1873, 1892, 1899, 1910, 1915, 1929, 1935, 1945, 1957, 1969, 1987	16.8
6	Bakchet river flood-plain, Lower Angara region, 57°04' N, 95°00' E	Scots pine/red whortleberry/herb stand	1624-1994	1635, 1645, 1651, 1662, 1692, 1700, 1716, 1725, 1729, 1745, 1778, 1797, 1802, 1809, 1818, 1840, 1847, 1859, 1867, 1874, 1884, 1893, 1901, 1909, 1915, 1918, 1926, 1938, 1951, 1959	12.3
The forest-steppe zone					
7	Yukseyevo Scots pine stand, Yenisei river terrace, Krasnoyarsk forest-steppe, 56°51' N, 93°25' E	Scots pine/sedge/herb stand	1845-1997	1880, 1896, 1899, 1903, 1911, 1916, 1921, 1926, 1929, 1935, 1944, 1946, 1953, 1961, 1983	10.1
8	Masleyevo lake, Kansk forest-steppe, 57°00' N, 95°13' E	Scots pine/feather moss/herb stand	1715-1994	1738, 1751, 1784, 1791, 1800, 1804, 1813, 1828, 1837, 1847, 1863, 1873, 1880, 1900, 1904, 1908, 1915, 1928, 1936, 1948, 1954, 1970, 1980	12.1
9	Pogorelsky Scots pine stand, Krasnoyarsk forest-steppe, 56°23' N, 93°00' E	Scots pine/feather moss/red whortleberry stand	1880-1998	1891, 1898, 1909, 1911, 1917, 1925, 1929, 1932, 1934, 1939, 1943, 1946, 1958, 1978	8.4
Mountain forests					
10	Talovka river valley, Sayan foothills, 55°20' N, 93°14' E	Scots pine/sedge/spiraea stand	1748-1998	1782, 1800, 1819, 1834, 1851, 1871, 1884, 1902, 1921, 1931, 1954	22.7
11	Zherzhul river valley, Sayan foothills, 55°21' N, 93°17' E	Scots pine/herb stand	1782-1998	1808, 1819, 1826, 1838, 1846, 1853, 1867, 1871, 1883, 1902, 1911, 1919, 1933, 1947, 1982	14.4

3. Prescribed Burning of Logging Sites in Plain and Low-Mountain Dark Coniferous Forests

3.1. The Region of Interest

Prescribed fires and their estimation regarding environmental effects were done in central Siberian southern taiga dark conifer forest stands found in plains and low mountains. Descriptions of this region were taken from the following literature sources: Volobuyev (1960), Galakhov (1964), Gerasimov (1964), Yerokhina and Kirillov (1964), Zhukov et al. (1969), Lapshina et al. (1971), Smagin et al. (1977), Babintseva and Cherednikova (1983), Gorbachev and Popova (1992), and Atlas of Krasnoyarsk Region (1994).

The region of interest encompassed the Angara-Kan part and Angara Lowland of Yenisei Mountain Ridge. Yenisei Mountain Ridge is a low-mountain massif found at the western edge of Central Siberian Plateau. This mountain massif stretches, as a fairly narrow strip, along Yenisei river, north of Trans-Siberian Main Line. Regarding topography and tectonic features, the region can be divided into three parts: northern the (trans-Angara), Angara Lowland, and the southern (Angara-Kan).

The Angara-Kan part is a folded region dissected due to the latest block lifts (Volobuyev 1960). The highest elevation (550-660 m a.s.l.) was measured at the axis of the mountain ridge. The massif is characterized by flat-top, heavily dissected mountain relief with denuded chimney rocks and rocky crests.

The eastern slope of Yenisei mountain ridge is soft, heavily dissected, and has small flat-convex ridges. Its western slope is also diverse in topography.

Angara Lowland (Kazachinsk Depression) is found at the northern boundary of the mountain ridge. This area includes flat watersheds dissected by small flat-bottom valleys at places. Angara and Yenisei river terraces can be clearly seen.

Although climate prevailing over Yenisei mountain ridge is continental, it is milder than in other parts of central Siberia found at the same latitude. The ridge receives 450-600 mm

of precipitation annually, as compared to 300–400 mm in Kan hollow (Galakhov 1964; Atlas of Krasnoyarsk Region 1994).

No dry spells occur in the southern part of Yenisei mountain ridge due to steady, fairly high air humidity in summer and a long-standing deep snow layer in winter (Lapshina et al. 1971).

Angara-Kan part of Yenisei mountain ridge reflects soil and vegetation characteristics observed in the southern taiga subzone.

The southern Yenisei mountain ridge soil cover is represented by podzolic soils (Lapshina 1971), which stay frozen for a long time, however, no permafrost is present (Yerokhina and Kirillov 1964). While soil horizons are hard to distinguish in the upper parts of slope, they appear to be quite distinct in the lower parts.

Apart from podzolic soils, grey forest soils having a fairly high fertility potential underlain by loamy sand and loess-like loams can be found under dark coniferous woody canopy in Kazachinsk Depression.

3.2. Vegetation

Today's vegetation cover of Yenisei mountain ridge reflects diverse effects of its geomorphologic, lithologic, and climatic conditions. Yenisei mountain ridge towering above West Siberian Plain receives a considerable amount of precipitation carried by Atlantic air masses and is, therefore, a natural precipitation break. The air and soil thermal regimes of the Yenisei-side part of Central Siberian Plateau experience a noticeable warming effect of Yenisei and Angara stream water (Gorbachev and Popova 1992).

The western macro-slope of Yenisei mountain ridge is characterized by multi-dominant taiga woody vegetation cover. Its structure, as well as species composition of ground vegetation is almost the same as in western Siberia. However, bog vegetation is not as abundant here as in western Siberia. The downwind eastern macro-slope is under more continental climate than the western slope and its vegetation composition is fairly similar to that of light conifer taiga forests of central Angara region.

Dark coniferous taiga forest vegetation of the western macro-slope is dominated by Siberian fir, because the slope environmental conditions are most favorable for this woody species, Siberian pine (*Pinus sibirica* Du Tour) and spruce occurring as co-dominants (Figure 3). Scots pine (*Pinus sylvestris* L.), Siberian larch (*Larix sibirica* Ledeb.), Asian white birch (*Betula pendula* Roth), and European aspen (*Populus tremula* L.) can also be found in these stands, with the contributions of the latter two species varying widely, from few individuals to 20–30% of the total number of trees of a stand. These stands are multi-dominant, well-stocked, and have closed woody canopies.

The eastern macro-slope that faces Kan hollow promotes Scots pine due to increasing climate continentality and decreasing humidity. Dark coniferous stands are limited to valleys and lower parts of non-south-facing (i.e. shaded) slopes.

Today's forest cover of Yenisei mountain ridge has a markedly complex pattern. Ecosystems differ in dynamic state. The major fir/spruce and fir/Siberian pine stands remained in the main watershed and someplace in the axis part of the ridge, whereas a considerable area is now under secondary forest stands representing different stages of the major woody species regeneration. Forests of Yenisei mountain ridge have experienced intensive logging with the use of heavy machinery. These logging practices have negative impacts on forest regeneration. Different forest regeneration stages were identified on logged sites.

Mountain taiga dark coniferous forests consist largely of mixed fir/spruce or spruce/fir stands with Siberian pine as a minor woody component and ground vegetation dominated by herbs (Babintseva and Cherednikova 1983). Fir and spruce stands with feather moss (*Hylocomium splendens* Hedw.) /short grass- or reed grass (*Calamagrostis obtusata* Trin.)-dominated ground vegetation found on flat interfluvial sites are the most common forest types. These are mostly uneven-aged two-storied high-productivity stands of varying tree density and canopy closure ranging 0.5 to 1.0. Minor woody components are represented by spruce (up to 40% of the total tree numbers), Siberian pine (10-20%), and aspen (10-20%). The major woody species regeneration is fairly good, 12-18,000 individuals, mainly fir, per hectare. Siberian pine and spruce seedlings are taller and occur in canopy gaps. Few boggy fir stands with tall grasses as ground vegetation, Siberian pine/tall grass, spruce / reed grass, spruce/feather moss, Scots pine/sphagnum, and Scots pine/lichen stands are also present.

Although these forests are characterized by generally low fire activity, forest harvesting presents a big problem in terms of forest fire protection. Logging sites increase in size year-to-year and, as a result, high-fire-hazard area and fire protection costs also increase. This is especially true with dark coniferous forest logging sites found on south-facing slopes, on which sites grasses proliferate. Fire is highly probable on these sites right after snow melting. Therefore, young woody regeneration growing on logging sites not covered by fire prevention measures is highly threatened by potential fire.

As fuel loading is great here (up to 70 t/ha), these sites stay highly ignitable during three or four months and even abundant green grasses and shrubs fail to reduce this high fire hazard level. Fires starting on these logging sites burn freely into the surrounding forest stands. For this reason, developing measures to reduce fire hazard on logging sites is a challenging task of the highest priority.

3.3. Logging Site Characteristics

Forest stands that have been subjected to logging are 160-180 years old. These are uneven-aged vertically closed fir stands of 230-250 cubic m/ha wood volume and with ground vegetation represented either by feather moss, sedges, and short grasses, or sedges and herbs (Table 2).

Clearcuts were conducted here in fall and winter, during the snow period.

Table 2. Forest stand characteristics

Plot # / year of burning	Relief	Forest type	Woody species composition*	Density of stocking**
1/1997	Lower part of a south-facing slope, up to 3° steep	Fir/feather moss/ short grass stand	3F2S2L 1SbP2A+B***	0.8
2/1997	Stream valley	Fir/feather moss/ short grass stand	3F3L2SP2S	0.8
3/1997	Fir /short grass/feather moss stand	Fir/feather moss/ short grass stand	3F3L2S 1SP1A	1.0
4/1997	Upper part of a south-facing slope	Fir/feather moss/ sedge/ short grass stand	5F3S1L1B	0.7
5/1997	Upper part of a northwest-facing slope, up to 3° steep	Fir/feather moss/ sedge/ short grass stand	5F1S1SP 1L2A	0.9
6/1997	Lower part of a south-facing slope, up to 3° steep	Fir/feather moss/ short grass stand	7F1S1L1A	0.9
7/1997	Lower part of a north-facing slope, up to 3° steep	Fir/feather moss/ short grass stand	6F2S1SbP1L	0.9
8/1997	Flat site	Fir/feather moss/ short grass stand	5F2SbP2S1L	1.0
9/1997	Flat site	Fir/feather moss/ short grass stand	6F2S2L	1.0

2/1999	Flat site	Fir /short grass/ feather moss stand	6F1SbP1S1B1A	0.8
3/1999	Flat site	Fir/sedge/feather moss stand	5F3S1SbP1B few L	0.7
4/1999	Upper part of a south- facing slope, up to 2° steep	Fir/sedge/herb stand	4F2S2SP2B+A	0.7
5/1999	Flat site	Fir/sedge/herb stand	5F2S2SP1A +SbP+L	0.6
6/1999	Upper part of a south- facing slope, up to 3° steep	Fir/sedge/herb stand	5F2S2SP1A +SbP+L	0.6

* In Russian forestry, stand woody species composition refers to woody species contribution by standing crop (wood volume). It is expressed through a 10-unit scale (e.g., 7SP3B means that Scots pine and birch contribute 70% and 30%, respectively) to a given stand.

** Density of stocking is stand DBH cross section area divided into the standard stand DBH cross section area assumed to be 1.0

*** F is fir, S is spruce, B is birch, SP is Scots pine, A is aspen, SbP is Siberian pine, L is larch, “+” means “few individuals”.

Table 3. Characteristics of young forest regeneration prior to and after overstory logging

Plot # / year of logging	Prior to logging				After logging			
	Woody species composi- tion	Amount (x 1000 ha)	Age (years)	Height (m)	Amount (x 1000 ha)	Proportion, %		
						Low-vig- or trees	Questio- nable trees	High- vigor trees
1/1997	10F	3	40	3	1	10	75	15
2/1997	9F1S	3	30	2.5	1,3	15	60	25
3/1997	10F	3	40	3	0,9	20	70	10
4/1997	8F2S	5	35	3	2,5	70	20	10
5/1997	8F1SbP1S	3	40	3	0,8	70	25	5
6/1997	9F1S	10	35	2.5	1.3	35	60	5
2/1999	8F2S	4	20	1	2,5	80	10	10
3/1999	6F2S1L1B	8	30	2	6	10	10	80
4/1999	10F	4	25	2.2	0,2	50	20	30
5/1999	10F	3	20	1.5	2	80	10	10
6/1999	10F	3	30	3	2	80	10	10

Pre-logging young regeneration density (3-10 thousand trees per hectare) appeared to differ from that after logging (5-40% of the initial density) (Table 3). Removal of canopy trees by logging induced micro-climatic changes and high young regeneration mortality (Figure 4). A year after logging, healthy regeneration was found to make up 5-25% of its immediate post-logging amount. Regeneration of this amount is insufficient to ensure conifer forest establishment. Young trees had continued to die and competition from grasses and small shrubs had increased over the next few years.

3.4. Logging Site Fire Hazard

Logging site fire hazard is largely controlled by fuel structure and loading. Ground vegetation ignitability is known to depend on amounts of fine fuels (mosses, lichens, litter, and forest floor organic matter) having a low (8-10%) moisture content and green grasses and small shrubs with moisture content ranging 120% to 400% (Kurbatsky and Ivanova 1987).

Woody fuel accumulation on and distribution across forest logging sites are determined by forest harvesting methodology. Today, there exist three main forest harvesting methodologies. The first involves removing cut tree branches in a logging site and skidding tree stems to a full-tree processing area. The second method includes removing tree branches at a full-tree processing area followed by transportation of tree stems or cut-to-length logs to a temporary wood store. The third methodology consists of transportation of untreated fallen trees from the place of cutting to a temporary wood store.

With the first methodology, logging slash occurs relatively uniformly across a logging site. Removed tree branches left on the site contribute considerably to the site fuel loading which becomes, therefore, greater as compared to that on non-logged sites. Skidding full trees from a dark coniferous forest logging site does not induce any changes of pre-logging surface fuel characteristics.

Removing tree branches in a full-tree processing area is the most widespread logging methodology in Yenisei mountain ridge, however, cutting of branches in logging site sections is also used someplace.

Forest is harvested by heavy machines, the use of which results in increasing logging slash, soil compactness and mineralization, and damaging young regeneration. Felling debris made up mainly of fine (up to 2.5 cm in diameter) fuels amounts to 200 m³/ha on some logging sites, with feather moss and litter totaling 1.0 to 20.9 t/ha (Table 4). This heavy fuel loading favors high-intensity fire occurrence throughout fire season, and even prolific green vegetation fails to prevent fires occurrence and spread on logging sites.



Figure 3. Logged area in dark coniferous forest



Figure 4. Young regeneration after logging

Table 4. Fuel loads on forest logging sites, t/ha

Site# /year of burning	Grasses and small shrubs	Litter and mosses	Forest floor, branches of D < 0.7 cm	Down deadwood, logging slash			Total
				Diameter, cm			
				0.7–2.5	2.5–7.5	>7.5	
1/1997	0.6	8.6	10.4	53.1	74.9	15.4	163.0
2/1997	0.7	3.2	3.7	67.5	63.6	0.0	138.7
3/1997	0.2	5.3	4.8	57.1	53.1	47.6	168.1
4/1997	2.5	1.3	13.1	24.0	29.9	0.0	70.8
5/1997	2.5	5.7	8.9	25.1	26.3	0.0	68.5
6/1997	1.7	1.0	14.1	44.4	36.9	68.4	166.5
7/1997	1.8	2.2	14.4	20.1	60.0	49.4	147.9
8/1997	0.4	11.3	16.6	50.7	51.4	61.6	192.0
9/1997	0.6	6.8	20.7	50.7	36.3	35.7	150.8
2/1999	0.3	13.9	9.5	16.4	16.2	54.1	110.4
4/1999	1.0	15.9	11.5	7.8	37.2	145.7	219.1
5/1999	0.1	20.9	13.5	7.4	3.9	32.7	78.5
6/1999	0.2	10.7	9.2	13.5	21.6	40.1	95.3

Table 5. Fuel load (t/ha) distribution by logging site section

Fuel site section	Fuel type					Total	Proportion of logging site area (%)
	Litter and mosses	Forest floor, branches of D < 0.7 cm	Fallen tree stems, logging slash				
			0.7-2.5 cm	2.5-7.5 cm	>7.5 cm		
Full tree processing area	14.4	8.7	25.5	24.8	67.4	140.8	8
Logging block	13.4	10.8	10.1	17.5	61.0	112.7	88
Skidding trail	1.4	3.9	1.8	0	0	7.1	4

Our experiments involved dividing logging sites into the following sections: logging block, skidding trails, full tree processing area (Table 5). Full tree processing area, where cut tree branches are removed, have usually the highest fuel loads. Logging blocks on dark conifer-

ous forest logging sites are characterized by generally natural (i.e. close to intact) ground fuel loads and structure. Little fuel was found on partly mineralized skidding trails.

Litter load was 13.4 t/ha on a logging block and 14.4 t/ha on a full tree processing area, with fuel totaling 140.8 and 112.7 t/ha on a full tree processing area and a logging block, respectively. These values agree with those found in earlier publications on southern taiga dark coniferous forest logging sites (Tsvetkov and Ivanov 1985). Forest floor occurred more uniformly across the logging area and averaged 10-12 t/ha. The total fuel load was high (Figure 5) and varied from 70 to 200 t/ha on clearcuts.

Along with fuel loading, fuel layer depth and compactness vary, which variations influence fire parameters. Fuel layer depth was determined to average 0.17 m at logging block and 0.35 m on full tree processing area, litter, forest floor, and logging slash compactness ranging 25 to 112 kg/m³ (60 kg/m³ on average). While fuel layer exhibited high porosity (average: 40 kg/m³) on full tree processing area, it was more compacted (66 kg/m³) at tree cutting area due to the presence of large-diameter downed woody fuels.

Ground fuels were found to have noticeably changed in loading five years following logging (Table 6). Fire carrier fuels averaged 10 t/ha. This allows us to conclude that logging site fire hazard remains high even when green vegetation is abundant.



Figure 5. Logging slash before prescribed burning

Table 6. Ground fuel loading on clearcuts

Time since logging (years)	Ground fuel load (t/ha)			
	Grasses and small shrubs	Fire carrier fuels		Total
		Forest floor	Litter and mosses	
2	3.7	10.3	9.1	23.1
3	3.2	10.4	10.8	24.4
5	12.3	11.0	10.7	34.0

Apart from forest fuel loading and structure, forest fire danger is controlled by weather conditions. In Russia, weather-dependent forest fire danger is rated based on complex meteorological index of Nesterov (1949):

$$NI_j = NI_{j-1} \xi_{j,j-1} + \tau_j (\tau_j - \tau_j) \quad (1)$$

where NI_j is Nesterov Index for j -th day of fire season; NI_{j-1} is Nesterov index of the previous day ($j-1$); $\xi_{j,j-1}$ is the previous 24-hour precipitation coefficient ($\xi_{j,j-1} = 1$ at precipitation less than 3 mm and 0 at precipitation of 3 mm and more); τ_j is j th day air temperature; and τ_j is j th day dew point.

Air temperature and dew point readings are taken at 13:00 local time. Precipitation exceeding 3 mm means that fire hazard downed to zero and Nesterov Index (NI) is calculated anew.

To practice NI, fire danger classes (FDC) are used that show the relationship between NI and forest fuel ignitability level. FDC I corresponding to 300 NI value indicates very low, if at all, fuel flammability; FDC II corresponds to NI of 301-1000 and indicates low fire danger; with FDC III, NI varies from 1001 to 4000 (moderate fire danger); FDCs IV and V correspond to NI values 4001-10000 and over 10000 suggesting high and extreme fire danger, respectively (Fire prevention regulations 1993).

Fire statistics shows that fairly high fire danger occurs annually in taiga forest. Numerous forest fires induced by a high fire danger level, become an out-of-control disaster (Kurbatsky 1975).

Forest fuel composition, structure, and drying rate are known to vary with forest and logging site type. Dead and living ground vegetation absorbs radiation in open sites, whereas in the forest solar radiation is absorbed mainly by tree canopy. Temperature of a surface absorbing radiation is known to be higher than that of ambient air and shaded surfaces and the greater the temperature difference, the more favorable the moisture evaporation conditions. Fuels often constitute the main radiation-absorbing surface in forest logging sites; this is where the most favorable fuel drying conditions (Sofronov 1970). Dark coniferous forest clearcuts burn at NI of 250-300, whereas dark coniferous forests become burnable only at NI over 2000 (Melekhov 1983).

Fire season usually lasts for 140-160 days, from mid April through September, in the region of interest. While dark coniferous forests stay highly ignitable 15-25% of the total fire season, logging sites can burn during more than 75% of its duration.

Great logging slash amounts are characteristic of uncleared cuts and loosely packed fire-carrying fuel layers promote high-intensity fire spread. As fuel is distributed non-uniformly across logging sites, the site sections differ in time needed for fuel to achieve high flammability and burning of site section having high fuel accumulations induce spot fire occurrence before the main fire front. Clearcuts staying burnable through almost entire fire season due to great amounts of fuel and its specific drying patterns can be characterized as high-fire-hazard sites.

3.5. Logging Site Prescribed Burning Technologies

Controlled fires with prescribed weather and fuel-dependent parameters (fuel consumption rate, prescribed burning rate, etc) are conducted on logging sites for reducing fuel load and enhancing forest regeneration. Desired fire parameters can be obtained using different burning technologies that include both burning methods and ignition or firing patterns. In each case, a burning methods chosen based on a given logging site characteristics, such as site area, presence of burning-forbidden places, fuel structure, loading, and distribution.

Broadcast burning methods

Progressive burning (Figure 6). With this method, a fire is ignited at several points simultaneously along the fireline located on a site downwind side so that fire could move into the wind. The entire site is burned at a time. This burning method is effective for 10-20 ha logging sites surrounded by safe control lines having no young regeneration, seed trees, forest pockets left intact, and other elements forbidden to burn. This method enables rapid and highly effective burning of logging slash.

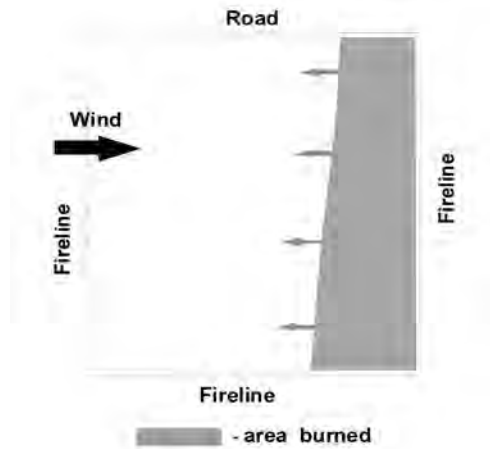


Figure 6. Progressive burning

Local burning (Figure 7). This method involves successive burning of different parts of a logging site. As soon as one part is done, the next part is ignited, etc. this labor-saving method is effective where there exist young regeneration pockets, or seed trees, or a weather-caused risk of fire escape. In the latter case, site parts to be burned are surrounded by additional fire lines.

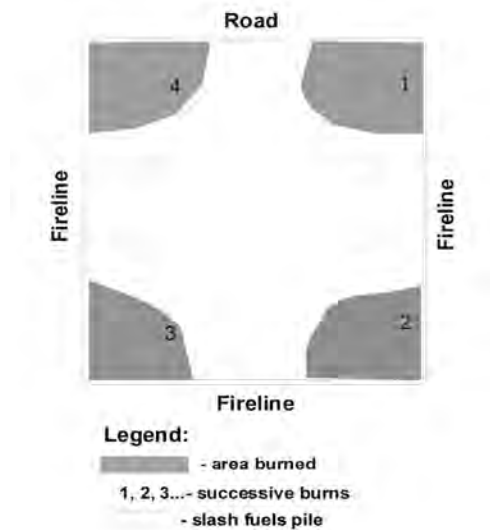


Figure 7. Local burning pattern

Two-stage burning (Figure 8). At the first stage, logging site sections characterized by high fuel loads (full tree processing areas and skidding trails etc.) are burned. This can be done at FDC I and II or when grasses and small shrubs become abundant. The second burning stage is conducted at FDC III when fine fuel is dry enough to carry fire. The parts of a logging site already burned should be linked by plowed lines for fire safety. While burning stage I can be carried out in August and September, the second stage should be delayed until May or early June next year. This is the safest of all burning methods, which does not require high prescribed burning skill.

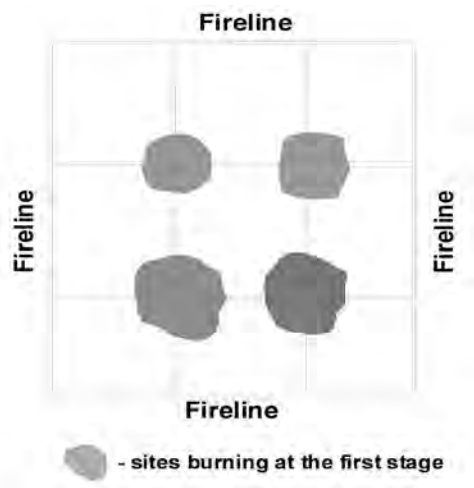
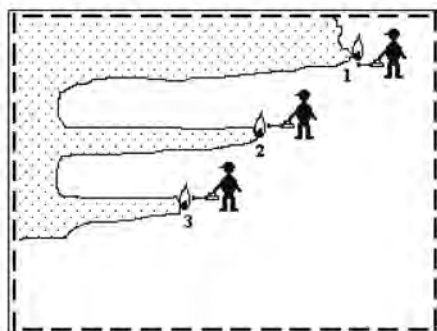


Figure 8. Two-stage burning pattern

Firing patterns are selected depending on burning objectives, weather characteristics, topography, logging slash load and occurrence, adjacent intact site current fire hazard rate, reliability of firelines, natural fire barriers, and available fire suppression resources. Firing patterns (or techniques) determine general prescribed fire intensity. Three ignition patterns are currently in use.

Linear ignition (Figure 9). A continuous line is ignited along the fireline on one side of a logging site to produce a uniform fire line (Line 1 in Figure 9). This ignition pattern is best to use where logging slash is uniformly distributed across a logging site and its load is fairly low, at wind speed less than 1.5-2.0 m/s.

To speed up and control burning intensity (e.g., for achieving close-to-complete logging slash consumption by fire at FDC II or III), one more continuous line is ignited parallel to the first line (Line 2 in Figure 9), fire line intensity depending on ignition line spacing. As soon as the strip between ignition lines 1 and 2 burns out, the third line is ignited at a determined distance from line 2. The final line is ignited along the opposite side of a logging site. This is so-called line step burning.



Legend:

- - - fireline
- ☁ - area burned
- 3 - successive ignition

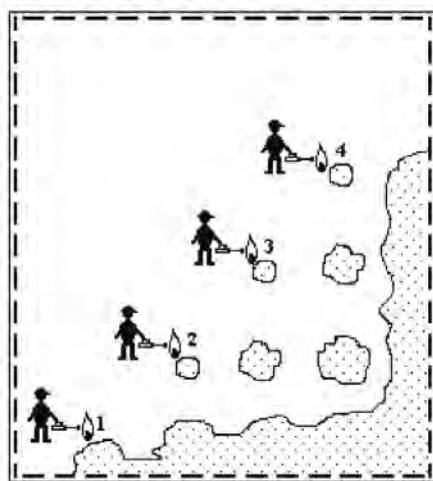
Figure 9. Linear ignition pattern



Legend:

- - - fireline
- ☁ - area burned
- 3 - successive ignition

Figure 10. Circular ignition pattern



Legend:

- - - fireline
- ☁ - area burned
- 3 - successive ignition

Figure 11. Point ignition pattern

Circular ignition (Figure 10). Initially, the central part of a logging site is ignited (1 in Figure 10). As soon as the center begins to burn intensively, logging slash is ignited in a line circling the central fire at a distance of 20–30 m (2 in Figure 10). One more circle is ignited, where necessary. Finally, logging slash found along the site fireline is ignited (3 in Figure 10). This ignition pattern is most effective at wind speed up to 1.0 m/s and where it is necessary to increase burning rate and intensity.

Point ignition (Figure 11). Separate logging site points are ignited, heavy logging slash accumulations (in full-tree processing areas, along skidding trails, and in temporary large-diameter logging slash storing places) treated first.

Numerous points are then ignited having lower logging slash amounts. This ignition pattern allows to speed up burning, increase combustion efficiency, and is best applied where grasses and small shrubs are abundant.

Consider prescribed fire conducted on a logging site in a fir/sedge/herb stand (prescribed fire 6/1999 [Figure 12]). This 5-ha 2 deg. sloping fir/sedge/herb site characterized by 5F2S2SP1A+SibP+L woody species composition, 0.6 density of stocking and 20-year-old young fir regeneration of 3000 trees/ha density was clear cut using LP-49 forest harvesting machine in winter. Post-logging young regeneration density was 2000 trees per hectare, of which amount 10% were healthy, 10% were questionable, and 80% were dead; 77%, 20%, and 3% of fuels totaling 125 m³/ha were found in logging blocks, full tree processing areas, and skidding trails, respectively. The logging site was surrounded by a fireline 3 m wide and ignited using the linear firing pattern at 15°C air temperature, 55% relative humidity, and 1808 NI value (FDC IV) at 19:00 on a calm day (2 September 2, 1999). The site was broadcast burned.

Tactically, the first ignition line was established on the eastern side of the site (Figure 13). One more ignition line was made parallel to the first line to increase rate of burning. After these two lines converged, the third line was ignited. The final ignition lines were constructed along the northern, western, and southern sides of the logging site.

The fire was contained with the help of backpack water sprayers. Firebrands were observed to jump beyond the site downwind boundary. The entire site was burned during 3 hours. Fire consumed all logging slash elements up to 7 cm in diameter and 73% of larger elements. The burn was patrolled for four days.

Other logging site prescribed burning cases are described in Valendik et al. (2000).

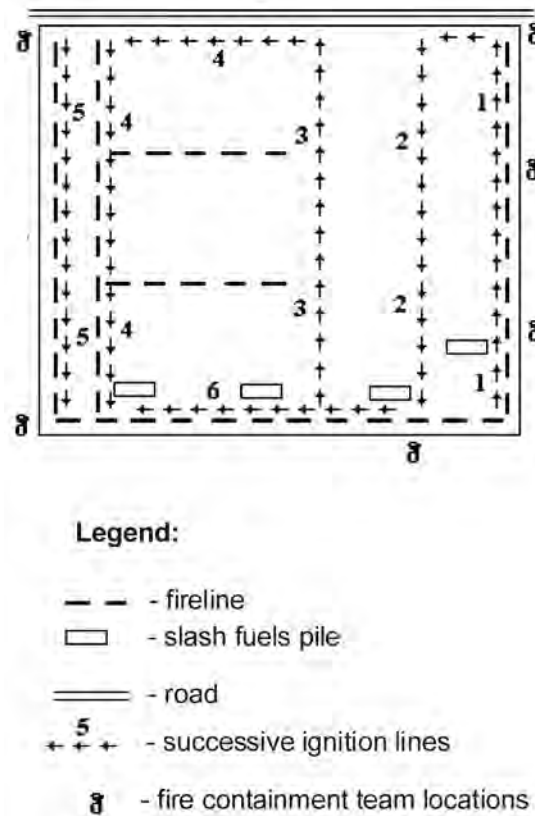


Figure 13. Firing pattern used for burning a fir/sedge/herb logging site (Site 6/1999)

Logging Site Prescribed Burning

Burning of logging sites differs from that of forest. These differences are related with high loading and non-uniform distribution of carrier fuels over logging sites, as well as numerous burning spots. Forest fuel combustion process can be divided into four phases: (1) fuel ignition, (2) fire spread, (3) combustion, and (4) flame extinction. Depending on logging site firing pattern, either progressive or area burning regimes can be achieved. While a distinct fire line is characteristic of the progressive burning regime, this line is hard to discern with the latter regime. The progressive burning regime can be described by the parameters commonly used for characterizing forest fire (rate of spread (m/s), flaming zone width (m), fuel consumption rate (kg/m² s), and fireline intensity (kW/m) and is effective where logging slash load is low (e.g. skidding trails and logging blocks) resulting in a flaming zone width much less than the distance between neighboring ignition points.

Area burning regime is used where logging slash load is high (full-tree processing and logging block areas). This burning regime has specific characteristics, such as flame residence time (s), fuel consumption rate ($\text{kg/m}^2 \text{ s}$), and flame length (m). A heat release value (kW/m^2) can be obtained considering heat of combustion (kJ/kg). As fuel heat of combustion depends on fuel type, heat release rate was calculated on the assumption that forest fuel heat of combustion averages $18,000 \text{ kJ/kg}$.

To describe the entire logging site burning process, fuel consumption rate, m ($\text{kg/m}^2 \text{ s}$), showing average consumption rate for different ignition patterns and fire line spread rate was used (Valendik et al. 2007).

$$m_b = \Delta M / t_b,$$

where ΔM is amount of forest fuel consumed (kg/m^2), and t_b is average time needed to burn a hectare logging site (s).

The time needed to completely burn a logging site (t_b) consists of several components:

$$t_b = t_i + t_s + t_r,$$

where t_i is time of ignition, t_s is time needed for fire to spread from ignition point to a given point within a logging site, and t_r is flame residence time.

With progressive burning regime, time of ignition can be ignored, as it is much less compared to other components due to high carrier fuel loading.

Fire line spread time was calculated as:

$$t_s = L / 2U,$$

where L is average distance between ignition points (m) and U is fire rate of spread (m/s), which is determined by wind speed, topography, fuel layer depth, and other factors. Fire spread rate was measured during prescribed burning.

Flame residence time was calculated for the progressive burning regime as:

$$t_r = B / U,$$

where B is flaming zone width (m); and U is fire spread rate (m/s).

Forest fuel rate of consumption, i.e. amount of fuel consumed during flaming combustion, was obtained using

$$m_c = \Delta M / t_r$$

where ΔM is consumed forest fuel (kg/m^2) and t_r is flame residence time (s).

With the area burning method, time needed for fire to spread can be ignored, while time needed for fire ignition determined by igniter's movement speed increases. Flame residence time was measured during the prescribed burning and frontal fireline intensity was determined by Byram's (1959) method.

Twenty two sites (blocks) 5-30 ha in size characterized by uniform forest fuel structure and loading were selected to investigate fire development and spread. Prescribed forest fuel burning was conducted at a wind speed up to 3 m/s and air temperature and relative humidity ranging 9 to 27°C and 34 to 80%, respectively (Table 7).

Table 7. Weather characteristics obtained during logging site prescribed burning experiments

Site # / year of burning	Date	Start of burning (time)	Air temperature (°C)	Relative humidity (%)	Wind direction	Wind speed (m/s)	Fire danger class
1/1997	23.06	20:00	27	38	S	2	III
2/1997	24.06	14:00	20	34	SW	3	IV
3/1997	25.06	12:00	23	58	0	0	IV
4/1997	26.06	11:00	22	60	0	0	IV
5/1997	26.06	14:00	22	73	NE	3	IV
6/1997	26.06	19:00	22	80	NE	2	IV
7/1997	19.08	16:00	22	48	W	2	I
8/1997	20.08	16:00	22	48	W	2	II
2/1999	27.06	19:00	20	49	SW	3	IV
3/1999	30.08	15:00	19	40	S	2	III
4/1999	01.09	18:00	15	55	0	0	III
5/1999	02.09	21:00	9	50	0	0	IV
6/1999	02.09	19:00	15	55	0	0	IV

Either progressive or area burning regime was used depending on weather conditions, fuel loading and distribution. These two regimes differ in several parameters, namely flame residence time is 207 seconds in average with the progressive burning regime, which is seven times less than with the area regime, and the time needed to burn 1-ha logging site in progressive burning regime (averaging 3 hours) is twice that needed with area regime (Table 8). These differences occur because fire spreads slowly as compared to the speed at which an igniter moves and should be considered when selecting ignition method.



(a)



(b)

Figure 12 (a, b). Clearcut № 6/1999 in fir/sedge/shrub stand (a) before, and (b) after prescribed burn

Table 8. Fuel consumption dependence on combustion parameters and prescribed burning regime

Parameters of burning			Burning regime	
			Progressive	Area
Fireline intensity (kW/m)			578.9	-
Flaming zone width (m)			0.94	-
Consumed fuel (t/ha)			66.6	87.4
Consumed fuel (%)			57.9	64.4
Fuel consumption (%)	Litter and feather mosses		87.3	97.8
	Duff		56.4	82.3
	Down deadwood, logging slash	0.7-2.5 cm	72.8	85.5
		2.5-7.5 cm	53.3	72.0
		>7.5 cm	39.4	52.2
Heat release (kW/m²)			648.7	134.8
t _i , s			0	3950.00
t _s , s			10317.98	0
t _c , s			207.35	1425.00
t _B , s			10525.33	5375.00

The progressive burning regime results in lower frontal fire intensity (580 kW/m) than the area burning regime. While the progressive burning regime is labor-saving regarding burning process management, it results in less fuel consumption than the area regime. The probability of fire jumping beyond the site with increasing fire intensity, which increase often induces fire whirls, high convection column, and strong thermal radiation capable to heat fuels found 3-4 m beyond the fireline to ignition temperature.

Progressive and area burning regimes resulted in an average fuel consumption of 67 and 87 t/ha (averaging 58% and 64% of the total fuel amounts), respectively. This difference was primarily due to different pre-fire fuel loads.

Since prescribed burning is aimed at reducing logging site fire hazard, fuel consumption is a major indicator of the effort effectiveness. Carrier fuel elimination by prescribed burning is vital for wildfire hazard reduction. Consumption of fuels by fire varies among their types (Table 9). It decreases with increasing fuel size class.

Table 9. Fuel consumption with the progressive prescribed burning regime

Site # / year of burning	Fuel combustion (g/s·m ²)	Fuel consumption, %					Fire danger class
		Litter	Duff	Downed deadwood, logging slash (diameter in cm)			
				0.7-2.5	2.5-7.5.	>7.5	
1/1997	4.0	98	89	79	31	20	III
2/1997	30.8	97	46	56	85	46	IV
3/1997	45.5	94	60	81	60	35	IV
4/1997	22.6	98	41	55	72	31	IV
5/1997	20.0	94	53	58	38	48	IV
6/1997	53.1	88	78	73	40	13	IV
7/1997	44.2	95	69	49	22	20	I
8/1997	58.1	88	68	52	73	2	II
2/1999	28.8	84	47	84	53	50	IV
4/1999	34.8	71	54	56	35	37	III
5/1999	46.0	78	63	98	100	100	IV
6/1999	32.0	97	57	95	50	21	IV

Forest floor organic matter consumption exhibited a strong correlation (a correlation coefficient of 0.77) with its rate of consumption (Figure 14). With the progressive burning regime, consumption of forest floor was found to increase with increasing fuel rate of consumption and to decrease with increasing fuel moisture content (Figure 15). Prescribed fire appeared to consume less than 60% of the total fuel load at fuel moisture over 100%.

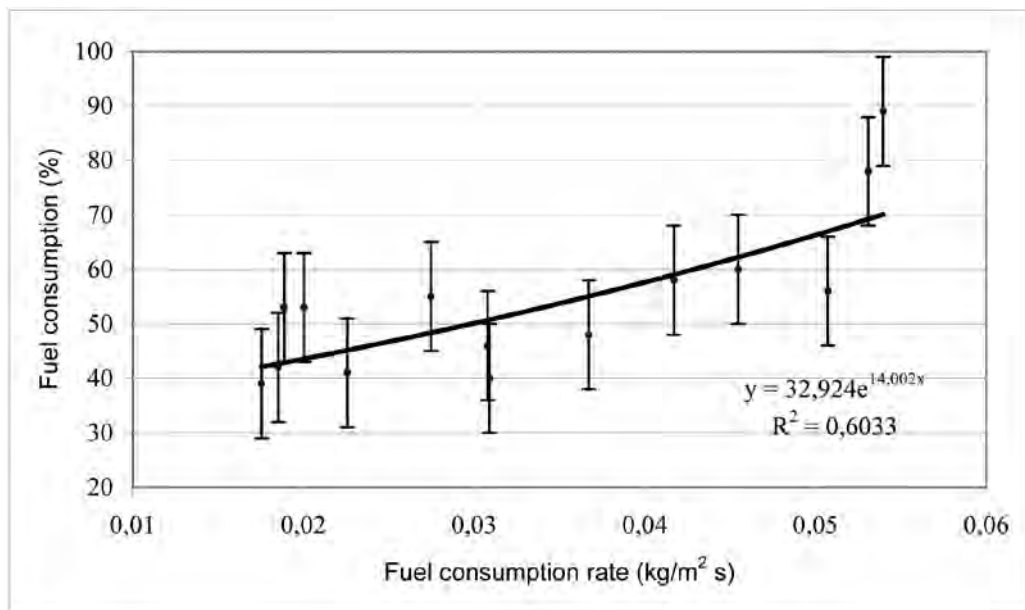


Figure 14. Forest floor consumption dependence on its consumption rate

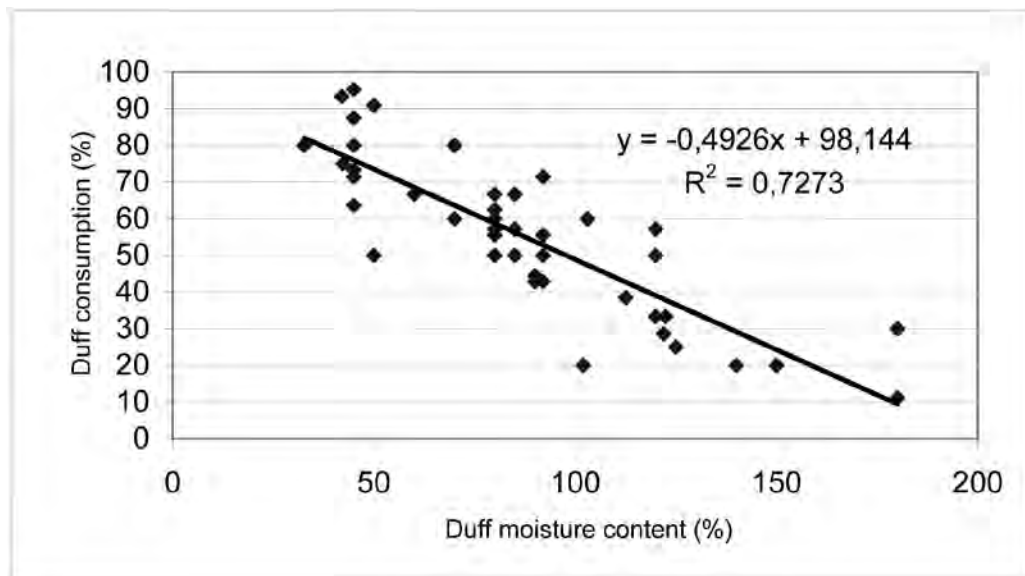


Figure 15. Duff consumption dependence on its moisture content

Although logging slash elements exceeding 7.5 cm in diameter account for less than 10% of the entire logging site area, they make up about 70% of the site total fuel loading. While most fine fuels (up to 7.5 cm in diameter) are consumed in fire flaming zone, fuels of greater diameters are consumed mainly during the smoldering phase, consumption depending on their distribution and rate of decomposition. When flaming combustion is over, a logging site remains usually covered by a “net” of unconsumed tree branches and stems smoldering where they contact each other.

Our prescribed burning experiments involved determination of unburned fuel amount after flaming combustion was over. Where smoldering big-diameter fuels occur after prescribed fire, forest floor becomes burned through and, thus, soil is heated, as smoldering can last for several days. Although smoldering combustion intensity is very low, it results in complete forest floor consumption and can increase soil surface temperature to levels lethal for soil microorganisms. Moreover, smoldering-caused high soil temperature induces soil chemistry changes. Our experiments and investigations of other scientists (Buzykin 1964; Ivanov 1965; Sannikova 1977; Matveyev et al. 1987) showed that where forest floor smoldered completely, a microenvironment occurs, which is favorable for post-fire seed germination and seedling establishment.

Flaming combustion with the area prescribed burning regime used on full-tree processing areas having high logging slash loads lasts for 15-30 minutes. Fuel consumption rate depends on oxygen availability which is in turn determined by wind speed, fuel size class, the area of the site under the treatment, and other factors. Flame is 2.1 m long in average, with some flames reaching 4 m in length. These burning parameters provide complete fuel consumption, as opposed to the progressive burning regime.

Fuel consumption is controlled by fire danger class (FDC). With the area burning regime, for example, FDCs II and IV differ 1.5 times in fuel consumption, which averages 47% and 70% of the total fuel amount, respectively (Table 10). The rate of fuel consumption at FDC IV is almost twice that at FDC II, although flame residence time is the same at both FDCs.

Table 10. Fuel consumption at different prescribed burn parameters

Fire danger class	Flame residence time (s)	Fuel combustion rate (g/m ² c)	Fuel consumption, %					
			Total fuel	Ground fuels				
				Litter, mosses	Duff	Downed deadwood, logging slash		
						Diameter (cm)		
						0.7-2.5	2.5-7.5	>7.5
II	1500	4.75	47.2	92.3	75.0	58.0	65.0	48.0
IV	1400	8.40	70.1	99.7	84.7	94.7	74.3	53.6

Prescribed burning resulted in almost 50% forest fuel loading reduction. Post-broadcast burning fuel amount varied among fuel groups on the treated logging sites (Table 11, Figure 16), with litter not exceeding 450 g/m². Ratio between fuel group loading amounts left on logging sites after using the progressive and area burning regimes is important to know for estimating prescribed burning impact on forest regeneration. Deep litter and forest floor organic layers control clearcut microenvironment. However, prescribed fire was found to reduce >7.5 cm-diameter fuel element projective cover to not more than 5% of the total logging site area and thus these elements did not hamper young regeneration growth.

Table 11. Post-burning fuel loading, t/ha

Site # / year of burning	Ground Fuels					Total
	Litter, mosses	Duff	Downed deadwood, logging slash			
			D=0.7-2.5 cm	D=2.5-7.5 cm	D>7.5 cm	
1/1997	0.27	1.14	11.15	51.68	12.32	76.6
2/1997	0.52	2.00	29.70	9.54	0.00	41.7
3/1997	0.83	1.94	10.85	21.24	30.94	65.8
4/1997	0.03	7.75	10.80	8.37	0.00	26.9
5/1997	0.33	4.20	10.54	16.31	0.00	31.4
6/1997	0.59	3.11	11.99	22.14	59.51	97.3
7/1997	0.22	4.45	10.25	46.80	39.52	101.2
8/1997	1.32	5.30	24.34	13.88	60.37	105.2
9/1997	0.53	5.17	21.29	12.71	18.56	58.3
2/1999	1.7	4.2	2.09	4.9	27.1	40.0
4/1999	4.1	5.26	3.3	23.52	92.64	128.8
5/1999	4.06	4.99	0.15	0.00	0.00	9.2
6/1999	0.15	2.84	0.28	11.76	21.73	36.75

Fire spread across a prescribed burned area is impossible due to insufficient fine fuel (litter and forest floor) amounts. A forest fuel load exceeding 0.3 kg/m² (oven dry weight) is needed for a fire to spread (Valendik and Isakov 1978).

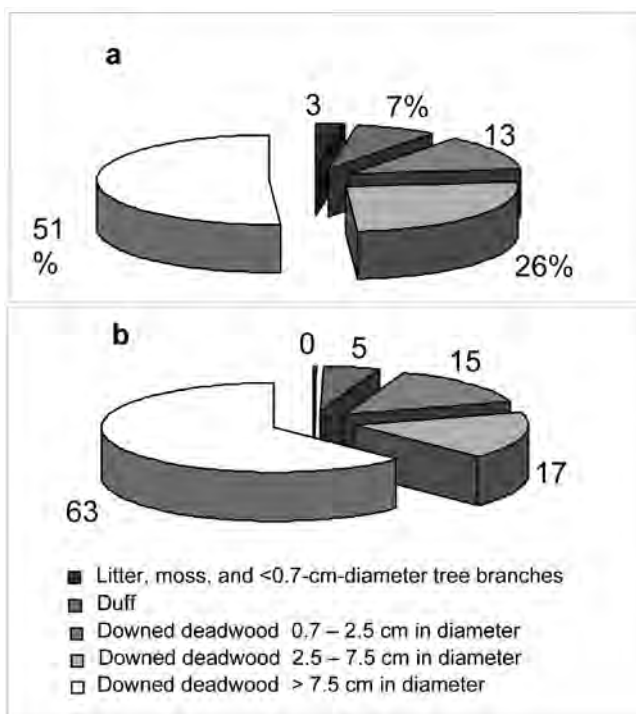


Figure 16. Fuel amounts on logging sites burned using the progressive (a) and area (b) burning regimes

Mineral soil exposed after prescribed burning appeared to account for 1-100%, averaging 59%, of the total burned site area. Soil mineralization was found to correlate with forest floor consumption (Figure17).

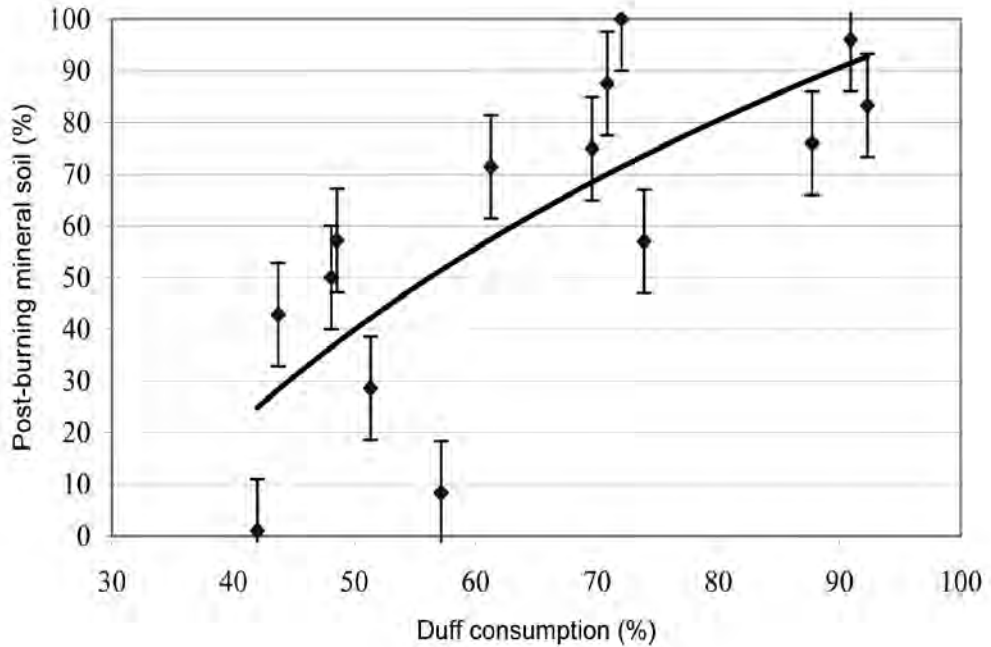


Figure 17. Correlation between post-fire mineral soil area and duff consumption

The logging site burning characteristics found can thus be concluded to be determined by high fuel loading, mosaic fuel distribution, and the presence of multiple ignition points. Use of either progressive or area burning regime enables reduction of target fuel group loads down to prescribed levels.

4. Prescribed Burning of Mountain Dark Conifer Logging Sites

Forest logging site prescribed burning in mountains is markedly different from that in plains, as slopes influence many factors controlling fire spread (Davis 1959). Mountain and valley air mass circulation causes frequent wind shift, which, in turn, changes combustion characteristics. Since wind speed constantly exceeds 5 m/s on tops of slopes, the risk of firebrand jumping beyond the logging site under treatment and, hence, spotting increases in these places. It is hard to control prescribed fire behavior, as wind speed and direction change round the clock. Therefore, mountain forest logging sites are often prescribed burn at nighttime, when fire fighter effort coordination becomes problematic. Fire intensity increases drastically, where fire burns upslope. Moreover, a big convection column is created that draft firebrands in. These firebrands are then lifted to an elevation of 500-1000 m and can be dispersed far beyond the logging site under burning to result in numerous spot fires. As these spot fires are hard to detect, they can grow big. Also, prescribed burning on steep slopes results in that large-diameter logging slash elements begin to roll from fireline downslope creating spot fires, which rapidly spread upslope endangering lives of fire fighters standing downslope from the initial ignition line.

Mountain logging site prescribed burning parameters (fire intensity, spread rate, and duration) should thus be adjusted to consider the above factors and provide maximal fuel consumption and minimal soil disturbance using as little fire fighting resources as possible. This can be achieved by selecting optimal meteorological parameters, fuel moisture content, as well as proper burning methodologies.

4.1. Study Area

Prescribed fires were conducted to enhance forest logging site recovery in eastern Sayan Mountains. These mountain forests are found within the Altai-Sayan mountain forest vegetation zone (Forest Types 1980; Korotkov 1994). The study area characteristics were taken from Krasilnikov (1961), Gudoshnikov (1963), Zvereva (1966), and Zhukov et al. (1969).

4.1.1. Topography, Climate and Soils

The study area is a mountainous area, elevations above sea level (a.s.l.) ranging 400 to 900 m, with some mountains as high as 1500 m. The area is dissected by numerous narrow and deep stream valleys. Mountain slopes are 5 to 35° steep.

Mountain soil development is heavily dependent on topographic factors, such as slope, aspect, and elevation a.s.l., as well as vegetation characteristics. The study area is largely covered by soddy soils podzolic to different rates. While peat podzolic soils are widespread in river valleys, meadow soils are less common here. Soil particle distribution analysis shows these are mostly loams, with loamy sand someplace. Slightly podzolic soddy soils containing moderate amounts of rubble are found in lower and middle parts of slopes. These fertile soils support conifer stands with feather moss- or herb/sedge-dominated ground vegetation. Gentle north-facing slopes are covered by less common grey forest loamy soils.

The study area is characterized by fairly warm summer and fairly cold winter. Monthly air temperature averages 16.4°C, with a maximum of 38°C. This is an excessively humid area, average annual precipitation reaching 604 mm. Precipitation mainly occurs in July, August, often as showers, and September. Spring is a fairly dry season. About 25 days passes between the end of growing season and permanent snow cover development. Snow cover does not melt for over five months. The time period between complete snowmelt and growing season onset is ten days. Snow layer depths average 56 cm and 22 cm under forest canopy and on open sites, respectively, the greatest depth characteristic of early March. Snow melts 5-10 days earlier on south-facing slopes as compared to north-facing slopes. Soil freezes as deep as down to 240 cm on open sites.

Southwestern wind prevails throughout the year. Average annual wind speed ranges 1.6 to 2.6 m/s, the prevalent wind having the highest speed. Strong winds occurring mostly in May and June contribute to forest fire danger considerably.

The growing season lasts for up to 135 days in mountains and 149 days in the forest-steppe part of the study area. The frost-free period averages 96 days, from 79 to 105 days. Light night frost can occur in any month. Absolute air temperature fluctuation can reach 96°C.

The study area is in continental climate characterized by fairly warm summer and fairly cold winter. Snow cover does not melt for a long time and spring is a low-precipitation season. This factor combined with low relative humidity, strong winds, and the presence of a loosely compacted cured grass layer accounts for high fire hazard on logging sites.

4.1.2. Vegetation

As the area of interest is a mountainous area, altitudinal forest belts can be clearly seen here. Low-mountain light conifers are replaced by Siberian pine/fir stands in middle mountains, which stands are in turn replaced by pure Siberian pine forests higher, on subgolets.

Light coniferous forest found between 300 and 700 m a.s.l. (i.e. mostly in low and partly in middle mountains) is represented by Scots pine/larch and pure larch stands. Since this forest has been heavily logged and, as a result, frequently burned by wildfire, big sites are now occupied by secondary birch and aspen stands.

Low-mountain Scots pine stands are uniform in that they exhibit topography-determined spatial distribution similarity, in both overstory and sub-canopy woody layers. Scots pine stands with feather moss-dominated ground vegetation are common on convex north-facing slopes. These stands contain minor amounts of larch, fir, and Siberian pine, with the latter two species making the major forest regrowth components. Scots pine/herb stands occupy vast sites covered by soddy forest soils. Most of these stands are old, contain a minor larch component, and were subject to logging, wildfire, and resin extraction.

A dark conifer forest belt found in middle mountains (700-1300 m a.s.l.) is represented by Siberian pine/fir and pure Siberian pine stands (Figure 18) with mainly feather moss as ground vegetation. These are highly closed mostly overmature stands containing a poorly developed sub-canopy tree layer made up by fir on slopes and spruce in valleys. However, young woody regeneration is enough for establishing new forest stands. Post fire and post-logging stand regeneration occurs through woody vegetation conversion. Siberian pine/feather moss stands are widely spread on the eastern Sayan slope characterized by continental climate (Krasilnikov 1961; Gudoshnikov 1963; Cherednikova 1963; Forest Types... 1980).

4.1.3. Fire Activity

Although fire activity has increased over several past decades in eastern Sayan as compared to other parts of Krasnoyarsk Region, it still remains among the regional lowest. Steadily increasing fire frequency and extent in eastern Sayan foothills (former Mana Forest Management Area [FMA]) (Figure 19) have resulted from intensive forest harvesting.

All-time highest number of fires (77) was detected in the area of interest in 1999. The total area burned, 35,428 ha, was equal to the total area subject to logging during a decade. Large fires account for 23% of all fires, which are mostly surface fires, and 97% of the total area burned in the study area. Crown fires make only 5% of all fires (Table 12).



Figure 18. Dark coniferous forests in eastern Sayan middle mountains

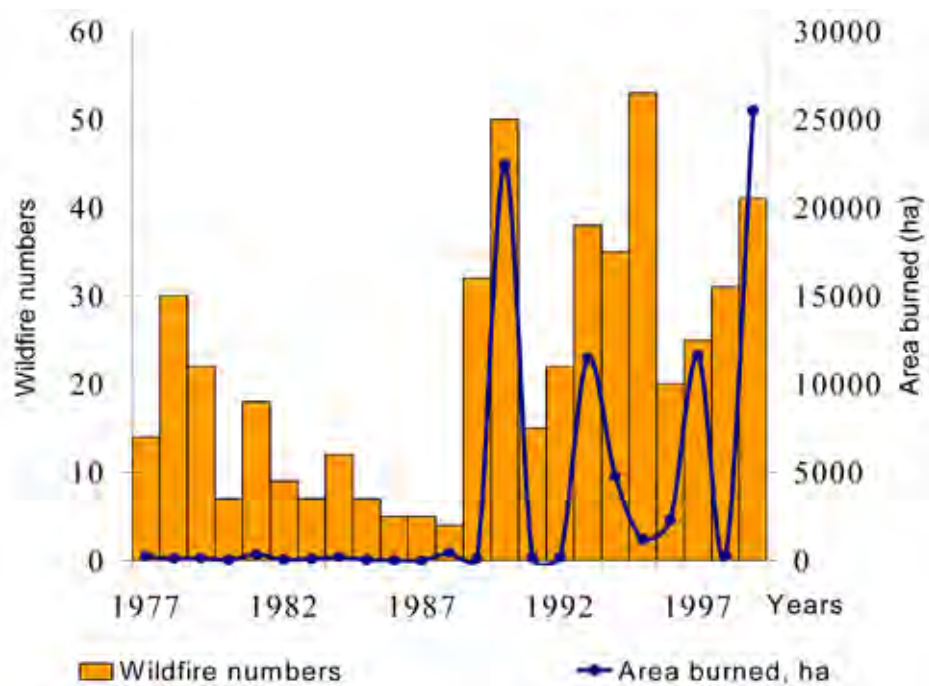


Figure 19. Wildfire activity in the former Mana FMA

Table 12. Fire types, numbers, and area burned

Year	All fires		Large fires		Fire type	
	Number	Area burned (ha)	Number	Area burned (ha)	Surface	Crown
1991	30	1024.5	8	930	25	5
1992	19	114.3	-	-	19	-
1993	52	11264.5	11	11125	47	5
1994	52	1941.8	15	1728.5	50	2
1995	62	1752.3	9	1595	59	3
1996	45	4109.6	19	3761	45	-
1997	52	17901.5	20	17595	52	-
1998	48	582.0	4	260	48	-
1999	77	37953.8	13	37515	72	5

A forest fire rarely reaches 5 ha in size, however, combinations of certain factors, such as long drought, strong wind, and steep slope, can enhance crown fire development and, as a result, big forest sites are burned. Six fires each exceeding 10,000 ha have been detected over the past decade (and two in 1999) in the study area (Figure 20).

Human carelessness is the cause of 82% of all forest fires, compared to only 15% caused by lightning (Figure 21). Lightning fires occur mostly in July.

Fires burn mainly in May, immediately after snowmelt, and can extend to cover large areas, as relative humidity is low, winds are strong, logging sites and slopes contain high amounts of previous year cured grass. Peak fire activity is observed in May and June, 41% and 23% of all forest fires, respectively.

Fires grow considerably less active in early July as a result of green biomass proliferation both under forest canopy and on logging sites. As soon as green grass amounts to half or two thirds of its maximum possible loading, the period of high spring fire hazard ends (Sofronov 1967).

Logging sites, old burned areas, and unclosed planted forest sites are the major contributors to the total area burned (Figure 22). Forest has been intensively logged since 1930s in the study area, especially large forest areas were logged in the 1970s and 1980s. In Ungut Forest District (FD), for example, sites logged between 1978 and 1998 totaled over 15,000 ha (16.6% of the FD area). Many forest sites experienced repeated (two or even three) fires during these two decades. This can be attributed to fire intensity and fuel loading accumulated since last fire. Logging area burned was equal to forest area burned in 1991, 1996, 1998, and 1999 and even greater in 1997 (Figure 23).

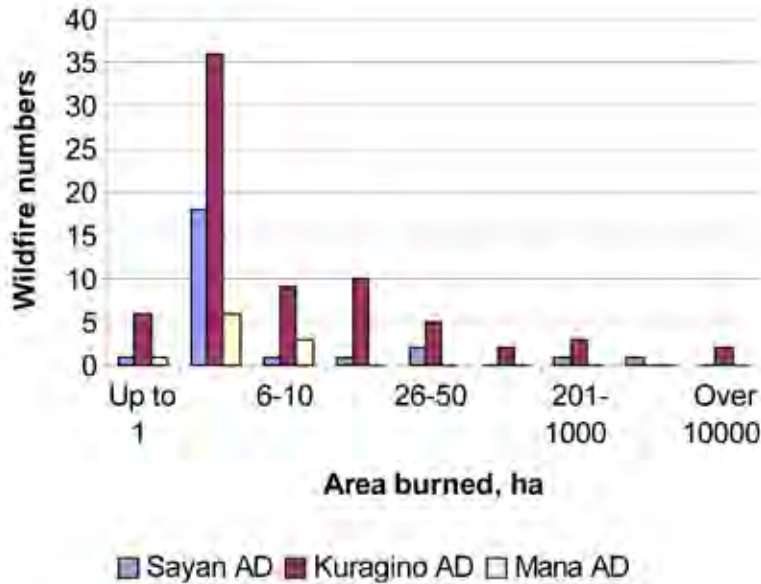


Figure 20. Occurrence of forest fires detected in forest districts protected by different local Aerial Forest Protection Service bases (*Avialesookhrana* districts)

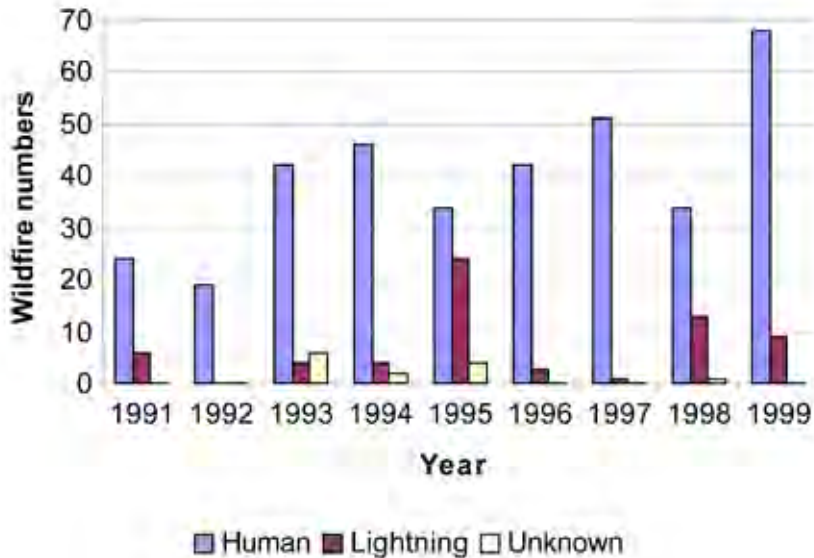


Figure 21. Causes of forest fires



Figure 22. Logging sites colonized by fireweed

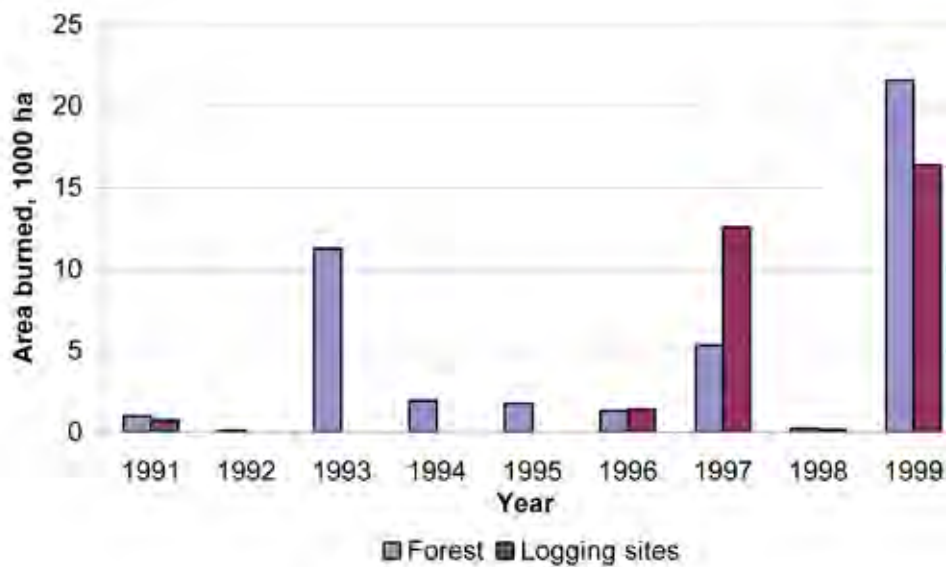


Figure 23. The forest and logging areas burned in the former Mana FMA

About 25% of conifer seedlings planted in bare soil strips die from fire, because they occur between permanent lines of big logging slash piles made by a bulldozer when building these bare soil strips. These logging slash piles burn with high intensity and, as a result, planted seedlings die from lethal temperatures.

4.2. Dark Conifer Logging Site Types in Eastern Sayan Mountains

The current condition of Siberian taiga forests is largely a result of human activity. Practically all accessible forest areas have been disturbed by logging. Therefore, in-time complete logging site afforestation by commercially valuable woody species based on an improved logging site classification became urgent. Forest logging site recovery processes were classified based on the logging site type doctrine proposed by Melekhov in the 1950s. This doctrine helps select appropriate methods of forest restoration on logging sites. Mountain forest logging site recovery processes were addressed by a number of studies (Buzykin 1964; Babintseva 1965; Pobedinsky 1965).

Forest canopy removal by logging induces drastic changes of site conditions. It immediately changes light conditions, air temperatures, and soil thermal regime. Fairly even air temperature found under forest canopy differs greatly from that of logging sites. Young conifer regeneration remained after logging experiences a strong thermal stress hampering seedling growth. Species composition of grasses colonizing mountain logging sites is controlled by topography. Xerophytic grasses, such as sedge (*Carex macroura*), forest-steppe herbs, and shrubs, such as pea shrub (*Caragana arborescens*), cotoneaster (*Cotoneaster microphyllus*), and spiraea (*Spiraea trilobata*) are more common on steep, convex, well-lit slopes than on shaded slopes. Mesophytes dominate ground vegetation cover on smooth (< 10 deg.) slopes of any aspect. Logging sites found on these slopes are characterized by changing dominant grass species abundance and composition with time since logging (Figure 24).

Most of 2-3-year-old logging sites (50%) belong to the long-leaved reed grass/tall grass site type. Herbs and sedges begin to dominate logging site ground vegetation (52%) by the time a new conifer stand canopy begins to close (more than 10 years after logging), while the long-leaved reed grass/tall grass site type decreases to 23% and the feather moss site type does not occur at this logging site age (Ivanova and Perevoznikova 1994). Reed grass (*Calamagrostis obtusata*) is the major competitor species during first several post-logging years and it hampers, due to its bunch-like root system, conifer seedling occurrence and, hence, new stand establishment.

High amounts of logging slash completely covering logging sites is one more factor that slows down conifer seedling occurrence (Figure 25). Logging slash loads resulting from winter forest logging in Ungut FD was calculated to average 50-120 t/ha, with the total fuel load

ranging 72 to 154 t/ha (Table 13). Separate fuel loads appeared to change with time since logging. Litter load was found to decrease due to rapid decomposition characteristic of this fuel component. Feather moss also showed a gradual decrease in load, in open place, since it failed to compete with grasses. Conversely, >7.5-cm-diameter woody fuel load was recorded to increase, as more dead and small-diameter trees that had been left standing fell down. This was especially true with logging sites characterized by a thin soil layer and, hence, shallow tree root systems.

Table 13. Average fuel load on logging sites of different ages by fuel component

Time since logging, years	1	2-3	4-5	6-10
Fuel component	Loading (t/ha)			
Grasses and small shrubs	0.9	2.2	3.1	2.1
Feather moss	0.4	0.3	0.1	0.1
Litter	26.8	26.4	20.5	17.6
Duff	7.5	11.8	9.9	10.0
<7-cm-diameter down woody fuels	3.2	3.3	3.2	3.1
>7-cm-diameter down woody fuels: undecomposed half decomposed	79.1	55.9	102.7	103.7
	68.9	41.4	95.1	14.3
	10.2	14.5	7.6	89.4
Total	117.9	99.9	139.5	136.6

Conifer regeneration was estimated to be poor on eastern Sayan clearcuts. Post-logging regeneration appeared to be only 50-60% of its pre-logging amount. Many young trees of big diameter were wind-thrown, particularly on >18-degree slopes. As dark conifer forests contain not less than 5% of birch and aspen, these deciduous species regeneration dominated logging sites. This domination combined with frequent fire occurrence on logging sites results in woody vegetation conversion, i.e. conifer stand replacement by low-value deciduous species and logging rotation period becomes as long as several decades.

Average logging slash loading was estimated to be 50-120 t/ha, with the total fuel load amounting to 154 t/ha, in former Mana FMA. This fuel amounts contribute greatly forest fire hazard. Fire appeared to have burned 20%-30% of the total areas of several FDs found in this FMA.

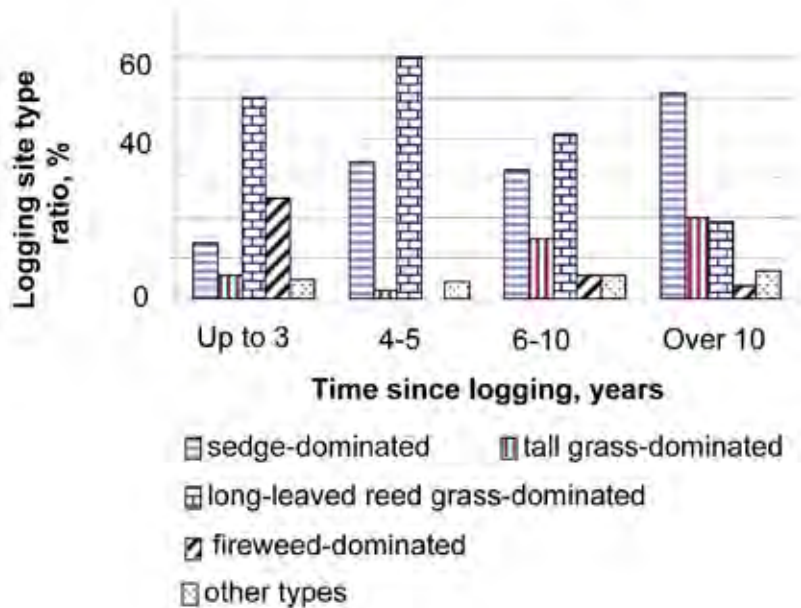


Figure 24. Logging site types in the area of interest. Note: In Russian forestry, logging site type is determined by dominant ground vegetation species.



Figure 25. A logging site on a well-sunlit slope

High fire hazard and low rate of recovery of eastern Sayan dark conifer logging sites are recognized to be a big problem. Over half Sayan mountain afforestation area needs to be restored using site-specific forest restoration methodologies.

4.3. Forest and Logging Site Descriptions

Prescribed fires were conducted on logging sites containing high logging slash amounts and unable to recover through natural conifer regeneration. These logging sites were selected in fir/herb/feather moss and fir/short grass/feather moss stands to cover a range of slopes and aspects (Table 14).

Table 14. Dark conifer stand characteristics prior to logging

Site # / year of burning	Aspect / slope (deg.)	Forest type	Woody species composition	Density of stocking	Standing crop (m ³ /ha)
1/1998	NE/13-18	Fir/feather moss/sedge stand	4F4S1SibP1A+L,B	0.6	350
1/1999	W/15	Fir/feather moss/sedge stand	5F5S+SP,L,SibP,B	0.5	320
1/2000	W/15	Fir/feather moss/sedge stand	5F5S+SP,SibP,B	0.6	350
2/2000	W/18	Fir/feather moss/sedge stand	5F5S+SP,SibP,B	0.6	350
3/2000	N/26	Fir/feather moss/reed grass stand	5F3A1SibP1SP	0.7	280
4/2000	NE/15	Fir/feather moss/reed grass stand	5F3B1SP1A+SibP	0.6	320
5/2000	E/26	Fir/sedge/herb stand	7F1SibP1B1A	0.8	300

Conifer regeneration was counted both prior to and after logging (Table 15). On most logging sites, the regeneration appeared not exceed 23% of its pre-logging amount, with an exception of one logging site where about 40% of conifer regeneration remained.

Table 15. Dark conifer regeneration characteristics prior to and after logging

Site # / year of burning	Prior to logging					On logging sites prior to prescribed burning		
	Regeneration composition	Regene- ration (amount per ha)	Average height (m)	Age (years)	Regene- ration (amount per ha)	Regeneration vigor (%)		
						Healthy	Damaged	Dead
1/1998	6F3A1S+SibP	2800	3	30	280	15	35	60
1/1999	4F4A2SibP+S, B	3200	4	35	260	25	55	20
1/2000	3F3A2SibP2B	3200	2	30	260	30	35	35
2/2000	3F3A3SibP1B	3000	4	35	490	40	50	10
3/2000	5F2A2B1SibP	4500	2	25	1920	20	72	8
4/2000	3B3A2SibP1F1S	3400	6	40	800	10	75	5
5/2000	4F2S2SibP2A	3000	4	35	270	20	60	20

Ground vegetation remained almost undisturbed on logging sites, as logging was conducted in winter and resulted in only slight soil mineralization. Logging slash was distributed non-uniformly across the sites depending on forest stand structure, tree felling and skidding methods. Post-logging fuel loading was greatly contributed by large- and small-diameter logging slash elements including additional needle litter, big tree branches, tops, and non-commercial wood accounting for the highest proportion of the total fuel (Table 16). Large-diameter logging slash and down deadwood elements made up 50-70% of fuel on the previous-winter logging sites, whereas green grasses were highly insufficient (0.5-2%) to stop spreading fire.

Table 16. Logging site fuel loads (t/ha) prior to prescribed burning

Site # / year of burning	Litter and moss	Duff	Logging slash diameter, cm			Grasses and small shrubs	Total fuel load
			0.7-2.5	2.5-7.5	> 7.5		
1/1998	24.2	18.9	0.6	1.6	55.2	1.1	101.6
1/1999	23.5	16.4	0.8	2.5	61.2	1.6	106.0
1/2000	21.4	16.2	0.6	1.8	76.0	0.4	116.4
2/2000	18.9	16.5	1.4	3.4	105.3	0.8	146.3
3/2000	25.8	6.8	1.0	4.1	112.4	1.6	151.7
4/2000	26.8	15.7	0.3	1.7	53.6	2.4	100.5
5/2000	24.8	7.5	0.6	1.7	49.6	1.1	85.3

Heat released from burning litter and moss loading of 2 kg/m^2 appeared to be sufficient to ignite large-diameter logging slash elements, burning of which contributed greatly to fire intensity. As amounts of green grasses were very low, their influence on fire behavior was ignorable.

4.4. Burning Methods

Burning method should be selected so that site-specific burning conditions, such as logging slash type, loading, structure, distribution, and the presence of no-burning places to be considered.

Logging sites found on 10-15-degree slopes were ignited mostly by either linear, or point ignition method. These methods can be combined depending on fire parameters. We applied a strip fire ignition method (i.e. a combination of line and point ignition methods) to accelerate burning procedure.

Line ignition method (Figure 26)

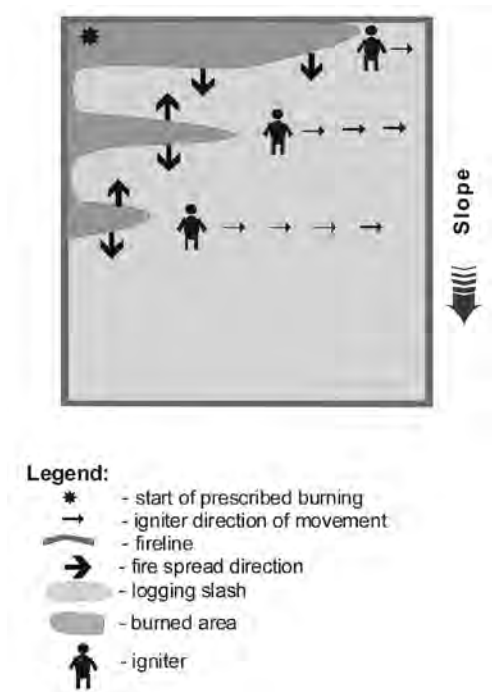


Figure 26. Strip line ignition

Fire is ignited along the upper fireline. Then igniter moves several meters downslope to extend the ignition line along one of the site flanks. Igniters try to make the ignition line straight and continuous in effort to make fire spread only down slope. This is critical for achieving complete fuel consumption and providing burning safety. This ignition method is effective to use in spring and summer, before green grasses and small shrubs amount to their maximum loads. As wind speed is only 5 m/s, wind shifts largely do not influence fire spread.

Point ignition method (Figure 27)

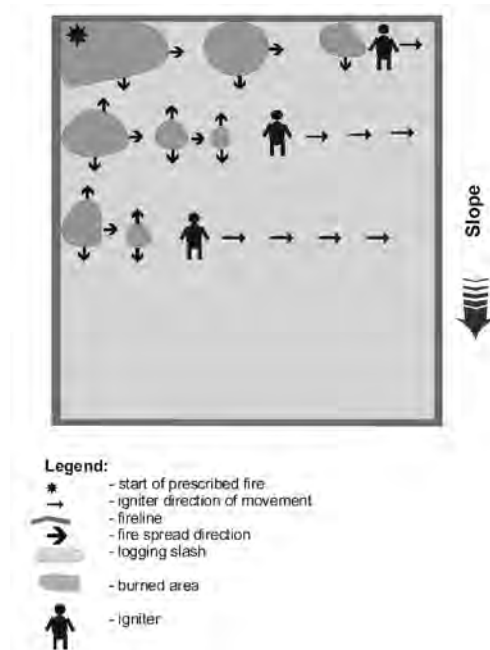


Figure 27. Strip point ignition

This ignition method is effective in a wide range of topography – from plains to mountains. With this method, not a continuous line, but separate points are ignited. First, fuels accumulated on full-tree processing sites and skidding trails, as well as large-diameter logging slash piles are ignited. This done, points selected in lower-fuel-load places are ignited to constitute a continuous ignition line. This ignition method allows to increase fire intensity and fuel consumption by fire on sites characterized by high green grass biomass amounts. Of all available ignition methods, this method proved to be the most effective under maximum development of grasses and small shrubs.

Strip fire ignition method (Figure 26 and 27)

Like with line ignition, fire is ignited along the upper side of a logging site. As soon as a strip 10-20 m wide is burned, the next line parallel to the first one is ignited, a certain distance from this strip down slope. From this line, fire begins to spread both down and upslope, its rate of spread upslope increasing drastically. As soon as the first fire line spreading down slope converges with that spreading upslope, the next line is ignited. This method allows reducing time needed to burn the logging site and control fire intensity and fuel consumption.

Similar strip fire ignition can be used with the point ignition method.

4.5. Fire Spread

Logging site fuel loading and moisture content were determined and weather conditions (air temperature, relative humidity, Nesterov drought index, and fire danger class) were analyzed prior to prescribed burning. Wind speed appeared to be a major factor influencing the prescribed burning procedure (Table 17). We prescribed burned the selected logging sites under optimal weather condition, i.e. neighboring forest stand fuel moisture content was sufficient to prevent fire spread beyond the logging sites and wind was low and did not have marked influence on fire intensity and spread rate.

Table 17. Weather conditions prior to logging site prescribed burning

Site # / year	Date of burning	NI ^{*)}	Air temperature (°C)	Relative humidity (%)	Wind direction	Wind speed (m/s)
1/1998	15.08	974	18	54	E	1-2
1/1999	06.07	767	23	48	NW	1-2
1/2000	02.08	751	18	50	W	2-3
2/2000	03.08	951	19	60	calm	–
3/2000	07.09	790	19	75	NW	1-2
4/2000	08.09	1010	22	62	N	1-2
5/2000	10.09	1410	21	68	calm	–

^{*)} Nesterov Index

Pre-burning fuel moisture content was at the next-to-fuel-ignition level, needle litter, cured grass, and fallen tree branches up to 0.7 cm in diameter being the driest fuel elements (Table 18). As duff moisture content varied from 93% to 159% among the logging sites treated, only the upper duff layer was consumed by fire.

Table 18. Fuel moisture content on logging sites at the time of prescribed burning

Site # / year of burning	Litter		Moss	Duff	Logging slash diameter (cm)			
	Needles	Cured grass			< 0.7	0.7-2.5	2.5-7.5	> 7.5
1/1998	14.5	20.6	24.2	93.3	24.5	29.1	35.3	45.6
1/1999	11.7	18.2	29.6	116.4	13.5	13.2	18.9	18.9
1/2000	21.1	19.7	-	95.7	19.3	35.7	30.6	32.1
2/2000	20.9	17.7	34.8	159.0	14.0	33.2	36.7	35.4
3/2000	38.2	24.1	-	127.9	31.1	32.8	36.6	83.3
4/2000	13.5	18.4	27.0	94.6	18.9	19.1	21.6	70.8
5/2000	15.5	17.9	-	104.0	14.3	24.6	31.0	67.3

Burning operation took from two to five hours depending mainly on logging site area and fuel loading (Table 19).

Table 19. Prescribed fire parameters

Site # / year of burning	Site characteristics		Time of burning, hr	Average fire spread rate (m/s)		Flame length (m)	
	Area (ha)	Slope (deg.)		Upslope	Down- slope	Average	Maximum
1/1998	3	15	2	1.0	0.3	1.5	3
1/1999	10	15	5	1.7	0.5	1.5	up to 5
1/2000	3	15	2.5	0.4	0.1	0.5	1.5
2/2000	3	18	2.5	0.4	0.2	1.2	2
3/2000	6	26	2	0.2	0.1	0.7	1.5
4/2000	5	15	3	0.5	0.3	0.8	2
5/2000	3.5	26	2	0.5	0.3	1	3

The monograph by Valendik et al. (2001) describes several examples of prescribed burning. Consider the 1999 prescribed burning of a logging site (Site 1) found in Ungut FD, former Mana FMA. This 10-ha logging site was located on a west-facing slope 15 degrees steep.

The site duff layer depth averaged 2.7 cm and fuels totaled 106 t/ha. These were mostly big-diameter logging slash elements, ground fuels and small-diameter logging slash elements occurring as small accumulations, where fallen tree branches were cut off, uniformly across the site. Prescribed burning was begun at 21:00 on 6 July 1999 under the following weather conditions: an air temperature of 22°C, relative humidity of 56%, northwestern surface (2 m above the ground) wind speed of 1-2 m/s, Nesterov Index of 1258, and fire danger class III. The logging site was fired by the step ignition method and broadcast burned.

The first line (1) was ignited along the upper fireline (Figure 28). The next ignition line (2) was established along a road separating the experimental site from the rest logging site. As fire front spread down slope, fire whirls were observed to occur before it and throw fire-brands beyond the site under treatment. Each igniter continued, after reaching the fireline, to ignite fuels beyond the site flank down slope to make a buffer line 10-15 m long before the main fire front could reach the site flanks.

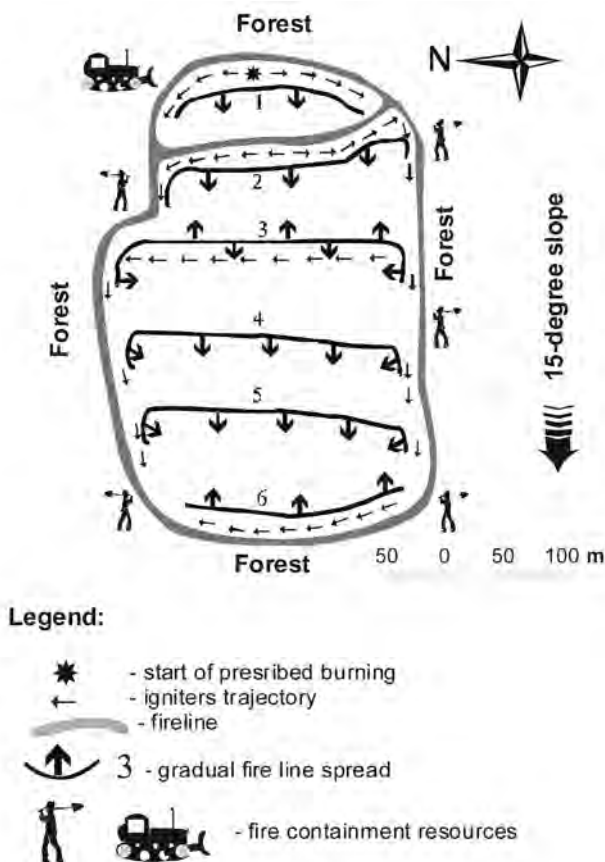


Figure 28. Prescribed burning of Site #1, 1999

After burning one third of the logging site, step ignition (3) was attempted, however, it had to be cancelled because of a high risk of fire whirl development. As soon as the main fire front had spread down slope as close as 30 m away from the lower fireline, counter fire was ignited from this line to spread upslope (6). Two spot fires were contained beyond the site during its prescribed burning. Average flame length was 1.5 m reaching 5 m in fuel accumulations. Fire spread at 0.5 m/s down slope and 1.5-2.0 m/s upslope. Flaming combustion lasted for 5 hours, while tree stumps and large-diameter logging slash elements smoldered for 4 day after prescribed burning. As much as 95% of the total logging site area was burned. Fire reduced the pre-burning duff layer depth by 1.3 cm on average. Ten fire fighters equipped with backpack pumps, shovels, axes, and a chainsaw moved along the site flanks parallel to the main fire front spreading down slope to contain the fire within the logging site boundaries. Three fire fighters equipped with backpack pumps mopped up the upper part of the logging site periodically. Five employees of the FMA suppressed fire sources using hand tools and TLP-4 tractor the next day after prescribed burning. The prescribed burned logging site was mopped up for four days.

4.6. Prescribed Burned Logging Site Characteristics

Fire consumed not more than half of fuels on each prescribed burned site. Fine carrier fuels with moisture content up to 30% burned most intensively (Figure 29a) and, as a result, their pre-fire loading was reduced by 65-70% (Table 20). Duff consumption varied from 19% to 48% depending on duff moisture content ($r = -0.87$), fire duration ($r = -0.75$) and intensity ($r = -0.81$). The depth of duff that remained intact was determined to be optimal for conifer seed germination.

Prescribed fire consumed averagely 15-25% of the total amounts of large-diameter down deadwood and logging slash. The latter usually become charred and hence non-ignitable.

Table 20. Post-burning fuel loads (t/ha) and fuel consumption (%) by prescribed fire

Site # / year of burning	Litter and mosses	Duff	Logging slash diameter (cm)			Grasses and small shrubs	Total load/total consumption
			0.7-2.5	2.5-7.5	> 7.5		
1/1998	7.3/70	7.4/61	0.2/67	1.0/38	48.1/13	0.7/36	64.7/36
1/1999	4.9/79	9.0/45	0.3/63	1.0/60	42.0/31	1.1/31	58.2/45
1/2000	7.5/65	10.8/33	0.2/68	0.6/67	68/11	0.2/50	87.3/25
2/2000	6.1/68	9.6/42	0.3/79	1.5/56	78.8/25	0.6/25	96.9/34
3/2000	19.4/25	6.1/10	0.6/40	2.9/29	107.5/4	1.3/19	137.8/9
4/2000	6.8/75	8.4/46	0.1/67	1.0/41	41/24	1.8/25	59.1/41
5/2000	5.8/77	3.0/60	0.2/68	0.8/53	37.4/25	0.8/27	48/44

Table 21. Duff consumption by prescribed fire

Site # / year of burning	Burned area (%)	Average duff layer depth (cm)		Duff consumption (%)
		Prior to burning	After burning	
1/1998	75	3.4±0.6	2.3±0.4	32
1/1999	95	2.7±0.6	1.4±0.7	48
1/2000	70	2.5±0.8	1.8±0.7	28
2/2000	90	3.1±0.7	2.2±0.8	29
3/2000	30	3.2±0.4	2.6±0.6	19
4/2000	60	2.9±0.5	1.9±0.5	35
5/2000	80	3.0±0.5	1.8±0.8	40

The amounts of fire carrier fuels consumed were largely controlled by the fuel moisture content and fire intensity (Table 22). This characteristic exhibited weak correlations ($r = 0.12 - 0.45$) with near-surface air temperature for all fuel types.

Table 22. Fuel consumption correlation with different factors

Factor	Litter	Duff	Logging slash and down deadwood diameter (cm)		
			0.7-2.5	2.5-7.5	>7.5
Fuel moisture content (%)	-0.99	-0.36	-0.67	-0.31	-0.42
Air temperature (°C)	0.45	0.22	0.26	0.21	0.12
Relative humidity (%)	-0.67	-0.38	-0.62	-0.52	-0.34

Our prescribed fires conducted on mountain dark conifer logging sites produced about 1.5 tons of ash per hectare and resulted in partial soil mineralization, the two factors promoting post-fire forest regeneration. In the first post-prescribed burning year, living ground vegetation exhibited the most pronounced structural changes. Numerous ground vegetation communities occurred due to duff depth of burn variability, the proportion of tall grasses decreasing greatly. Fireweed-dominated ground vegetation communities were observed to clearly prevail in the second post-burning year. With wildfire, post-fire ground vegetation composition depends solely on fire intensity. Fireweed dominates ground vegetation where duff was heavily burned. Otherwise, tall grass-dominated communities containing different

proportions of fireweed occur. Low-intensity wildfire usually enhances deciduous woody species regeneration by root suckers.

Grass biomass amount and moisture content are among the major logging site fire hazard controls. Grasses found in places of logging sites burned at different fire intensities, as well as those growing in the area adjacent to each logging site treated were sampled for moisture content. Grass biomass was determined by cutting grass on three replicate 1x1-m sample plots on each prescribed burned logging site. Grass samples were oven-dried to absolutely dry weight and weighted to within 0.1 g. Dynamics of green grass load by duff depth of burn is shown in Figure 30.

Unlike in the first post-fire year, ground vegetation grew strongly determined by micro-environmental conditions, which also controlled the vegetation biomass dynamics two years after burning. Ground vegetation biomass showed no dependence on depth of burn and only a small increase compared to unburned sites next year after burning. In the second post-fire year, above-ground living ground vegetation biomass was found to increase twice and 1.6 times on heavily and slightly burned sites, respectively, as compared to unburned sites.

Grass moisture content was determined to reach its maximum during the period of intensive grass growing (late May to early June) and it showed a decrease both on the burned and unburned logging site parts, with a considerably smaller decrease in burned than unburned sites, by midsummer. Grass growing on heavily burned sites was calculated to contain 14.6% less moisture in May two years after burning (Figure 31). In summer, the difference in grass moisture content was found to range 5% to 7% between the first and second post-burning years, which difference falls within the average statistical error. This might be attributed to the fact that ground vegetation structure and species composition remained practically unchanged.

Prescribed burning of mountain dark conifer logging sites conducted in the second half of summer reduced logging slash amount by about 50%, ground vegetation projective cover and biomass by 30-40% and 1.5 times, respectively, and considerably increased living ground vegetation moisture content as compared to unburned logging sites. Prescribed burning also proved to be useful here from a fire science viewpoint, since it resulted in marked reduction of logging site fire hazard and practically did not reduce diversity of grass communities as could be seen from a fairly high (0.65) coefficient of floristic composition similarity with unburned logging sites. Regarding forest uses, prescribed logging slash burning promoted fireweed on the sites treated, which grass species is known not to hamper post-fire conifer forest regeneration. Also, it was also concluded that prescribed burned logging sites did not need additional soil preparation for conifer species sowing or planting.



(a)



(b)

Figure 29. (a) Prescribed burning of logging site; (b) Logging site after prescribed burning

5. Prescribed Burning of Scots Pine Forest Logging Sites in the Lower Angara Region

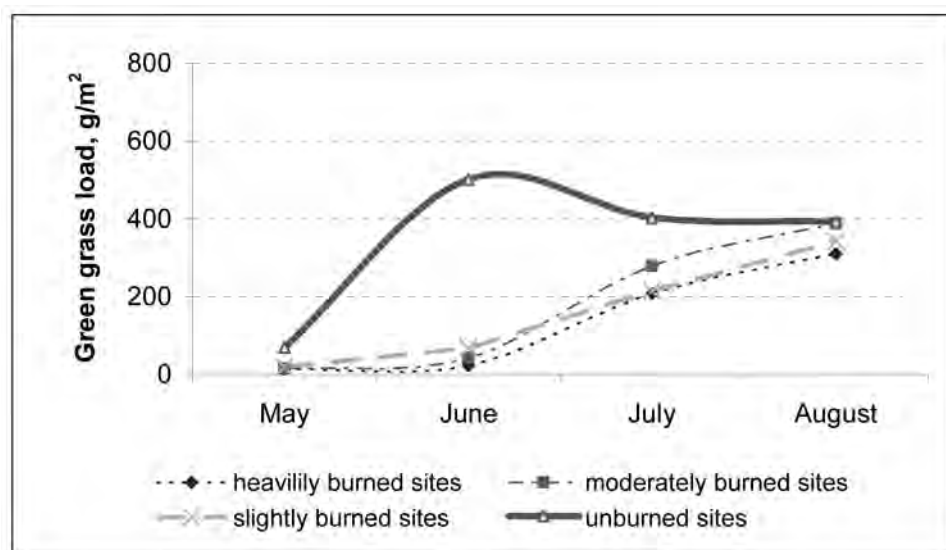
Angara region is the major forest harvesting zone of Krasnoyarsk Region. The forest area is dominated by mainly Scots pine and fires occur mostly on logging sites in this zone. The total logging area of Angara region increases annually by about 30,000 ha. Light conifer logging site fuels become readily ignitable only two or three days earlier than under forest canopy. Therefore, fire spreading from logging sites to surrounding forest is a common situation in this region. Furthermore, living ground vegetation present on logging sites fails to reduce fire intensity and rate of spread. As a result, the risk of high-intensity fire occurrence remains high throughout the snow-free period of time.

5.1. Environmental Characteristics of the Lower Angara Region

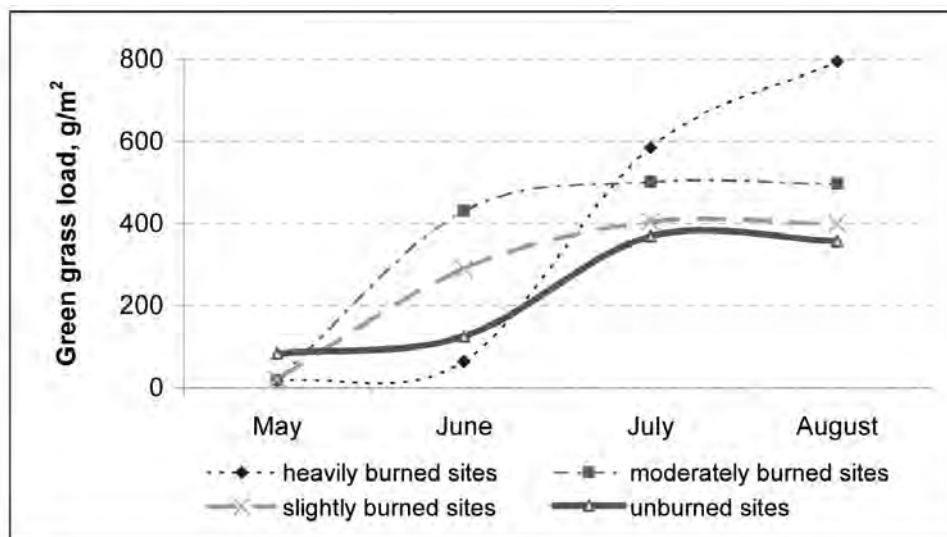
Lower Angara region is characterized by wide diversity of site conditions and, hence, highly diverse vegetation patterns. This is where the southern taiga subzone encompassing the Trans-Angara area, Angara Lowland, and Chuna-Birusa Tableland borders subtaiga, or subzone of forest with grass-dominated ground vegetation, that is found in the northern edge of Kan-Usol Hollow (Lubimova and Khotinsky 1960).

Regarding topography Lower Angara region is an even tableland, low mountains alternating with inter-mountain depressions. This entire area is slightly elevated and elevation has marked influence on climate, which shapes, in turn, the regional vegetation cover (Korzhujev 1975).

The region is under extremely continental climate with summer much less warm than in southern taiga landscapes in average. The above-zero and especially high air temperature periods are shorter here, because of great cooling of the air in winter. Very much solar and advective heat is needed to heat severely cooled continental landmass (Krauklis 1975). This results in that air temperature begins to exceed zero point and, hence, summer sets on later.

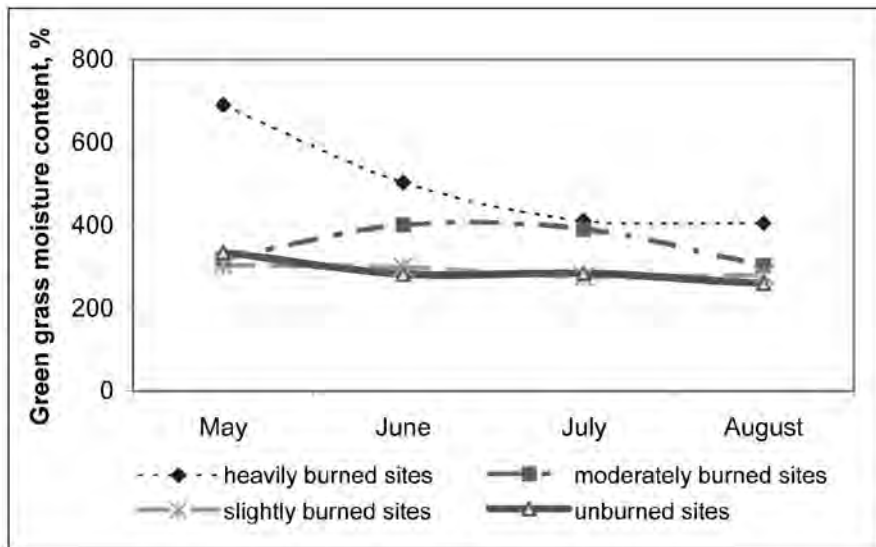


(a) First post-prescribed burning year

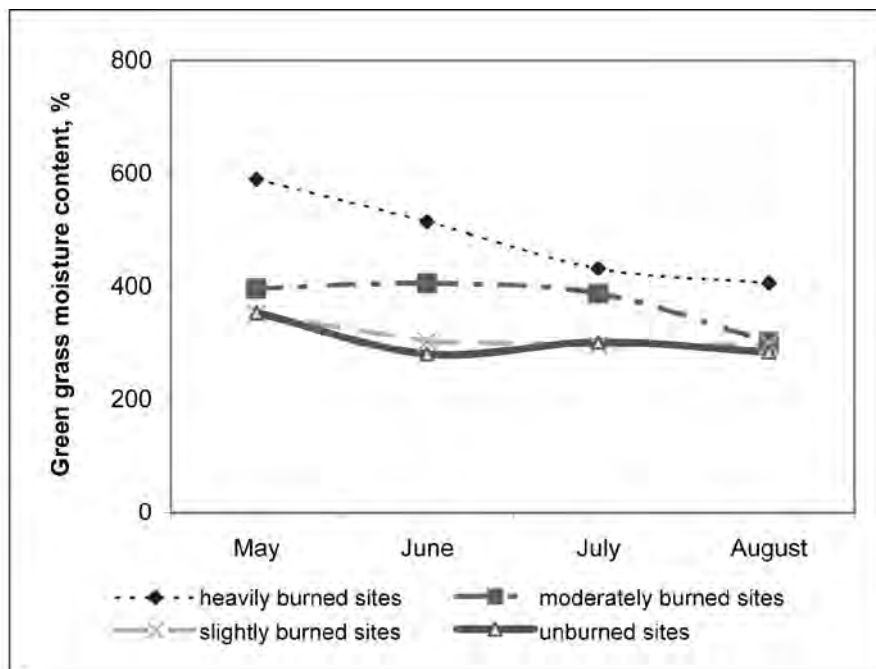


(b) Second post-prescribed burning year

Figure 30. Dynamics of green grass loads by duff depth of burn vs. unburned sites. Fuel load values are in g/m² oven-dry weight.



(a) First post-prescribed burning year



(b) Second post-prescribed burning year

Figure 31. Living grass moisture content by depth of burn

The frost-free period can be as long as 78-99 days. The regional air temperature (mean July temperature is 17-18°C) is not lower and even slightly higher in general than in other southern taiga regions (Krauklis 1975). Average annual air temperature is about -3°C, a minimum and maximum of -58°C and 35°C, respectively.

Average annual precipitation is fairly low in central Angara region (300-360 mm in plains and 400-450 mm in mountains), because the region is found in the interior Russia. Angara regional precipitation is lower than in other regions. Spring and fall are usually dry seasons accounting for 10-11% of the annual precipitation norm, while 53-57% (166-171 mm) occurs in summer.

Vegetation cover of Trans-Angara area and Angara Lowland is represented mainly by light coniferous forests (50-60%), whereas dark conifers account only 10-15% of the total forest land (Pobedinsky 1965). Scots pine forest is mostly found on south-facing slopes covered by light loams and loamy sand. The regional ecosystem diversity is low; only two forest type groups, Scots pine/feather moss and Scots pine/lichen groups, were identified by Falaleyev (1956) (Figure 32). Scots pine/feather moss group consists of three forest types (Scots pine/red whortleberry/feather moss, Scots pine/blueberry/feather moss, and Scots pine/herb/feather moss types) and the latter forest type group includes Scots pine/lichen/red whortleberry and Scots pine/stone/lichen types. Conifers account for 4/5 of the total Angara southern taiga forest land, Scots pine-dominated stands making up 37%. The rest forest area is shared by larch (18%), Siberian pine (13%), spruce/fir (11%), and deciduous (21%) stands.

Scots pine standing crop ranges 60-100 to 500-600 m³/ha. Scots pine/herb/red whortleberry, Scots pine/red whortleberry/herb, and Scots pine/feather moss forest type groups accounting for 70-90% of all Scots pine forest and represented mainly by mature and over-mature stands are of the highest commercial value in Angara region. Young and middle-aged Scots pine stands have increased in area, while the proportion of mature and overmature stands has decreased due to intensive forest use. Scots pine occupies 41% of the total forested land. Scots pine commercial importance has decreased in the south of the subzone as a result of increasing dark conifer area. Larch stand contribution to the forest cover increases proceeding to the northeastern part of the region. Human activity has lead to an increase in deciduous woody species proportion in the forest cover.

5.2. Logging Sites

Wood is extracted mainly in Scots pine/herb/red whortleberry, Scots pine/red whortleberry/herb, and Scots pine/feather moss stands of the Angara forest harvesting zone. Tree cutting and skidding result in an increase in ground vegetation area, and this change influences,

in turn, climate and soil. Scots pine/herb and Scots pine/red whortleberry/herb stands are converted into bush grass- and herb-dominated logging sites. Scots pine/red whortleberry/herb stands are replaced, depending on slope aspect and time since logging, by logging sites with herb-dominated or fireweed/reed grass/herb ground vegetation. Big amounts of conifer tree branches, tops, and fallen deciduous tree parts are left on forest sites subject to logging (Figure 33). This logging slash contributes greatly to site fire hazard in spring and summer; it constitutes, in combination with cured grass, a readily ignitable loosely packed fuel layer. At present, a number of methods are used in Russia's forestry to clear out logging slash, such as heaping logging slash and then burning it during fire-free period, leaving it in heaps to decompose with time, collecting, chopping, and dispersing logging slash over a logging site. All these methods are extremely labor-taking and require special equipment.

Logging site broadcast burning is the least expensive and most effective alternative to the above method. Until recently, forest prescribed burning was prohibited in Russia (Valendik et al. 2000). Applying prescribed logging site broadcast burning requires to develop scientifically justified regulations that would prescribe weather, fuel, economic conditions, and fire parameters providing the most effective achievement of certain forest management objectives.

Prescribed fires were conducted on three light conifer clearcuts (7 to 15 ha each) in the former Usol FMA, Krasnoyarsk Region. This effort allowed us to determine certain combustion characteristics. Our investigation used methods to estimate forest regeneration (Pobedinsky 1965), forest fuel loading (Kurbatsky 1970), determine forest fire and meteorological parameters. Logging blocks¹ accounted up to 90% of the total logging site area, 8-10% were skidding trails and their close vicinities, and loading area occupied up to 2% of the total logging site area. Our analysis revealed that fuel loading varied from 65 to 80 t/ha across the logging site (Table 23), except for loading area. Although near-skidding trail zones were not big in area, fuel accumulation was measured to exceed 100 t/ha in some of them. The presence of these heavily fueled zones complicates forest fire suppression and containment.

Table 23. Fuel loading (t/ha) in different logging site sections

Logging site section	Duff	Living ground vegetation	Litter	Logging slash			Total fuel load
				Diameter (cm)			
				0.7-2.5	2.5-7.5	> 7.5	
Logging block	14.5	1.3	6.6	3	8.5	31.2	65.1
Skidding trail vicinity	9.6	0	30.7	11	17.6	48.3	117.2

¹ A logging site block is a strip of forest being logged located between two skidding trails



Figure 32. A Scots pine/feather moss stand in Angara region. Photo: V.V. Ivanov



Figure 33. Logging slash on a logging site. Photo: V.V. Ivanov

Since logging slash contributed 2/3 to the total fuel loading, fire intensity was high. Logging slash amounts this high complicate wildfire control and increase its cost. Duff load appeared to be 1.5 times less on and near skidding trails than in logging blocks. This might be attributed to partial fuel removal due to skidding operations. However, the loading of needles and small tree branches (up to 7 cm in diameter) accumulated on and along skidding trails was almost 5 times that in logging blocks. High fire carrier fuel loads are responsible for generally high fire hazard of this area. The burning methodologies described earlier in the text were used to reduce forest fuel loading.

5.3. Scots Pine Logging Site Prescribed Burning Methodologies

Logging sites with relatively uniform logging slash distribution were broadcast burned, while step-by-step burning methodology was used where most large-diameter logging slash elements were heaped. A bulldozer was used to construct firelines. Logging sites were burned (Figure 34) within the following burning prescriptions: fire danger class III, an air temperature of 20-25°C, relative humidity ranging 30 to 40%, and a wind speed of up to 2 m/s. The level of fire spread control and, hence, human resources needs depended on flame length (Table 24), weather conditions, fuel type, loading, and moisture content.

Table 24. Prescribed fire parameters

Logging site section	Flame length, m	Frontal rate of spread, m/min	Flaming zone width, m
Logging block	0.2	0.13	0.35
Along skidding trails	0.6	0.25	0.50

5.4. Prescribed Fire Spread and Effects

The goal of our prescribed burning efforts was to reduce logging slash and fire carrier fuel amounts on logging sites (Figure 35). Prescribed fire was found to consume 44% and 48% of fuels in logging blocks and along skidding trails, respectively (Table 25).

Fire burned across about 90% of the total logging area and consumed 60% of <2.5-cm-diameter and 26-46% of moderate- and large-diameter logging slash elements.



Figure 34. Prescribed burning of a light conifer logging site with ground vegetation of feather moss and herbs

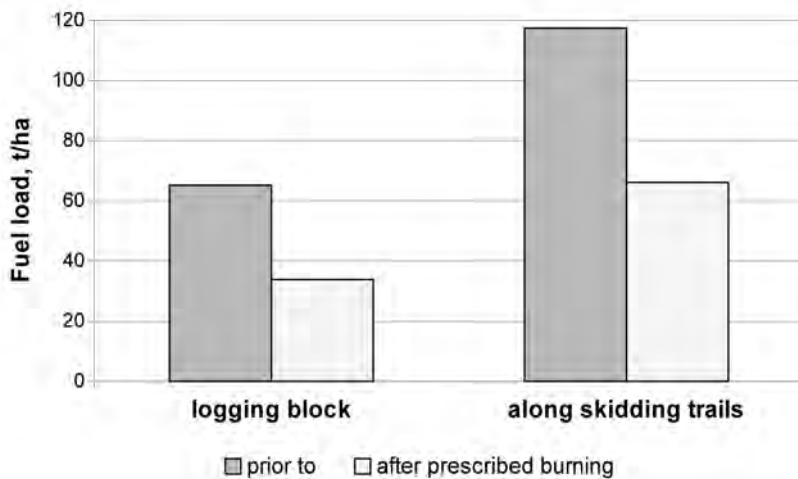


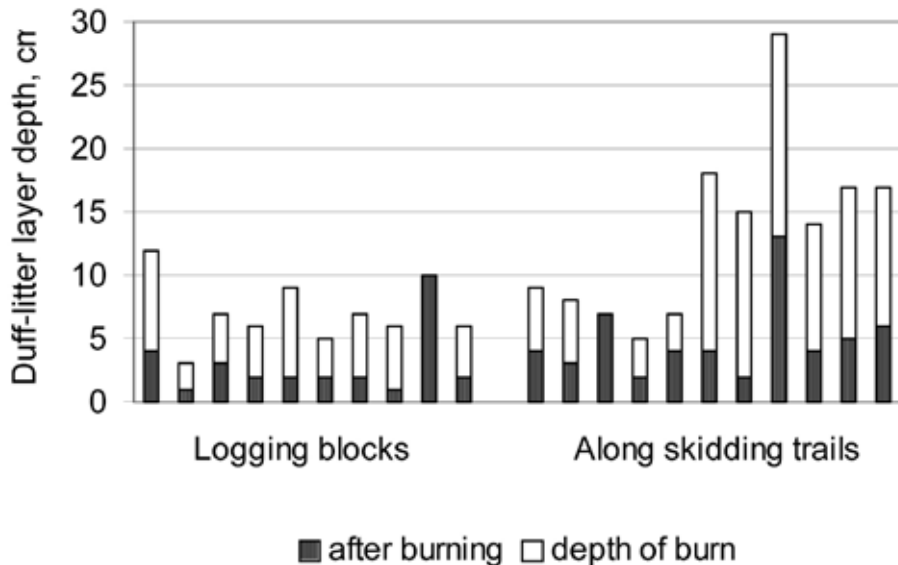
Figure 35. Fuel loads on logged sites before and after prescribed burn

Table 25. Logging slash consumption by prescribed fire

Logging site section	Logging slash consumption (%)			Total consumption (%)
	Diameter size class (cm)			
	0.7-2.5	2.5-7.5	> 7.5	
Logging block	63	46	39	42
Along skidding trails	85	33	26	36

Post-burning fuel loading was found to be at the lowest level sufficient for fire spread (200-300 g/m²). This indicates that prescribed burning allowed us to reduce logging site fire hazard.

Thick duff and litter layers are known to hamper conifer seed germination and planted seedling establishment. Only a duff-litter layer less than 3 cm in depth is optimal for forest regeneration (Sannikov 1978; Melekhov 1983; Mätkonen and Levula 1996). Our investigation showed that the depth of the combined layer of duff and litter ranged 4-12 and 5-29 cm along skidding trails and in logging blocks, respectively, of light conifer clearcut sites. About 60% of this combined layer was consumed by prescribed fire (Figure 36). Post-prescribed burning sites ready for forest restoration (with a duff-litter layer depth of up to 3cm) made up 80% of the total logging block area and about 40% of the area along skidding trails.

**Figure 36.** Depth of the combined duff and litter layer prior to and after prescribed burning

Fuel consumption by fire and feasibility of fire spread control depend on fire intensity, which is in turn determined by weather conditions and burning methodology.

Every logging site type has certain specific characteristics. For example, light conifer, especially park-like and containing a minor component of deciduous woody species, stands with feather moss in ground vegetation cover exhibit high fire hazard only in spring. Forest logging-induced conversion of ground vegetation dominant species begins as late as two or three years following logging. Prescribed burning of logging sites of this type in summer, although it takes much labor, is highly doubtful as to its effectiveness, since the presence of prolific green grass reduces fire intensity and, hence, fuel consumption. For this reason, these logging sites should be prescribed burned only at a high fire danger class.

Unlike in Scots pine/feather moss stands, recently logged sites found in Scots pine/lichen stands usually supported by dry sandy soils can be successfully prescribed burned at a Nesterov Index of as low as 300, i.e. even at fire danger class I. These fresh logging sites contain little loads of fuels hampering fire spread. This allows to burn them at low fire danger classes II or III. Even a low-intensity prescribed fire results in an acceptable logging slash and duff consumption level.

The results of our studies were based upon in developing prescribed burning recommendations. Light conifer logging sites, for example, can be most effectively burned by igniting numerous points within a project area. Ignition lines and points should be spaced 5-10 m (which distance is less than for dark conifer logging site) and up to 5 m, respectively. A combination of linear and point ignition yields the best results.

Light conifer woody species are more adapted to fire and regenerate on prescribed burned logging sites more actively than dark conifers, because they are less demanding regarding site conditions and usually suffer only from insufficient sunlight. Therefore, planning and conduction of light conifer logging site prescribed burning should consider the most probable logging site type that will occur after prescribed burning, since this type controls the amount of sunlight that will be received by post-burning young light conifer regeneration.

The above characteristics were considered when developing optimal weather recommendations for prescribed burning of Scots pine logging sites of Lower Angara region (Table 26).

Our investigations lead us to preliminary conclude that prescribed burning is an acceptable, money-saving, and effective method to clear Scots pine logging sites from logging slash in Angara region. This method enabled to reduce logging site fire hazard and promote growth of fireweed, which plant does not hamper post-fire light conifer regeneration.

Table 26. Burning prescriptions for the Lower Angara Scots pine forest

Fire season part	Logging site type	Fire danger class	Nesterov Index	Relative humidity (%)	Wind speed (m/s)
20 May – 10 June	Feather moss/ herb	III	900-1800	< 60	< 3
	Red whortleberry/herb	II - III	900-1800		< 2
10 June – 10 July	Red whortleberry/ feather moss	III - IV	900-3000	< 40	< 3
	Red whortleberry/herb	II - III	600-1800		< 3
10-30 July – 10 August	Feather moss	III - IV	1100-4000	< 30	< 5
	Lichen	II - III	600-2000		< 4
10-30 August – 10 September	Feather moss	III - IV	1100-4000	< 30	< 5
	Lichen	II - III	600-3000		< 4

6. Prescribed Burning of Dark Conifer Forest Areas Defoliated by Siberian Moth

About 13 million hectares of conifer forest found between the Ural Mountains and the Pacific Ocean have died from Siberian moth (*Dendrolimus superans sibiricus* Tschetw.) outbreaks over the past 100 years (Kulikov 1971). Siberian moth severely damaged not only mature mixed stands of spruce (*Picea obovata* Ledeb.), fir (*Abies sibirica* Ledeb.), and Siberian pine (*Pinus sibirica* Du Tour), but also the species young regeneration in southern taiga. Siberian larch (*Larix sibirica* Ledeb.) stands found in the northern parts of this area also exhibit high Siberian moth-caused mortality. Ideally, establishment of new forest stands of species compositions similar to pre-Siberian moth will take 150-200 years.

Siberian moth outbreaks resulting in high dark conifer forest mortality occurred in 1909, 1914-1917, 1920-1924, and 1942-1946 (Furyaev 1966), the most catastrophic outbreak that resulted in forest dieback across huge areas recorded in 1952-1956. Once defoliated, conifer trees grow weakened and are infested by xylophagous insects destroying wood. As dead standing trees (snags) lose their steadiness, it is dangerous to cut them.

For this reason, the USSR Ministry of Forestry recommended not to control wildfires occurring in these damaged forests and, additionally, conduct prescribed fires. The burning methodology was simple and involved ignition of fire, which was then let burn freely across a died forest area. The first prescribed fire usually consumed down trees and standing snags. Forest fuels accumulation increased 3-4 years following prescribed fire due to contributions by grass vegetation and falling down of trees slightly burned by prescribed fire and, as a result, the treated area experienced repeated wildfires (Furyaev 1966). Bee-keepers benefited greatly from these fires, because fireweed, the major honey plant species, colonizes burned sites and proliferates there for 4-5 years following fire. These areas were repeatedly prescribed burned during 20-30 years to result in effective clearing of the areas from dead forest and promotion of deciduous forest stand establishment. Developing methods that would enhance conifer species regeneration on Siberian moth sites is the main scientific challenge for foresters.

6.1. Siberian Moth Site Fire Hazard

Pest-damaged forest stands become readily ignitable and loose productivity (McRae 1986). Tree defoliation results in increasing amount of sunlight reaching soil surface and promoting certain grass species. In completely dead stands, living grass loading is twice to 2.5 times in partially damaged stands. This increase is mainly contributed by tall grasses. As one year is insufficient for full decomposition of these grasses, they accumulate and create an up to 20-cm deep litter layer. Cured grass is the most fire hazardous of all forest fuels. Its heavy loading results in that forest sites damaged by Siberian moth become easily ignitable at a fire danger class as low as II. Forest fuels are continuously added by falling small and big tree branches, as well as standing snags on these sites. Therefore, fires can occur here throughout a fire season (Furyaev 1966; Stocks 1987).

Maximum forest fuel buildup (including both fire carrying and retarding fuels) was observed in completely dead stands (Table 27). Standing wood volume was estimated to be 200-220 m³/ha in a stand prior to Siberian moth outbreak, and post-outbreak standing snag wood volume appeared to range 150-180 m³/ha. This can be attributed to the fact that fallen snags contributed to ground forest fuel loading. These amounts of fuels are sufficient to support high-intensity fires, which are very hard to control even using heavy machinery. As a result, these fires spread freely into surrounding stands.

Table 27. Fuel loads in forest stands damaged by Siberian moth to different levels

Level of stand damage (%)	Standing snag wood volume (m³/ha)	Duff (t/ha)	Mosses (t/ha)	Grasses and small shrubs (t/ha)	Dead fuel load (t/ha)				Total ground fuel load (t/ha)
					Diameter (cm)				
					< 0.7	0.7–2.5	2.5–7.5	>7.5	
0	0	3.4	3.6	0.5	2.2	2.4	6.5	28.7	47.3
0-25	30	3.5	2.9	0.6	2.8	3.1	8.2	35.4	56.5
25-50	80	4.2	3.2	0.8	4.3	3.8	11.3	39.2	66.8
50-75	120	4.8	3.1	1.0	5.8	6.0	12.6	40.6	73.9
75-100	170	6	3.1	1	6.6	7.3	14.1	46.8	84.9

Fire activity has increased drastically in the former Usolye FMA, due to the presence of Siberian moth-damaged stands, since 1999. The pre-Siberian moth outbreak ground fuel load appeared to have been highly contributed by needle litter, fallen small-diameter tree branches, cured grass, and fallen snags over five post-outbreak years. Average annual area burned increased 27 times (from 150 ha in the previous five years to 5000 ha during the first five year following the Siberian moth outbreak), although number of fires increased only 1.7 times (Valendik et al. 2004) (Table 28).

Table 28. Fire numbers and area burned in the former Usolye FMA prior to and after a Siberian moth (*Dendrolimus superans sibiricus* Tschetw.) outbreak

Period of time	Average annual number of fires	Average annual area burned (ha)
Prior to the outbreak (1995-1998)	23.5	174
After the outbreak (1999-2003)	40.8	4778

Forest fire hazard reduction and regeneration depend largely on standing snag removal and reduction of high ground fuel accumulations. Siberian moth forest site clearing by wildfire would seem to be the best way to solve this problem. That is not that simple, however. As wildfires occur randomly, they cannot be used to achieve forest management objectives. Our observations showed that wildfire often does not kill but only char standing snags under non-extreme burning weather.

Vigorous growth of tall grasses, the main contributors to soil sodding, is the major factor hampering conifer forest regeneration. It is hard for natural conifer regeneration to develop on soil full of tall grass bunch-like roots. Forest restoration by seedling planting is also impossible here because of the presence of high amounts of down deadwood and standing snags, cutting of which is economically and technically infeasible.

6.2. Study Area

Dark conifer forest is not as widely spread as Scots pine in the Low Angara region. This forest usually represented by fir stands is found on moist and wet sites (Figure 37a). Fir stands are of uneven age and contain several co-dominants in the overstory. Mixed birch/fir and spruce/fir stands with ground vegetation dominated by *Carex macroura*, which species contributes considerably to soil sodding in mature and old stands, are common. These stands are usually supported by soddy-podzolic soils podzolized to different levels. These fir stands, even where they have not been disturbed by fire or forest harvesting, contain permanent minor components of spruce, Siberian pine, birch, aspen, and Scots pine or larch someplace. The stands are dominated by fir trees of age classes VI and VII and their standing wood volume ranges 150 to 300 m³/ha. The subcanopy shrubs are sparsely distributed and represented by single individuals of *Daphne mezereum*, *Sorbus sibirica*, *Rosa acicularis*, and *Sorbaria sorbifolia*.

The feather moss layer is well-developed in stands approaching maturity. Mosses usually occur as pockets confound to large-diameter down deadwood elements.

They cover 20-90% of the total site area and are dominated by *Hylocomium splendens* with minor components, depending on nano- and microrelief characteristics, of *Rhytidadelphus triquetrus*, *Ptilium crista castrensis*, *Pleurozium schreberi*, *Dicranum scorapium*, *Mnium cuspidatum*. Mixed fir/larch stands with sedges and herbs in the ground vegetation are characterized by high (up to 500 m³/ha) productivity. Unlike in other forest types, ground vegetation of these stands contains a considerable group of species typical for light conifer stands with herd-dominated ground vegetation (Lashchinsky 1969). Fire occurs only at high fire danger classes in these stands.

The mid-1990s Siberian moth outbreak resulted in damaging about 480 thousand hectares of dark conifer forest in the Angara-Yenisei region (Grodnitsky et al. 2001), thereof 50,000 ha (50-75%) was heavily damaged forest and the completely dead forest area was 240,000 ha. In the former Usolye FMA, for example, Siberian moth area amounted to 170 thousand hectares of forest, which was over 22% of the total FMA, with 70 ha characterized by 75% tree mortality (Bulletin 1996). Xylophag invasion that followed resulted in duplication of the disturbed forest area (Grodnitsky et al. 2001).

6.3. Fuel Loading in Siberian Moth Stands

A fuel load sample plot was laid out in a Siberian moth site found in a fir/horsetail/big herb stand. The stand contained 10% of birch and few individuals of spruce and Siberian pine. The fir stand was 20 m high with an average tree diameter of 16 cm and 0.9 relative density of stocking. Standing snag wood and down deadwood volumes were estimated to be 130-180 and 40-60 m³/ha, respectively (Table 29).

Ground fuel (litter, duff, grasses, small shrubs, and downed deadwood) loading structure, and occurrence across the plot and in the surrounding area were determined prior to and after downing of standing snags. Ground fuel loading was sampled along the 15-m sides of an equilateral triangle subplot established within the fuel sample plot (McRae et al. 1979). A metal pin was placed at each triangle top to recognize the triangle during post-burning ground fuel inventory. Down deadwood and cut standing snag load was determined by the line intersect method (Van Wagner 1968; McRae 1979; McRae et al. 1979; Brown et al. 1981). All down fuels found along the triangle sides were classified by diameter size (<0.7 cm, 0.7-2.5 cm, 2.5-7.5 cm). State of wood was recorded for large-diameter elements. Down deadwood loading was estimated by existing methods (Brown 1974). No conifer regeneration was observed under the stand canopy. Tree crown fuel load was not measured.

To sample litter and duff, twelve 20x25 cm sample plots were laid out. Four plots were established on each triangle side, 1 m beyond and 1 m into the triangle subplot, at the right angle to the triangle side and at distances of 5 m and 10 m from the triangle tops. Feather

moss was sampled for loading using the same methodology. Grass loading was sampled on 50x50 cm plots laid out next to the feather moss and litter sample plots (Valendik et al. 2000, 2001). Fuel depth of burn was measured with the help of depth of burn pins placed one at each triangle top and near each fuel load sampling plot. Fuel loads determined prior to and after downing standing snags in the Siberian moth-damaged fir stand of interest are given in Table 29.

Table 29. Fuel loads in a Siberian moth fire stand prior to and after downing of standing snags

Site condition	Standing snag volume (m³/ha)	Duff (t/ha)	Mosses (t/ha)	Grasses and small shrubs (t/ha)	Down deadwood (t/ha)				Total ground fuel loading (t/ha)
					Diameter (cm)				
					< 0.7	0.7–2.5	2.5–7.5	>7.5	
Prior to downing	180	6	3.1	1	6.6	7.3	14.1	46.8	84.9
After downing	70	6.1	3.2	1.1	8.2	14.2	23.5	96	152.3

Vigorous growth of raspberry and well-developed mountain ash-dominated under-story vegetation with minor components of elder, spiraea (*Spiraea*), and red currant (*Ribes rubrum*) were observed where 75% of trees died. The litter layer depth averaged 5–10 cm and duff was 5 cm deep. A 40 cm deep ground vegetation layer was dominated by sedge and bush grass with minor components of vetch, fireweed, horsetail, and fleawort.

Down woody fuel diameter size distribution prior to and after standing snag falling down is shown in Figure 38. As is clear from this figure, down tree stems accounted for the most part of the total fuel loading.



Figure 37. (a) A fir/herb/feather moss stand; (b) a fir stand damaged by Siberian moth

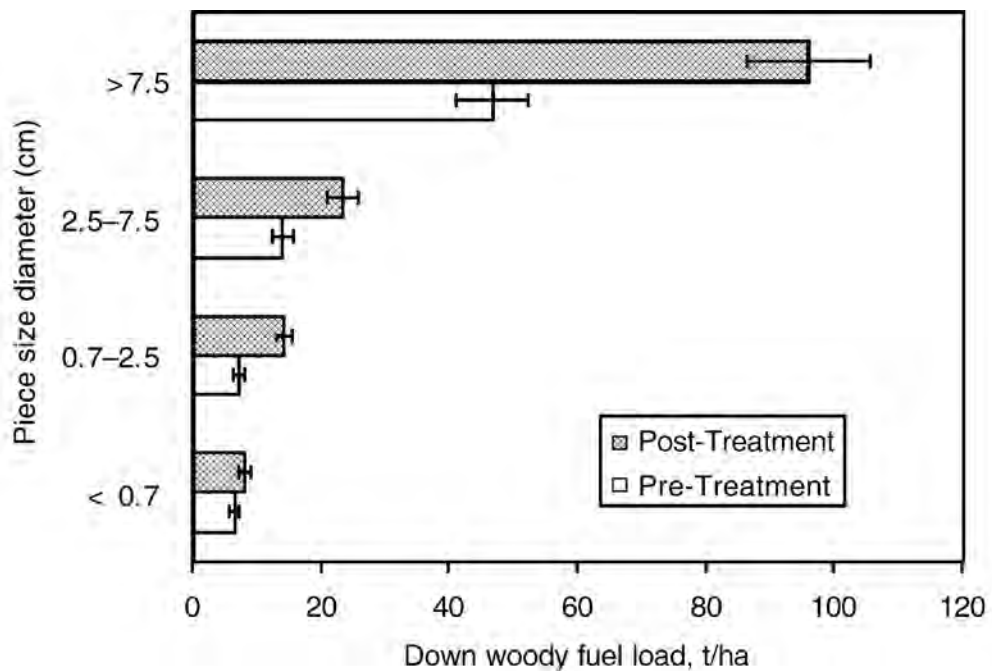


Figure 38. Down deadwood loading in a Siberian moth site

6.4. Preburning Activities

A 200x300 m site found at the periphery of a forest stand damaged by Siberian moth was prepared in late August – early September of 2001 for prescribed burning. Firelines were built using a bulldozer with a 3 m wide blade (Figure 39) designed by Institute of Fire Protection and Forestry Mechanization, Krasnoyarsk, Russia (Kharinsky et al. 1991).

The 300 m long southern side of the project site was adjacent to a road 10 m wide. The western and eastern sides, each 200 m long, and the 300 m northern side were delimited by a 6 m wide fireline. Standing snags were fallen down in strips 15-20 m apart by the dozer shuttling across the project site. During this operation, a part of standing snags fell down ahead of the bulldozer, while the other part fell to the sides onto the dead trees that remained standing to result in increasing down deadwood fuel load by 50-60% and that of >7.5-cm diameter fuels by 83%. All trees found within a 20-30 m strip along the fireline were fallen down to prevent their falling during prescribed burning operations and prescribed fire spreading over their crowns beyond the project site. Firelines were also constructed at 50, 100, and 150 m distances on the downwind side to prevent spot fire creation by firebrands

transfer beyond the site by prescribed fire convection column. Standing snag downing and construction of a fireline around the project site were accomplished in late August – early September, as ground is sufficiently hard in this period of time to support APL-55 dozer weighting 30 tons. The remaining standing snags were partially wind thrown in fall and winter to contribute additionally to the site down deadwood loading.

6.5. Prescribed Burning Methodology

Any prescribed burning methodology involves measures (an appropriate firing pattern and mop-up operations) to prevent prescribed fire spread beyond a project area. The site prepared was prescribed burned on 20 July 2002 at 18°C air temperature, 40% relative humidity, and northeastern surface wind of 2.0-0.2 m/s. Nesterov drought index was 1900 indicating high (Class IV) fire danger. The site was ignited at 20:00.

The firing scheme was selected so that fire safety be ensured. The igniters moved from the initial ignition point, at the northeastern corner of the site, along the site northern side making a continuous ignition line using drip torches. The eastern side was then ignited. As soon as the fire front had spread 20-30 m from the firelines, the site was ignited in its center. As the fire spread further toward the western and southern sides of the site, these sides were also ignited. Fire intensity increased gradually to result in a convection column occurrence over the site center. High-intensity flames up to 5 m long (Figure 40) obtained in the site center burned standing snags and a strong indraft to the center of the site produced by these flames reduced the probability of spotting beyond the project site. Surface wind of 4 m/s made the convection column to tilt 40-50 degrees and it transferred firebrands to start spot fires as far as up to 500 m southwest of the project site. Controlling the spot fires required additional efforts.

6.6. Fuel Loads Following Prescribed Burning

We measured fuel loading prior to and after prescribed burning to determine the amount burned. The depth of the fuel layer consumed by fire was found using depth of burn pins. Post-fire fuel samples were oven-dried to calculate fuel loading.

A wildfire occurred near the project site at fire danger class III and Nesterov Index of 1500 in May 2002. The above methodology was used to obtain the post-wildfire fuel load values. The low standing snag consumption by the wildfire might be attributable to high wood moisture content. Wood layer-by-layer analysis revealed that wood moisture content



Figure 39. APL-55 forest fire fighting bulldozer



Figure 40. High-intensity prescribed burn of a Siberian moth site

differed considerably between standing and down trees and increased towards wood pith (Figure 41).

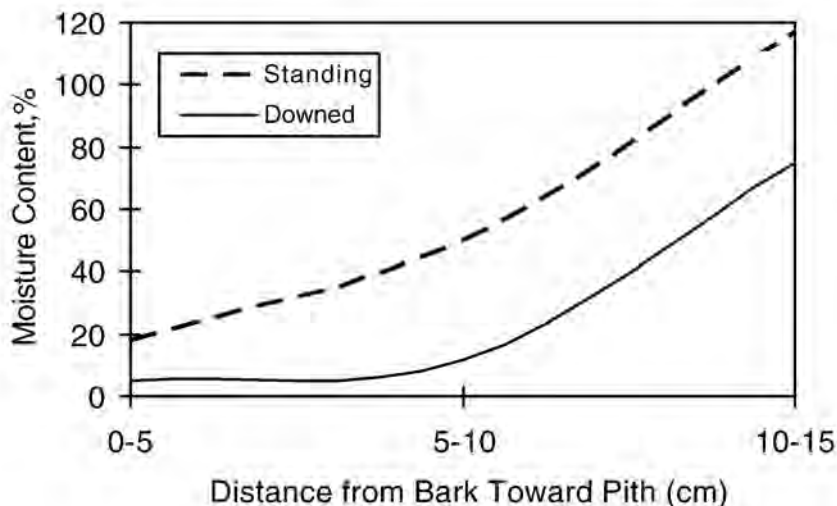


Figure 41. Moisture content at various depths in the wood of standing and downed snags 6 to 8 years after dying from defoliation by Siberian moth

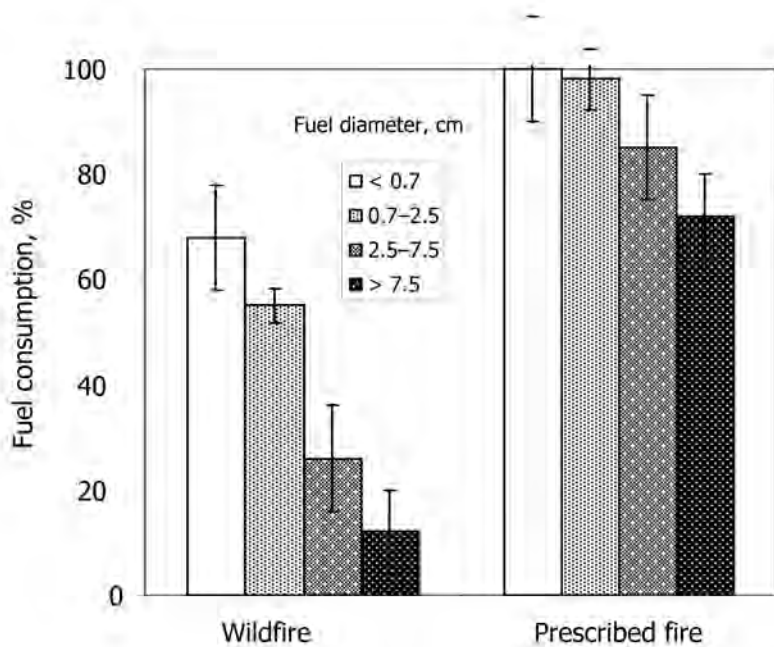
Each layer of standing snag wood appeared to contain twice to three times more water as compared to lopped dead trees. This suggests that, had standing snags been downed to the ground prior to prescribed burning, woody fuel consumption would have increased. Down- ing of all standing snags would have yielded maximum woody fuel consumption, but this would have increased the prescribed burning cost considerably.

Prescribed fire consumed on average 70% more dead woody fuel than the wildfire. Small-diameter fuels were burned almost completely in both cases, however the prescribed fire consumed much more large-diameter fuels than the wildfire (Figure 42a).

While both fires exhibited highly-effective grass consumption, the prescribed fire appeared to consume bigger amounts of litter, duff, and mosses than the wildfire (Figure 42b). About 25% of ground vegetation was consumed by the wildfire. Moss consumption by this fire was found to be only 2/3 of that by the prescribed fire. Duff and mosses hamper conifer seed germination and seedling establishment both in wildfire-intact and burned Siberian moth stands (Furyaev 1996; Kulikov 1971).

The prescribed fire reduced the duff layer to an average depth of 1.1cm and burned it completely in places. Duff this deep does not hamper conifer seed germination and seedling establishment.

a)



b)

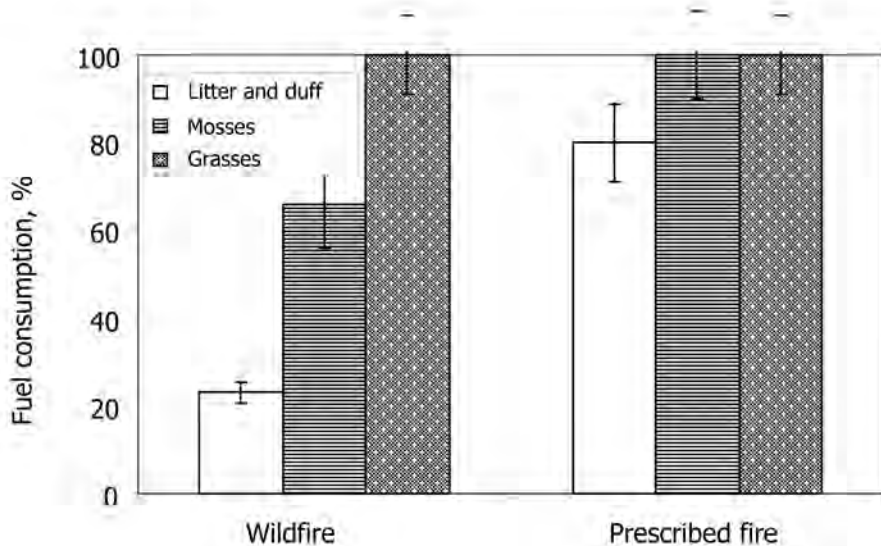


Figure 42. Consumption of (a) downed deadwood and (b) ground fuels by wildfire vs. prescribed fire

To remove more deadwood from a Siberian moth site, a part of standing snags need to be downed. This operation results in increasing fire intensity and, hence, the fuel consumption.

Downing of about 60% of standing snags prior to prescribed burning is considered to yield optimal deadwood utilization, as fire intensity is sufficient in this case to achieve satisfactory down deadwood consumption. This enables planting conifers without pre-planting soil preparation. Post-prescribed fire large-diameter fuel loading does not exceed 30 t/ha, minimal diameter of unburned fuel elements being 7 cm. Downing of this percentage of standing snags is possible provided that APL-55 paths are 10-15 m apart.

Prescribed burning of Siberian moth sites with high intensity appeared to disturb agrochemical soil properties. Soil temperature can be as high as 60°C at a depth of 2 cm in the mineral soil layer. However, soil temperature was found not to exceed 50°C on sites experiencing high-intensity fire (Figure 43).

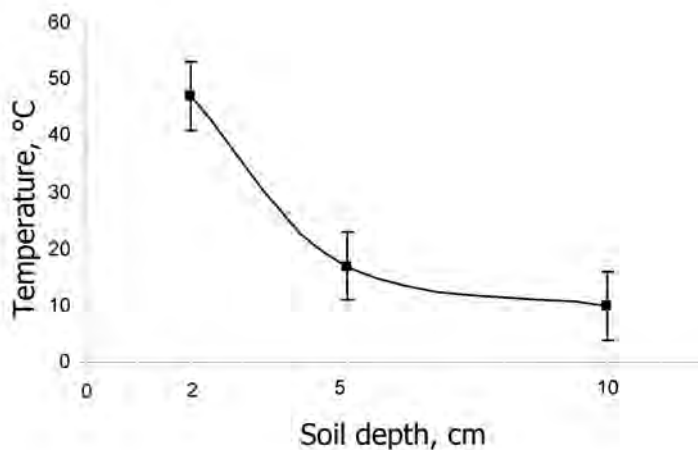


Figure 43. Soil temperature during prescribed burning

The results of our experiments showed that even high-intensity fire does not have considerable influence on soil thermal regime. Heating of upper soil layers during prescribed burning resulted in reed grass (*Calamagrostis obtusata* Trin.) root dieback and promotion of fireweed (*Chamerion angustifolium* (L.) Holub). Prescribed burned Siberian moth sites colonized by fireweed are favorable for conifer forest regeneration, as fireweed has only tap roots that do not contribute to soil sodding. Moreover, this

grass plant fails to compete with young woody plants and its canopy creates conditions favorable for dark conifer seedling growth (Ivanova and Perevoznikova 1994).

Downing of 70% of standing snags was found to result in unsatisfactory down wood consumption by prescribed fire. With APL-55 passes 30 m apart, the proportion of fallen trees appeared to be only 40% and large-diameter down wood consumption did not exceed 25-30%. This level of Siberian moth site clearance is insufficient for planting forest and additional soil preparation is required. Importantly, standing snags charred at their butts during prescribed burning fell down over the first several days after fire to increase down wood amounts and, hence, make forest restoration problematic.

Upper soil properties were observed to have changed two months following prescribed burning (Krasnoshchekov et al. 2007). Duff carbon and nitrogen losses were measured to be 7.7% and 49.6%, respectively. Large amounts of ash lead to decreasing the layer actual acidity and increasing ash content. The Siberian moth site prescribed burning resulted in increasing gross and movable potassium compounds 3.2 and 4.3 times, the same trend observed for phosphorus. Increases in amounts of these elements in the upper soil horizons are considered to be among positive fire impacts, as they enhance conifer regeneration during the first two years following fire. Soddy-deeply podzolic soils covering the prescribed burned Siberian moth site were found to maintain a level of biological activity sufficient for rapid recovery of their initial properties.

Our experiments showed that prescribed burning is the best method to clear Siberian moth sites from dead trees and other organic matter and promote conifer forest regeneration on them.

7. Prescribed Burning in the Forest-Steppe Zone

7.1. Prescribed Burning of Scots Pine Stands in the Wildland/Settlement Interface

Forest fires burning close to population units are very dangerous, as they often kill people, destroy dwelling houses and even entire settlements. These fire-caused catastrophes occur in forest areas around the world, including Russia (Table 30). Forest stands neighboring settlements are well-protected from fire. These stands contain sufficient fuels for supporting high-intensity surface fire. Structurally, these are usually three-layer stands, Scots pine regrowth and long mature tree crowns making a fuel ladder for surface fire to become crown fire. Since firebrands, smoldering bark and wood pieces can be transferred as far as up to 500 m, they ignite wooden houses found closest to the forest. Neither firebreaks, nor forest cutlines can stop crown fire. Moreover, their presence results in increasing surface wind speed and, hence, making fire control problematic due to dense smoke (Valendik et al. 1979).

In fact, two kinds of fire, forest fire and structural fire, burn simultaneously at a wildland/settlement interface. Fire control is extremely difficult in this zone, as these fire types require absolutely different suppression methods and resources. In addition, skills of structural fire suppression specialists differ greatly from those of forest fire controlling staff and they can not substitute one another.

Our arch goal was to investigate dynamics of fire activity in the interface forests, estimate the forest fire hazard, and develop prescribed burning methodologies to reduce surface wild-fire intensity and prevent crown fires in these forests. Our project region was Krasnoyarsk forest-steppe zone.

Table 30. Effects of forest fires in wildland/settlement interfaces across Russia

Fire date (year)	Fire location	Fire-destroyed settlements and structures		People affected		Source
		Dwelling houses	Other structures	Injuries	Deaths	
1921	Mari-El Republic	60 settlements	Farm-yard (1000 heads of cattle)	–	35	Valendik et al. (1979)
August 1972	Moscow region, Kostroma region, Vladimir region, Gorky region, Mari-El Republic	2 settlements, 100 houses, one railway station	5 young pioneers camps, peat processing enterprise	120	-	Valendik et al. (1979)
May 1996	Irkutsk region	69 houses	77 structures, 35 km of power lines, 27 km of communication line, 2 lower wood stores, village club, warehouse, cow-shed	35	6	Forest fire protection problems (1996)
May 1996	Buryatia	2 settlements, 21 houses	–	–	10	Forest fire protection problems (1996)
May 1996	Mari-El Republic	26 houses	–	79	–	Forest fire protection problems (1996)
May 1996	Tuva Republic	–	–	7	6	Forest fire protection problems (1996)
1998	Khabarovsk region	6 settlements	–	–	–	Stelmachovich (1998)
1998	Sakhalin region	6 villages, 80 houses	–	683	3	Stelmachovich (1998)
2010	Voronez, Ryazan, Vladimir, Ivanovo, Moscow, Nizny Novgorod regions, Republic Mordovia, Republic Tatarstan	77 settlements, 3000 houses	-	1882	63	www.wood.ru, Goldammer (2010)

7.1.1. Krasnoyarsk Forest-Steppe

Krasnoyarsk regional forest-steppe occurs as “islands” within the subzone of southern forest-steppe and conifer forests with grass-dominated ground vegetation (Central Siberia 1964). Geomorphologically, this forest-steppe is a pebbly plateau cloaked by loess-like rock (Bazhenov 1934). The mesorelief is represented by sand dunes of ancient Eolithic origin. The topography of the eastern part of this area is characterized by well-developed mounds alternating with flat-bottom depressions, whereas soft-slope stretched elevations up to 200 m a.s.l. are characteristic of the heavily dissected terrain of the western part.

Soils are formed by Quaternary sediments represented by loams and loamy sand with quartz pebble intrusions. Soddy-podzolic soils found on loamy sand and light loams are the most widespread soil type.

Annual solar radiation received by Krasnoyarsk forest-steppe ranges 86,600 to 88,000 kcal/m² (Golovin 1960). Growing season averages 144 days here and annual precipitation is 350–450 mm, which amount is sufficient for fairly rapid forest growth.

Average July air temperature is 18.3°C and annual precipitation, occurring mainly in July and August, averages 465 mm (Table 31) according to multi-year observations at Bolshaya Murta weather station. Low precipitation, low relative humidity, and presence of cured grass contribute to development of conditions favorable for fire occurrence and spread.

Table 31. Average multi-year monthly precipitation distribution, mm (numerator) and number of days with precipitation (denominator)

Weather station	Month												Average annual
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Suk-hobuzimo	15/14	11/10	15/9	29/10	38/11	49/13	75/12	68/13	45/14	41/13	34/14	24/15	444/148
Bolshaya Murta	19/15	15/11	14/10	24/10	36/12	54/13	79/12	66/14	49/15	40/17	38/19	31/18	465/166

Krasnoyarsk forest-steppe woody vegetation is largely represented by Scots pine/herb/red whortleberry, Scots pine/herb, and Scots pine/sedge stands characterized by a stocking density of 0.6. This forest-steppe zone falling within the Krasnoyarsk-Kansk Forest Harvesting District occurs at the eastern edge of West Siberian Lowland and its elevation above sea level (a.s.l.) ranges 250 to 350 m (Smagin et al. 1978).

Three peaks of forest fire activity, a spring-summer, summer, and summer-fall, are observed in Krasnoyarsk forest-steppe (Valendik 1963). Siberian forest-steppe areas are generally characterized by a fire season lasting from early spring through late fall. Early spring

and early summer are most favorable for fire occurrence. Spring fires are usually low-depth-of-burn surface fires of moderate-to-low intensity. Wide occurrence of this fire type is attributed to the fact that, in early spring, ground fuels, i.e. cured grass, needle litter, small tree branches, and cones become dry and ignite readily, while duff and large-diameter down deadwood remain wet. Surface fires often crown in young conifer regeneration pockets (Molchanov 1940, 1957; Kurbatsky and Ivanova 1987).

Early spring extreme fire activity decreases as a result of vigorous grass growth under the forest canopy. Forest fire occurrence and development is related with living ground vegetation loading. Many researchers (Melekhov 1947; Tkachenko 1952; Korchagin 1954; Balbyshev 1957) noted a distinct difference in fire hazard of forest sites with grass-dominated ground vegetation between spring and summer. Sofronov (1967) in his studies in mountains of southern Siberia found that spring fire peak goes down as soon as living grasses amount to half to two thirds of their maximum load.

Low-depth-of burn surface fires of low and even moderate intensity are not always destructive to Scots pine stands. In early spring, tree cambium is still dormant and relatively resistant to heating and residence time of these fires is not sufficiently long for cambium to be heated up to lethal temperatures (Girs 1982). Late May-early June fires are more dangerous for Scots pine stands, because this is the period of time when trees begin to grow, duff becomes dry, however, green grasses are still too short. Combinations of these factors promote fires of high depth of burn and, hence, the probability of dieback of Scots pine stands of age classes I and II is very high (Valendik et al. 2006). Growing trees are highly susceptible to fire (Girs 1982). In summer, high-depth-of-burn surface fires often become crown or ground fires.

Forest fire hazard decreases in fall due to frequent precipitation, fog, dew, and decreasing air temperature. Fires are characterized by low intensity in this period of time and, since trees grow more resistant to fire, as they are in the pre-dormant state, the probability of their dieback from fire is low (Kurbatsky 1962; Girs 1982).

7.1.2. Forest Fire Frequency

High fire frequency is observed in Scots pine stands found in the central forest-steppe zone. This part of the forest-steppe has a well-developed road system, many recreation sites, and numerous agricultural fields where stubble is cleared out using fire. Uncontrolled agricultural fires are responsible for up to 70% of all wildfires here.

Fires are most frequent in April through June (Figure 44) due to presence of a deep layer of cured grass from the previous year. As grasses grow vigorously in July through August, fires decrease in number in this period of time. Minimal number of forest fires is observed in September through October.

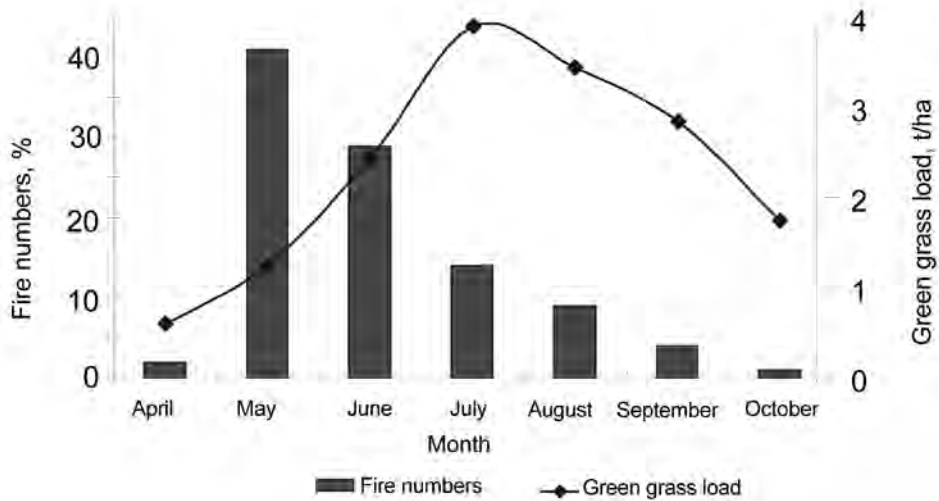


Figure 44. Relationship between green grass loading and forest fire numbers

The greatest number of fires occurs in recreation sites established at distances of 5-15 km from settlements (Figure 45). Year-to-year variability of number of fires is attributed to differences in weather conditions. Fire frequency decreases beyond 18 km from settlements.

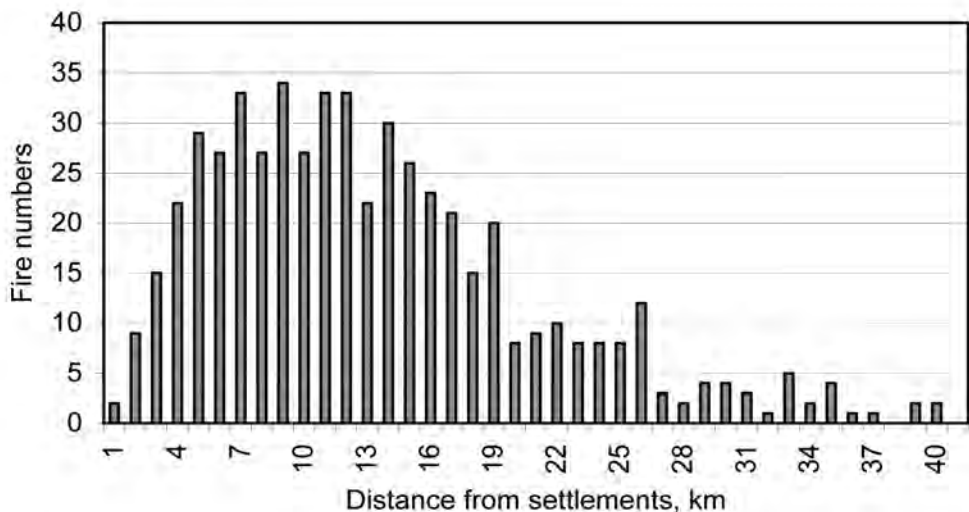


Figure 45. Forest fire occurrence by distance from settlements

Forests found in close vicinity to settlements (Figure 46) are classified as forest group I and receive intensive protection including fire protection. Fires occurring in these forests are fairly small in size. As fires have not burn in these forests over the past 40-50 years, ground fuels have built up to more than 60 t/ha to promote high-intensity fires. High amounts of down deadwood, standing snags, and domestic garbage, as well as highly compact duff layer enhance tall grass growth and microclimatic changes. These conifer-dominated stands are characterized by high fire hazard, whatever the ground vegetation.

Living ground vegetation and litter are the two major ground forest fuel components. Kurbatsky (1970) considers them as the major fire-carrier fuels. In good burning weather, these fuels burning can result in releasing heat sufficient to burn other fuel types. These two fuels blaze up first and are, in fact, fire promoters.

Forest site fire hazard depends largely on the ratio between living grasses and dead carrier fuels. Proliferating new grasses create a more humid microclimate and, hence, the rate of high ignitability attainment by fire carrier fuels is reduced (Kurbatsky and Ivanova 1987). Fire numbers and living grass amount are closely correlated. In Krasnoyarsk forest-steppe, for example, about half of all fires occur before grasses begin to grow. The number of fires decreases twice in early growing season, and fires occurring during the period of intensive grass growing account for as little as 15-20% of all fires.

The number of forest fires varies with the distance from settlements (Figure 47), because the level of recreational and other activities of local population in the forest depends upon season.

People visit the closest forest sites most intensively in spring and fall to rest and collect mushrooms, whereas in summer they go deeper into the forest for haying and collecting berries. Andreyev (1999) reported that the distances between recreational activity spots and settlements average 12.9, 17.9, and 16.2 km in June, July, and August, respectively. Our study shows that these distances correspond to maximum fire numbers.

7.1.3. Forest Fire Danger in the Forest-Steppe Zone

Precipitation pattern is the major factor determining forest fire danger class, since it controls air humidity and fuel moisture content. Several showers, 2.5-8 mm each, can saturate forest litter and duff with water much faster than long-time drizzle.

Three fire danger maximums can be identified in Scots pine stands of the forest-steppe zone. The first peak occurs in middle May that is followed by decreasing fire activity from late May through late June. The second fire danger maximum falls within late June-middle July. The third peak occurs in late August-early September and, as opposed to the first two, does not exceed fire danger class IV.

Although there are as many as three fire danger maximums, most fires occur in spring.

Forest fuel moisture content is a major factor accounting for fuel ignitability level and, hence, fire intensity and frontal spread. Our study revealed that the major fire carrier fuel (litter and duff) moisture content changed by 8% during 24-hr period. Minimum litter (10%) and duff (17%) moisture contents were recorded from 15:00 to 18:00 and from 18:00 to 21:00, respectively. From 18:00, litter and duff appeared to gradually increase their moisture content, which reached its maximum by 06:00.

7.1.4. Prescribed Burning Impacts on the Forest-Steppe Scots Pine Stands

Creating a forest stand structure that would hamper surface fire jumping to tree crowns requires to do selective cutting, which treatment is expensive. Forest underburning takes the least money and effectively reduces forest fire hazard. With this approach, the overstory layer remains intact, down deadwood is largely removed, soil is enriched by additional microelements, and repeated fire risk is reduced. Using wildfire-preventive underburning for creating fire resistant Scots pine stands was proposed by Furyaev as far back as in 1974.

Two 50x50-m experimental plots were laid out to conduct underburning in a Scots pine stand near Yukseyevo settlement, Bolshaya Murta district, Krasnoyarsk region (Table 32). Firelines were built along the plot perimeters.

Table 32. Yukseyevo Scots pine stand characteristics prior to underburning

Plot #	Stand type	Stand composition	Stand age (years)	Average stand height (m)	Average stand diameter (cm)	Density of stocking	Standing wood volume (m ³ /ha)	Fuel load (kg/m ²)
1	Scots pine/ feather moss/ sedge/ herb	10P	50	12	10	1.0	141	3.24
2	Scots pine/ sedge/herb	10P+B	90	17	22	0.7	190	4.05

Ground fuels ranged 3.24 to 4.05 kg/m² on the plots. Living ground vegetation consisted of various herbs, such as sedge, horsetail, brake fern, stone brake, wood geranium, and greater burnet. One plot was underburned in August and the other in May, before new grass began to grow (Table 33).



Figure 46. Dwelling houses found in close vicinity to forest

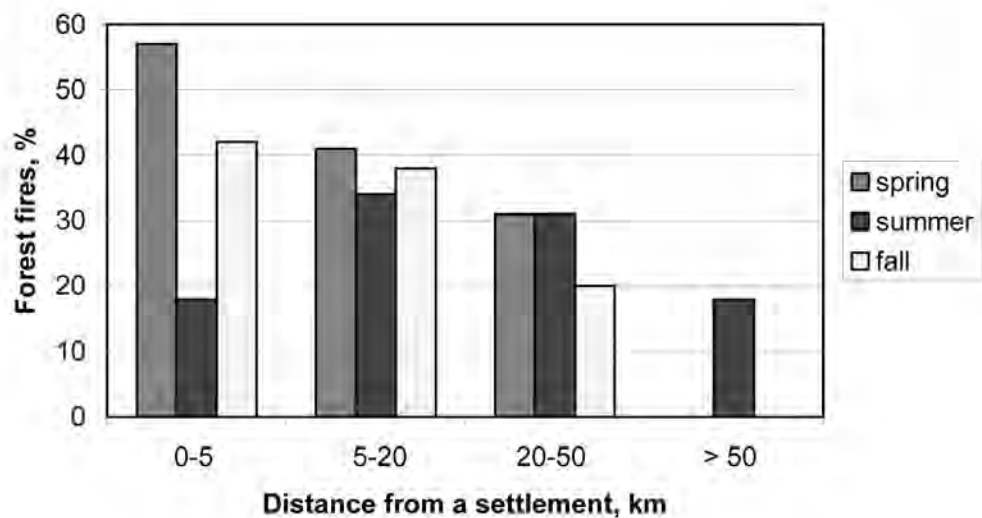


Figure 47. Seasonal forest fire distribution depending on distance from settlements

Table 33. Weather conditions and experimental fire intensity on the sample plots

Plot #	Date of burning	Weather conditions				Fire intensity (kW/m)
		Air temperature (°C)	Relative humidity (%)	Wind (m/s)	Nesterov Index	
1	17.08.1998	24.4	48	NW: 0.5-1	1186	271
2	05.05.1999	20.2	45	SW: 1-2	830	387

The experimental fires had low intensity (Figure 48), and frontal intensity was averaging 270 kW/m on the first plot and 390 kW/m on the second plot. The lower fire intensity recorded on the first plot was due to the presence of a considerable amount of new grass that hampered fire spread. Immediate post-fire fuel loading was found to decrease by 40% as compared to pre-burning (1.3 kg/m² vs. 3.24 kg/m²) (Table 34). On the second plot, a pre-burning fuel load of 4 kg/m² decreased by 47% after burning, unburned fuel load being 1.9 kg/m². The respective fuel loads were 2.6 and 3.2 kg/m² one and two years following fire on the first plot. Fuel appeared to be 2 kg/m² (i.e. half of the pre-fire loading) one year after burning on the second plot.

Table 34. Ground fuel loading (kg/m²) changes

Fuel type	Plot 1				Plot 2		
	Pre-fire	Immediately after fire	1 year after fire	2 years after fire	Pre-fire	Immediately after fire	1 year after fire
Green grasses	0.26	0.0	0.04	0.08	0.10	0.0	0.13
Mosses	0.20	0.0	0.07	0.14	-	-	-
Litter	0.78	0.0	0.58	0.65	1.84	0.0	0.86
Duff	2.00	1.34	1.92	2.32	2.11	1.9	1.03
Total	3.24	1.34	2.61	3.19	4.05	1.90	2.02

All trees and young conifer regeneration up to 2 cm in diameter were counted prior to and following burning on both plots. Tree condition was estimated based on conditions of needles. Trees having over 60% of green crown were considered as live, while those with living crowns of less than 60% were considered to be dying, and those with 100% yellow crown fell within the category of dead standing trees (Table 35).

Table 35. Distribution of trees (% of the total number) by condition category prior to and after burning

Time of inventory	Tree condition category			
	Live	Dying	Standing dead	Down dead
Plot 1				
Pre-fire	91	2	6	1
One month after fire	39	25	33	3
One year after fire	32	24	37	7
Two years after fire	28	16	46	10
Plot 2				
Pre-fire	97	1	1	1
One month after fire	47	15	37	1
One year after fire	44	5	41	10

Trees up to 6 cm in diameter dyed during the first two years after the experimental underburn on Plot 1 (Figure 49a), trees up to 2 cm in diameter exhibiting the highest (70%) mortality. Standing trees appeared to fall down uniformly independent on their diameters to show 12% mortality two years following burning. As for Plot 2, the underburn resulted in partial dieback of >14-cm-diameter trees, individuals up to 8 cm in diameter exhibiting the highest mortality level (Figure 49b). Trees over 8 cm in diameter were found to have died where ground fuel loading was high. When revisiting this plot a month after burning, we recorded no downed trees, while they were found to account for up to 20, 13, and 3 percent for tree diameters of up to 2, 4, and 6 cm, respectively, a year following fire.

Our underburns conducted in a Scots pine stand led to full dieback of subcanopy trees, which usually constitute a fuel ladder for surface fire to go up to the canopy. The experimental fires also reduced ground fuel loading and, hence, the risk of occurrence of high-intensity surface fire, which can result in the entire stand mortality.

7.2. Prescribed Forest Burning in the Forest-Steppe Zone of the Trans-Baikal Region

Agricultural fires, which are, in fact, uncontrolled burning of grassy sites adjacent to forest land, have historically been the major wildfire cause in the Trans-Baikal region (Figure 50) that includes Buryatia and the Trans-Baikal District. Since grazing land productivity is



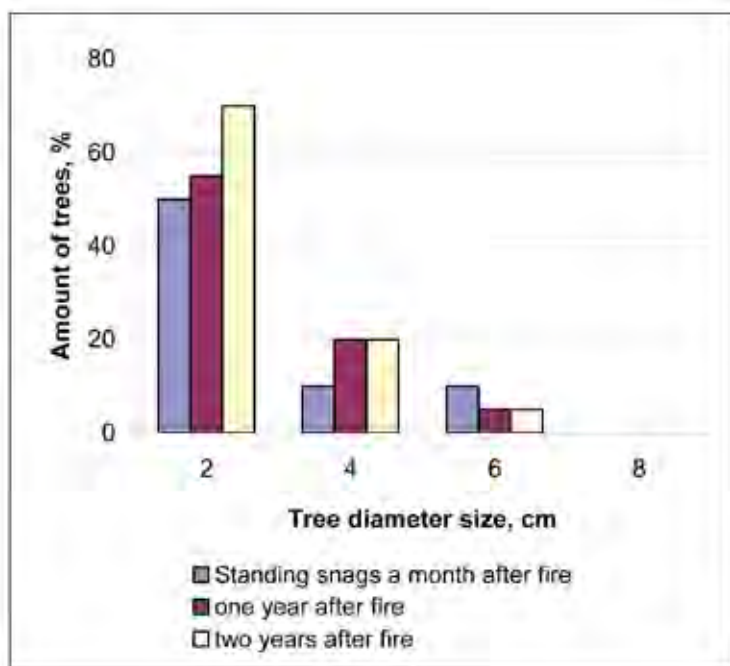
Figure 48. Underburning in a Scots pine stand

known to be improved by cured grass burning, enforcement of regulations prohibiting this type of burning has always been problematic. Treeless sites, such as glades, natural haying and grazing sites, agricultural fields, and roadside strips, account for over 14% of the total forest land in the Trans-Baikal region.

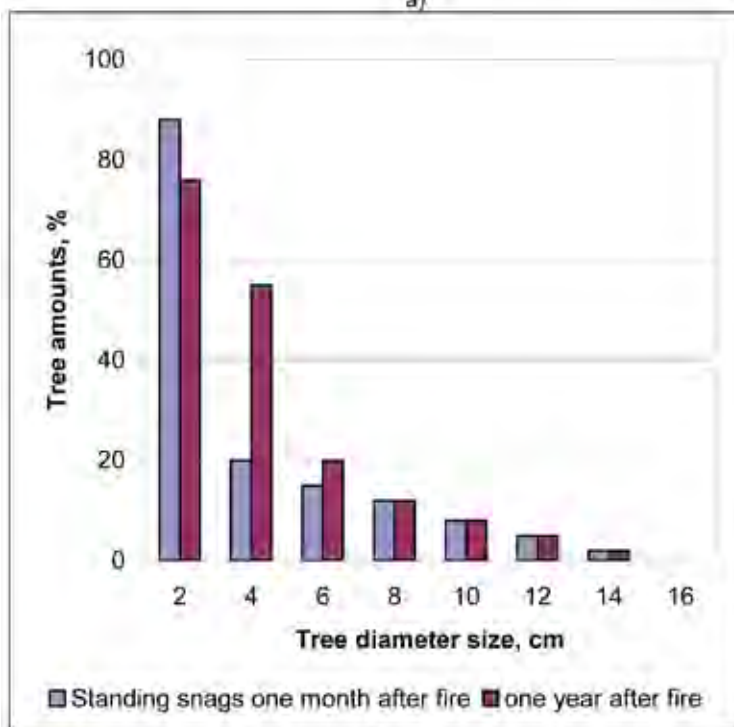
All these sites are characterized by high fire hazard in spring and once a fire occurs it spreads rapidly to the neighboring forest. Kuznetsov (1990, 2001), who has studied agricultural burns as a cause of forest fires since 1980s, investigated characteristics of these burns, forest fire occurrence, and fire effectiveness regarding vegetation cover improvement.

7.2.1. The Regional Characteristics

Topographically, the Trans-Baikal region is mostly middle mountains with numerous mountain valleys and well-pronounced altitudinal vegetation belts. The region is in extremely continental climate (Zhukov et al. 1969), daily and annual air temperatures fluctuating greatly. Average monthly temperature amplitude is 40-50°C, as the region is located far from oceans and circulation of moisture from the interior water bodies is low, this moisture does not contribute considerably to the regional atmospheric moisture. Relative humidity is fairly low



a)



b)

Figure 49. Tree mortality distribution by tree diameter size on experimental plots 1 (a) and 2 (b)

due to low moisture evaporation from cold surface. Precipitation ranges 230 to 350 mm in hollows. Two summer months account for 50-55% of the annual total precipitation. Winter is dry and lasts for 5.5 to 8 months. Early summer (summer lasts for 2 to 3.5 months) is warm and dry, whereas its second half is rainy. When snow comes, it falls mostly on already frozen soil and snow cover usually melts before soil thawing. For this reason, melting snow does not add effectively to soil water. Snow cover begins to melt in March or April, and it takes 1-3 weeks for snow to melt completely. Springtime is characterized by combinations of fairly low air temperatures with droughts associated with air heating in sunny and cloudless days.

Regarding forest growing conditions, the region is divided into northern, central, and southwestern zones (Gerasimov et al. 1965).

The northern zone encompasses the subzone of central mountain taiga larch-dominated forests. Conifers occupy 79% of this area. Larch/red whortleberry, larch/dwarf birch, and larch/herb are the most common forest types here. Most fires (83%), caused largely by agricultural burning, occur April through June. In spring, fire situation is aggravated by late (late May) onset of new grass growth on treeless sites.

Forests account of about 80% of the total area of the central Trans-Baikal zone, which occurs within Buryatia boundary. These forests are within the Baikal protection zone. These mostly conifer forests are dominated by Scots pine (46.7% of the total forest area). The most widespread forest types are Scots pine/red whortleberry, Scots pine/tall grass/herb, and larch/red whortleberry types. Growing season begins on treeless sites in early May. May and June are the highest-fire-hazard months accounting for 67% of all fires.

Mixed larch/birch and birch stands prevail in the former Chita region (52% and 34% of the total forest area, respectively). Scots pine stands can be found on south-facing slopes, while north-facing slopes are covered by larch stands with subcanopy woody layers consisting of *Rhododendron dahurica*, shrub-like alder, and *Betula gmelinii*. Stands having no or a very sparse woody subcanopy layer, but well-developed grass cover are more common. Forests with mixed grass- and rhododendron-dominated ground vegetation make up 65% and 26% of the total forest area, respectively. Agricultural burning is responsible for one third of all spring fires.

Seventy eight percent of southwestern Trans-Baikal forest area is conifers, the major woody species being larch (34.1%), Siberian pine (26.0%), Scots pine (18.1%), and birch (15.5%). The most common ground vegetation dominants are red whortleberry (*Vaccinium vitis-idaea*), rhododendron (*Rhododendron dahurica*), ledum (*Ledum palustre*), tall grasses, and mixed grasses, or herbs. Over 40% of spring (April-May) fires result from agricultural burning.



Figure 50. Agricultural fires in the forest-steppe zone of the Trans-Baikal region



Figure 51. The Trans-Baikal forest-steppe landscape. Photo: Yu.N. Krasnoshchekov

7.2.2. Steppe Areas

The Trans-Baikal steppes occur as fairly small islands between hills covered by forest (Figure 51), with the exception of eastern Trans-Baikal steppes occupying watersheds. These steppe areas are largely plowed, especially the so-called “soft” soils in bottoms of inter-mountain depressions, i.e. sites that were previously covered by feather grass and other tall grasses. Intensive use of these areas for cattle grazing has resulted in occurrence of low-productivity steppes. The Trans-Baikal steppe vegetation has low percent coverage and species diversity. For this reason, bare soil patches can be found in almost every grass vegetation community and the vegetation individuals are widely spaced. Also, vegetation layers are feebly marked.

Unfavorable weather hampers onset of new grass growth. Only few species begin to grow in late April and marked new grass cover can be observed not earlier than the second half of May. Growing season is short here. Green grass biomass increases until mid-August, and from thereon grasses begin to dieback. Cured grass gradually accumulates. This cured grass is fairly good food for cattle during free grazing in wintertime. According to Danilov (1936), presence of high cured grass amounts is the major factor hampering full development of new grasses as compared to burned sites. Prescribed burning has negative influence on neither species composition, nor productivity of Trans-Baikal steppe vegetation. Therefore, prescribed cured grass burning to improve grazing areas is widespread in this region and other parts of Russia. There does not exist a common scientific viewpoint regarding fire influence on grass vegetation (Rodin 1946, 1981; Ivanov 1952; Nefedyeva 1970; Rabotnov 1978). Several criteria related to fire impact on grasses were proposed by Kuznetsov (1990, 2001):

- Prescribed burning scheduling and post-burning soil moisture content are the major factors accounting for burning effects.
- Prescribed cured grass burning is beneficial when conducted during grass plant dormancy, i.e. in fall or spring (after or before growing season).
- The level of benefit from spring prescribed fires is determined by the time of grass growth onset, grass root system type, bud depth of location in soil, and grass species response to fire-caused environmental changes.
- The Trans-Baikal climatic characteristics and vegetation growing conditions indicate a necessity to conduct experimental prescribed cured grass burns in this region to properly schedule prescribed fires and estimate their influence on grass communities.

7.2.3. Prescribed Burning Technologies

Prescribed fires were conducted in the Trans-Baikal region to estimate fire influence on grass growth at different time during growing season and develop prescribed burning technologies to use prescribed fire instead of agricultural burning.

Our analysis of previous (Kuznetsov 1990, 2001) and our study results (Valendik et al. 2000, 2001) revealed that a cured grass burning technology should consider ground fuel drying time lag between open and under-canopy sites. Locations of grass sites relative to forest should also be taken into account.

Broadcast burning technology (Figure 52) is most productive and cost-effective where grass sites are surrounded by forest. When this is the case, the entire grass site is ignited simultaneously at different points, beginning from the lee side, than in the center, and finally on the opposite, windward, side of the site.

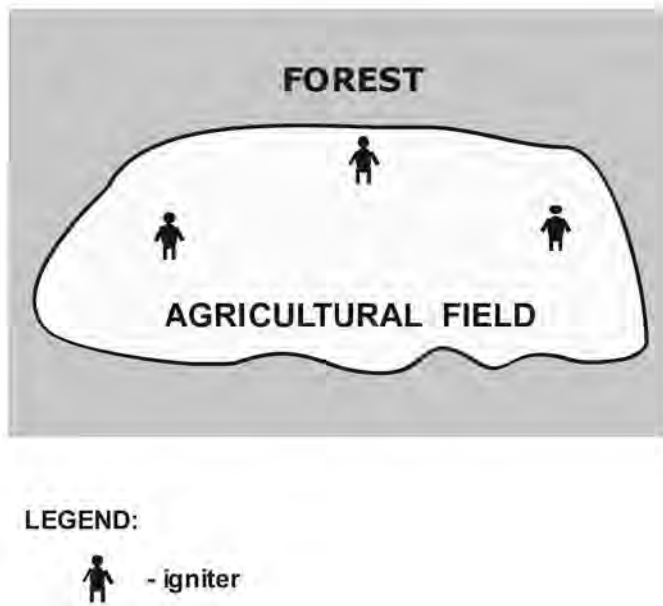


Figure 52. Broadcast burning

Burned firebreaks (Figure 53). This technology involves construction of firebreaks by burning to prevent fire spread to forest stands adjacent to agricultural land. The construction is a two-step procedure: step 1 includes building two 5-meter spaced firelines lining the forest using a plow or a milling cutter and step 2 is burning out the grass between these firelines (Figure 53). This is an effective method. However, it involves considerable expenses related with fireline building. Kuznetsov (1990) recommends to use this technology to protect Trans-Baikal larch forests from fire.

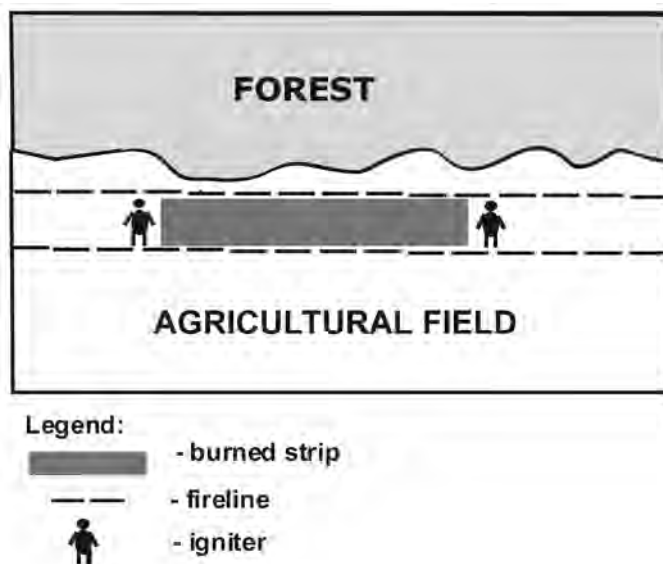


Figure 53. Fire break construction by burning

7.2.4. Optimal Prescribed Burning Weather

Optimal weather conditions for and timing of cured grass prescribed burning in the Trans-Baikal region were determined by Kuznetsov (1990) (Table 36).

Table 36. Optimal prescribed burning weather and timing

Trans-Baikal forest fire zone	Air temperature (°C)	Relative humidity (%)	Approximate time of burning
Northern	-5 to +5	30-60	Before 20 March
Central	-5 to +10	30-50	Before 20 March
Southern	-5 to +10	30-50	Before 01 March

The best local time for prescribed burning of treeless areas is from 12:00 to 17:00. Kuznetsov's studies were built on later. The All-Russia Center for Research and Information on Forest Resources developed "Guidelines for Cured Grass Prescribed Burning to Prevent Forest Fires" authored by Dichenkov (1997).

According to these Guidelines, fire breaks are required to be constructed in the forest by vegetation burning. Cured grass is allowed to be burned only on where natural fire breaks or base lines, such as mineral soil lines and roads, are present. Prescribed burned forest sites found between base lines become fire breaks that prevent fire occurrence and hamper fire spread.

These fire breaks are constructed on grassy treeless forest sites, such as around settlements and agricultural lands, along roads, railways, sparsely populated boundaries of forest districts and forest plantations, as well as in meadows, fields, and glades. If necessary, cured grass is prescribed burned in hilly areas having up to 25-degree slope.

Mineral soil lines (or firelines) to be used as base lines when constructing a fire break are built prior to carrying out prescribed burning. For example, if a road is used as a base line, a mineral soil line (at least 1 m wide) should be constructed parallel to the road at a distance of 20-25 m from it. Two short mineral lines are built from both ends of the long mineral soil line to the road. The area between the two base lines is divided into blocks by cross mineral lines 50-100 m apart.

Prescribed fire is conducted at over 50% relative humidity, air temperature not exceeding 15-20°C, fire danger classes I or II, and a wind speed lower than 2 m/s. One should always remember that fuels can differ greatly in moisture content at the time of prescribed burning. For this reason, the burning procedure should be divided into steps, beginning with the driest sites and moving further from them trying to use the short period of time safe for prescribed burning most effectively.

These guidelines on constructing fire breaks using cured grass prescribed burning were tested and recommended by the Russian Federal Forestry Agency for practical implementation.

8. Prescribed Fire Effects

8.1. Prescribed Fire Influence on Soil

Fire impacts on soil were addressed by several studies (Beadle 1940; Sampson 1944; Davis 1959; Belov 1973, 1982; Kozlowski and Ahlgren 1974; Popova 1979). Fire influence on soil is, eventually, soil heating. Fire can increase soil surface temperature to over 900°C (Davis 1959). Fire effects vary widely with fire and soil type. Scientific conclusions concerning fire influence on soil are usually general in character and do not account for low- and high-intensity fires. In most cases, fire has little influence on soil, because soil is a weak heat conductor. Soil heating is a function of forest floor organic layer depths. Fire-induced changes of soil microbial component are as important as those of soil chemical composition and soil heating. Post-fire soil changes are most often beneficial for forest regeneration.

The majority of soil heating models provide complete descriptions of soil physical characteristics (Campbell and Tanton 1981). Soil heat conduction decreases with increasing its organic element content and porosity. Partially decomposed organic matter conducts heat very poorly due to its high porosity, which dependence is obvious from duff capability to insulate heat. Air, an extremely poor heat conductor, is known to be one of the most effective heat insulators. Stony and sandy soils are heated more rapidly than clay mostly because stone is a better heat conductor. Agriculture specialists call these soils “warm soils” as opposed to clay. Although moisture contained in soil increases soil heat conduction, fire-induced soil temperature increase is slowed down, because soil moisture has a cooling effect and evaporates. In other words, wet soil is a better heat conductor than dry soil, however, much longer time is needed to heat wet soil up to temperatures critical for organic matter. Wet soils are largely cold soils.

The forest duff layer, i.e. the upper layer of half decomposed vegetation residues which are present in almost any vegetation community and build up during many years, is even more important for soil thermal regime. Duff, the organic layer closest to mineral soil, often constitutes the major fuel for vegetation fire. Fire can heavily destroy soil, especially infertile soil, where duff loading is high and its moisture content is low. However, high fuel consumption by fire does not necessarily results in soil destruction.

Davis (1959) identified four factors that should be considered separately regarding fire impact on soil: fire frequency, fire intensity and duration, forest type, and soil. Fire frequency determines time needed for fuels to accumulate. Presence or absence of duff and other fuel layers, as well as their loads, is a major factor (Belov 1973).

Soil physical characteristics, such as structure, moisture and organic matter contents, bedrock type, are required to be considered when estimating fire effect on soil. In conifer forests, for example, a thick duff layer found under old trees is only partially consumed by fire. Its lower part and soil usually remain wet and fire influence on soil can be neglected in this case. The entire duff can only be destroyed by fire following long drought or by repeated fires during several years. Repeated fires can result in mineral soil exposition and, hence, induce soil outwash. This is the most common and long-term negative fire effect (Viro 1974; Gossow 1996; Mälikonen and Levula 1996). Amounts of ash elements and mineral nitrogen readily available to plants from upper soil layers increase during the first 3-5 years following fire (Sushkina 1931). Duff volume weight increases twice to 3-fold after fire (Sannikova 1977).

Popova (1979), in her study of slightly soddy-moderately podzolic loamy sand supporting Scots pine stands, near Angara river in Irkutsk region, recorded increasing soil ammonia nitrogen after fires of any intensity, the highest amount of ammonium (93.6 mg/100 g of soil) occurring after high-intensity fire. The amounts of mobile potassium and phosphorus compounds in soil increased twice to 3-fold, whereas soil hydrolytic acidity decreased considerably. She found that these values recover back to the initial levels four or more years following fire. High-intensity, long-residence-time fire appeared to affect soil physical properties. In particular, it resulted in a 5-fold increase in soil density.

Fire consumes logging slash, litter, moss, and duff. Without fire, this organic matter has very little influence on soil fertility, since these elements decompose very slowly. However, they are potentially important for future soil fertility, as nutrients are allocated in them. Post-fire soil fertility remains high for a long time. Prescribed burning results in a great organic nitrogen loss, but, on the other hand, it increases mineral nitrogen. Most soils contain little calcium, and therefore, there exists a distinct correlation between soil fertility and calcium content. This relationship is important, as calcium promotes nitrogen-fixing microorganisms. Fire might result in small losses of soil magnesium and other microelements, which losses do not have any marked influence on soil fertility. Soil phosphorus loss is assumed to have a pronounce impact on soil fertility, however, soil studies done so far (Viro 1974; Humphreys and Craig 1981; Mälikonen and Levula 1996) have found no influence.

Podzolic soils, acidic by character, exhibit increasing acidulation when found under conifers, especially spruce. Literature data show that soil acidity has considerable influence on soil fertility and controls its biological activity, for example, nitrogen fixation and plant residue decomposition. Ash out-washing, post-fire grasses, colonization of burned sites by deciduous woody species – all these factors account for decreasing post-fire soil acidity by 1-2 units and enhance thereby soil biological activity (Viro 1974).

Fire has no noticeable influence on soil structure. Thermal destruction of organic elements, i.e. their oxidation, occurs slowly at a temperature of 200°C and rapidly at 400°C. Soil texture does not change at even 400°C destroyable for all organic matter. No structural changes were recorded down the soil profile after logging slash prescribed burning. Only crown fire can induce fairly small structural changes of the upper 2.5-cm deep soil layer. Moderate structural changes occur with increasing time since fire due to ash washing down to lower soil horizons. Fairly small soil porosity changes were documented to occur at a temperature not lower than 365°C and low-intensity fire appeared to result in increasing volumes of large soil pores (Humphreys and Craig 1981). Literature data analysis revealed that forest fire influence on soil is highly diverse.

Soil heating during prescribed burning of clearcuts was estimated by direct measurement of the upper 10-cm soil layer temperature. To do this, 67 sample plots were laid out on 8 clearcut sites (Table 37). Apart from soil temperature measurements, several fire behavior parameters, such as frontal spread rate, flaming zone depth, and flame length, were estimated visually. Post-fire duff depth was also measured. Soil temperature appeared not to exceed 43°C at a depth as shallow as 1 cm (Table 37).

Table 37. Soil temperature measured at different soil depths during prescribed burning

Clearcut # /year of burning	Ambient soil temperature (°C) at different depths (cm)				Maximum soil temperature (°C) at different depths (cm)			
	1	3	5	8	1	3	5	8
1/1997	14.0	12.3	11.0	10.4	32.0	28.5	24.0	18.0
2/1997	11.2	10.0	8.9	8.5	43.0	34.5	27.0	18.0
5/1997	17.9	14.6	14.6	11.5	34.2	28.3	24.2	18.5
2/1999	12.4	11.0	11.4	10.0	30.6	24.9	18.8	13.5
3/1999	18.3	16.0	14.1	14.0	39.9	28.1	21.3	15.6
4/1999	12.5	12.0	11.2	10.5	32.3	22.9	16.5	12.7
5/1999	11.0	9.5	9.0	8.8	19.9	16.1	12.7	11.4
6/1999	13.2	10.8	10.0	9.8	21.8	15.6	11.7	10.4

Soil heating by fire was found to depend on both fire parameters and soil moisture content (Table 38).

Table 38. Soil heating and fire behavior parameters

Plot # / year of burning	Post fire duff depth (cm)	Soil temperature (°C) at different depths (cm)				Fire parameters		Soil mois- ture con- tent (%)
		1	3	5	8	Flame length (m)	Flaming combustion (min)	
1/1997	2.4	18.0	16.2	13.0	7.6	0.6	12.0	63.0
2/1997	1.0	31.8	24.5	18.1	9.5	1.8	20.0	59.0
5/1997	2.5	16.3	13.7	9.6	7.0	2.2	15.6	75.0
2/1999	1.2	18.2	13.9	7.4	3.5	2.1	18.2	68.5
3/1999	1.1	21.6	12.1	7.2	1.6	2.4	22.3	50.0
4/1999	1.8	19.8	10.9	5.3	2.2	1.0	8.9	122.0
5/1999	4.7	8.9	6.6	3.7	2.6	0.3	13.7	132.0
6/1999	1.9	8.6	4.8	1.7	0.6	0.4	17.0	132.0

Soil temperatures were measured to be higher when prescribed burning mountain forest logging sites, the highest temperature occurring under logging slash accumulations. Temperatures measured at duff surface and 1-cm soil depth were 520°C and 120°C, respectively, whereas temperature did not exceed the 45°C, a critical value for soil microorganisms, in deeper soil layers (Figure 54). Duff was burned averagely to a depth of 0.5-1.0 cm due to its high moisture content (100-150%) and thus protected soil from overheating. Even high-intensity fire resulted in increasing soil temperature at a depth of 5-10 cm by as little as only up to 10°C compared to the background soil temperature.

Logging slash burning temperature can range 500 to 800°C (Gulisashvili 1931; Serebrennikov and Matreninsky 1937; Ivanov 1965). Our prescribed fires exhibited the highest temperature of 925°C in logging slash, 5-10 cm above the duff layer, average burning temperatures ranging 500-750°C (Figure 55). Average respective mineral soil temperatures appeared to be 18-25°C and 14-25°C at depths of 1 cm and 10 cm. Soil and duff heating was determined to occur more rapidly than their cooling. Average duff heating rate was 12.8°C/min at a depth of 1 cm and, after the temperature reached its maximum, it dropped at a rate of 4.9°C/min. the respective values for 1-cm deep mineral soil layer were 0.06 and 0.04°C/min.

The upper (0-10 cm) mineral soil layer grows cool much faster than lower layers. For example, when mineral soil surface is heated up to 300-400°C, temperature in a depth range of 8 to 20 cm remains fairly high during 1-3 days after fire, depending on season and weather conditions) (Tkachenko 1931).

The temperature of 0-10 cm mineral soil layer ranged 10-11°C on our control plots (Table 39).

Table 39. Temperature dynamics at different mineral soil depth during prescribed burning

Time since flaming combustion, min	Control plot			Fire intensity								
				Low			Moderate			High		
	Mineral soil depth, cm											
	1	3	8	1	3	8	1	3	8	1	3	8
10	10.0	11.0	11.5	24.8	22.2	21.4	43.6	44.8	39.7	69.7	56.8	44.5
30	9.1	10.4	11.2	12.3	14.2	14.9	30.1	33.4	31.6	40.2	41.6	42.5
60	9.0	10.2	11.2	12.2	12.8	14.2	22.4	26.5	25.4	29.3	31.6	30.2
90	8.8	10.1	11.2	12.0	12.5	14.1	20.0	24.7	25.2	28.1	30.8	30.1

Mineral soil heating, at the same depths, appeared to vary depending on fire intensity. On sites subject to high-intensity fire (20-25,000 kW/m), mineral soil showed a uniform temperature of 30°C one hour after burning. Soil was heated to 22-26°C during one hour on sites that experienced fire of about 1500 kW/m, while the soil temperature regime was recorded to be close to the background as soon as 30 min following burning where fire intensity was lower (about 500 kW/m).

The upper mineral soil layer was recorded to be heated to 70°C where logging slash accumulated and the entire duff layer was consumed by fire. High temperature is lethal for most soil microorganisms and animals. Prescribed fire was highly intensive on only 7-8% of the total site area. It can be concluded from our experiments that logging slash prescribed burning does not lead to complete soil biota dieback over the entire site treated. Soil temperature was found to be lower than lethal for soil biota where prescribed fire intensity was about 1500 kW/m.

Low and moderate heating has no negative effect on the plant rooting soil layer. However, only grasses having long roots reaching deep soil layers or high temperature-resistant grasses can survive where soil temperature stay 70°C after the flaming front has passed. Fireweed, which is favorable for post-fire forest regeneration, is one of such species.

Relatively low mineral soil heating can be attributable, apart from high (100-150%) duff moisture content, to the fact that heat largely goes upward with hot gases. Soil receives a small share of energy. Heat is dispersed non-uniformly: 18-25% is accounted for by lateral radiation, 70-80% is raised upward by convection and upward radiation scattering, and soil heat conduction is responsible for 3-5% of heat dispersion (Amosov 1958; Belov 1973, 1982).

Relatively low mineral soil heating by prescribed fire is not lethal for soil biota (Sokolov and Bogush 1999; Timoshkina et al. 2001). Post-prescribed fire mineral soil mesofauna remains the same as prior to burning, since prescribed fire impacts only duff biota. Duff invertebrate and small vertebrate densities recover back to the initial level as rapidly as on the second year following prescribed fire. Logging slash prescribed burning was also found to attract birds usually inhabiting open places.

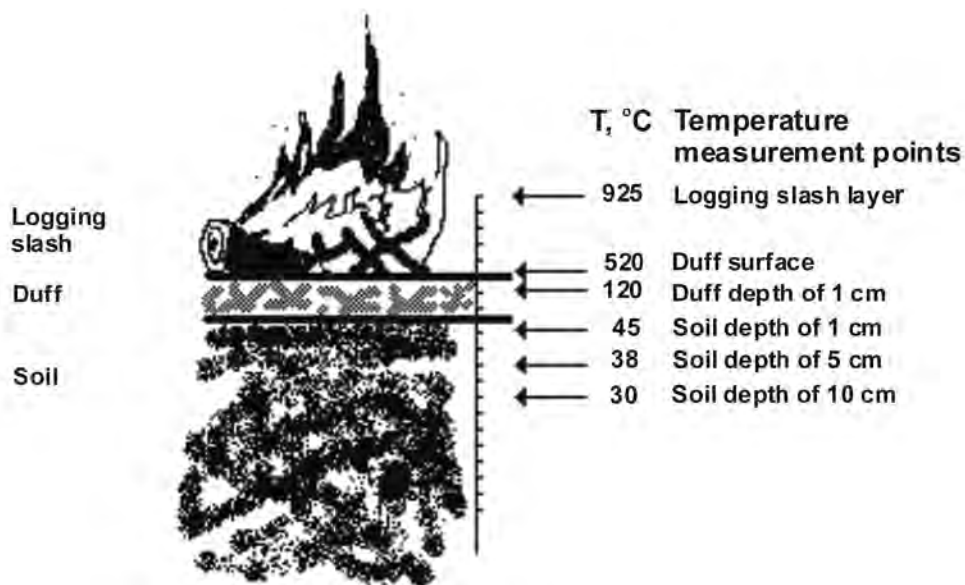


Figure 54. Maximum soil and duff temperatures (T) recorded during prescribed burning

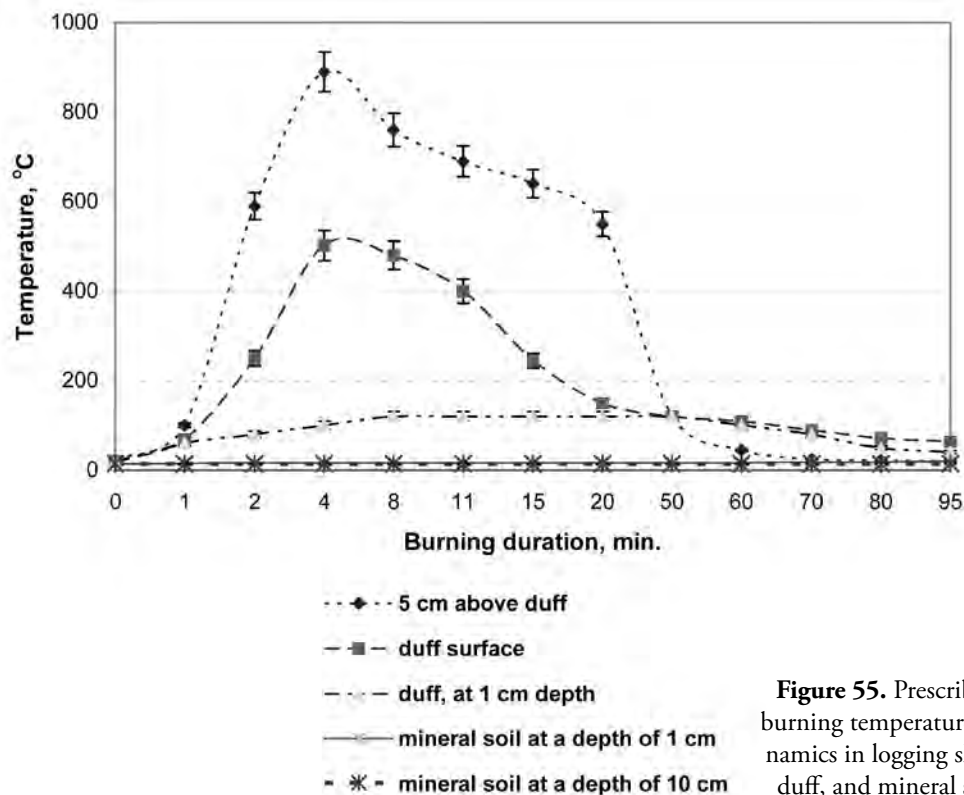


Figure 55. Prescribed burning temperature dynamics in logging slash, duff, and mineral soil

Piled logging slash prescribed burning results in much greater soil heating compared to broadcast burning. Duff is usually consumed completely under burning slash piles and mineral soil surface temperature can amount as high as to 750°C (Elpatyevsky et al. 1935). Soil temperature gradient depends on post-fire unburned duff depth and soil moisture content (Figure 56).

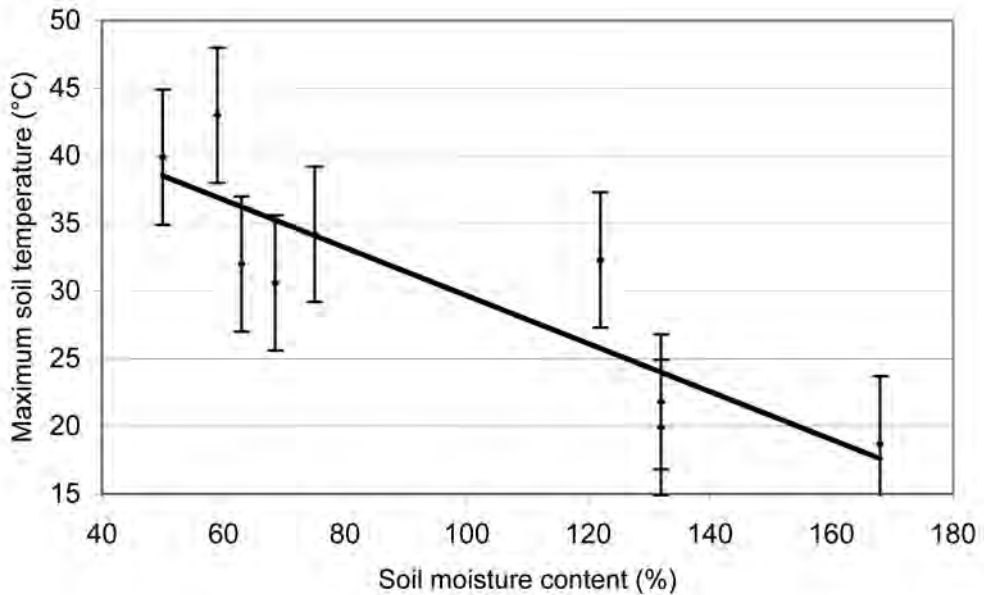


Figure 56. Maximum soil temperature dependence on soil moisture content at a soil depth of 1 cm

In our experiments, 1-cm-deep soil temperature increased by 10–35°C and usually did not exceed 45°C where duff was present. Consumption of as low as even 1.5 kg/m² of fuels resulted in 1-cm-deep soil temperature increase up to 70°C on duff-free skidding trails. This is attributable to the fact that fuel occur very close to soil surface on skidding trails and no porous and highly moist duff is present (Vallett et al. 1994). This indicates a necessity to leave an intact layer of duff under the piled logging slash treated. Soil temperature increase at a depth of 1 cm exhibited a certain relationship with thickness of the duff layer that remained unburned (Figure 57).

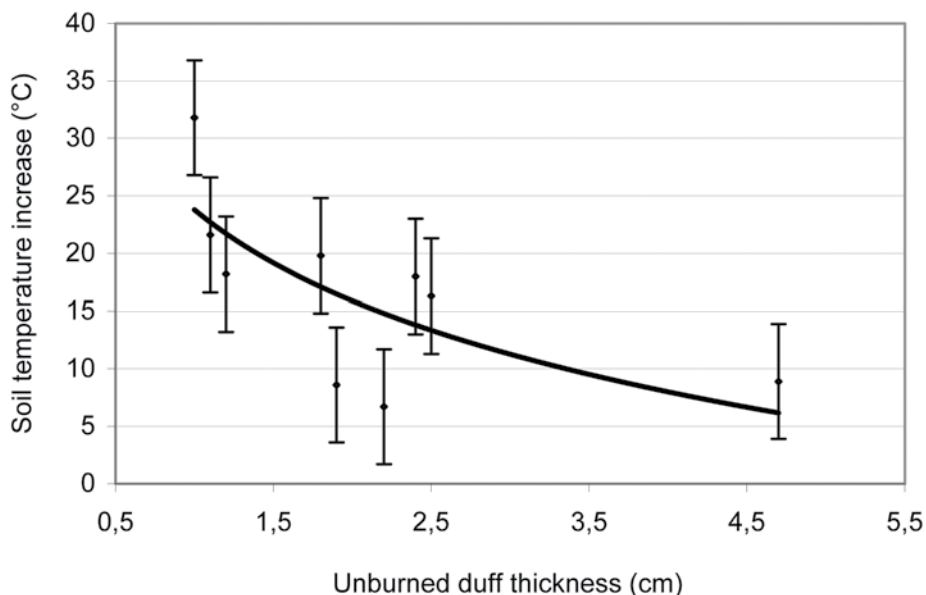


Figure 57. Relationship between 1-cm-deep soil temperature increase and unburned duff thickness

An increase in soil temperature induced by slash prescribed burning in forest harvesting blocks appeared to differ by only 9-10°C among the upper soil layers (Table 40).

Table 40. Soil heating in different parts of a forest logging site

Logging site part	Average heat release (kWt/m ²)	Average maximum temperature (°C) at different soil depths (cm)			
		1	3	5	8
Full tree processing site	1211	38.5	33.9	28.5	20.7
Logging block	570	29.8	24.1	19.3	15.1
Skidding trail	161	14.7	11.9	10.2	9.8

Duff thickness and moisture content account for flaming combustion duration and heat conduction. Lower fuel layers and soil found under logging slash accumulations are characterized by lower temperatures and higher moisture contents compared to in logging blocks and, hence, need more energy to be heated. Usually, the greater the fuel loading at a given point, the higher the moisture contents of the lower fuel layers, provided that a part of duff

was left after logging. Initial in-duff temperature is lower where fuel loading is high. Lower fuel loading leads to decreasing lower fuel layer moisture content and increasing in-duff temperature. This soil protection mechanism fails to work only in severe droughts. Although complete duff consumption by prescribed fire and, as a result, increasing soil temperature to maximum values can occur in parts of a logging site, the accumulative area of these parts is usually fairly small and does not have any marked influence on logging site recovery.

Soil samples for agrochemical analysis were taken prior to and after prescribed burning (Table 41). The project logging sites had high-to-moderate acid soddy-podzolic soils containing little humus, which humus content is characteristic of this soil type.

Table 41. Agrochemical characteristics of the upper soil horizon

Soil sampling time	Soil depth (cm)	Humus (%)	pH		Exchange cations (mg/equiv/100g)		V (%)	Mobile soil ions (mg/kg)	
			H ₂ O	KCl	H	Ca+Mg		N-NO ₃	P ₂ O ₅
Logging site 1/1999									
Prior to burning	0-5	1.86	5.52	4.70	4.71	10.8	69.3	4.01	2.5
The year of prescribed fire	0-5	2.41	6.05	5.45	3.79	25.2	86.9	13.8	45.5
Logging site 1/1996									
Prior to burning	0-5	1.80	4.95	4.02	6.97	24.0	77.4	10.4	65.0
Three years after burning	5-10	1.44	5.10	3.62	8.28	12.0	590	Traces	175.0

Logging slash prescribed burning produces three to four tons of ash per hectare. As mineral compounds are gradually washed from the soil surface down to lower soil layers, soil acidity (including hydrolytic acidity) decreases, while exchangeable calcium and magnesium show a 2-2.5-fold increase in amount. Decreasing soil acidity and increasing exchangeable bases account for a marked increase (up to 86.9%) in post-fire upper soil base saturation (V). Soil nitrifying capability also increases. Post-prescribed burning soil nitrogen content appeared to be three times that prior to burning. This was contributed by less acidic post-burning soil reaction, addition of ash elements to soil, and an increase in soil saturation with bases.

The project logging site soils were characterized by low mobile phosphorus content. Soil mobile phosphates were found to increase in amount after prescribed burning.

The proposed logging site prescribed burning technology lead to soil enrichment in microelements, which, in turn, enhanced conifer seed germination and young seedling development. Similar results were obtained in other studies (Ivanov 1965).

8.2. Living Ground Vegetation Recovery

Both prescribed and wildfire change site conditions drastically and immediate post-fire vegetation communities consist of species adapted to new fire-induced environment. Post-fire vegetation succession and species diversity largely depend on fire intensity. Vegetation diversity is manifested through abundance of different species, which indicates number of species in a community and the importance of each species (Wittaker 1980; Odum 1986; Lukina and Nikonov 1995).

Fire has multi-sided effects on forest ground vegetation development. Low-intensity fire result in partial mineralization of duff, decreasing its loading and thickness, and promote only few grasses and shrubs. Fire intensity variability has a noticeable impact on ground vegetation trends of recovery in that it changes ground vegetation species composition, as well as projective (i.e., percent) cover, occurrence, and importance of separate species and communities (Komarova 1992; Furyaev 1996). Fire can, for example, result in fireweed (*Chamerion angustifolium* L.) proliferation.

Post-fire ground vegetation regeneration under forest canopy differs from that on logging sites and depends on ground organic matter burning pattern. This pattern also controls ground vegetation species composition on ground patches burned by fire (Ivanova and Perevoznikova 1996).

Our investigation of burned dark-conifer logging site recovery in eastern Sayan Mountains revealed that fires of moderate and low intensity change ground vegetation on patches burned by mixed-severity fire. The proportions of these patches depended on fire intensity and fuel loading. Slightly burned patches (or sites) accounted for about 10% of the total area burned by moderate-intensity fire. Heavily burned patches were limited to where pre-fire fuel loading was the highest. Prescribed fire was estimated to reduce logging site down deadwood by up to 50%. Only slash over 4 cm in diameter was left unburned.

Post-fire vegetation development on logging sites of eastern Sayan is determined by altitudinal belt-specific climatic conditions and can occur through domination of either typical post-fire site colonizers, or other ground vegetation species. In the former case, domination of this or that post-fire colonizer-species depends on duff depth of burn (Table 42). Ground vegetation is more diverse and more dependent on site diversity in unburned areas.

Table 42. Changes of duff depths and grass loads on 2-year-old logging sites recovering through post-fire ground vegetation colonizer-species

Aspect, slope (degrees)	Logging site type	Duff depth (cm)		Post-fire grass load (t/ha)
		Pre-fire	Post-fire	
Northeast, 5	Fireweed-dominated	1.5	0	2.23
Southwest, 10	Reed grass -dominated	3.5	2	1.97
Southwest, 10	Fireweed-dominated	1.0	0.5	1.74
East, 5	Fireweed/reed grass-dominated	4.0	1.0	1.90
West, 5	Reed grass -dominated	2.0	1	2.76
Flat site	Fireweed-dominated	5.0	0.5	1.33
Flat site	Fireweed-dominated	4.0	0.2	1.46
Stream valley	Fireweed-dominated	5.0	0.5	2.08
Northeast, 15	Fireweed/ reed grass-dominated	2.5	1.5	2.07

In middle mountains of eastern Sayan, ground vegetation is dominated either by fireweed or reed grass in dark-conifer logging sites recovering after fires of moderate and low intensity. The fireweed-dominated stage of post-fire ground vegetation recovery on burned logging sites lasts usually for not more than 3-4 years. Developing ground vegetation made up purely by fireweed requires a logging site to be subjected to high-intensity fire or repeated fires.

As was mentioned earlier, fireweed/reed grass- dominated ground vegetation characteristic of burned logging sites of the region of interest is a result of low duff consumption by fires. Our prescribed fires led to a 1.4-1.9-fold decrease in duff layer depth (Table 43), and grass biomass decreased 1.4-1.7-fold compared to unburned logging site parts.

Table 43. Proportions of logging site parts characterized by low, moderate, and high duff consumption by fire and average duff depth

Logging site # / year of prescribed burning	Proportions of logging site parts with different duff consumption (%)			Average duff depth (cm)	
	Low *)	Moderate **)	High ***)	Prior to burning	After burning
1/1998	35	55	10	3.4±0.6	2.3±0.4
1/1999	35	45	20	2.7±0.6	1.4±0.7
1/2000	45	40	15	2.5±0.8	1.8±0.7
2/2000	35	50	15	3.1±0.7	2.2±0.8
3/2000	80	15	5	3.2±0.4	2.6±0.6

Note: *) duff reduction by up to 30%; **) 30-70%; and ***) 71-100%

Fireweed begins to dominate burned logging sites in the second post-fire year. Grass projective coverage varies widely from 5-10% to 90% of the total logging site area. Full-duff-consumption patches are scattered across a logging site and support mainly hypnum mosses, Marchantia (*Marchantia polymorpha* L.), birch (*Betula pendula* Roth) seedlings, reed grass, sedge (*Carex macroura* Meish.) sprouts, with fireweed sprouts being particularly promoted (80% of all sprouts).

About 80% of logging sites not subjected to prescribed fire are reed grass-dominated sites. Tall shrubs (elder, black currant and raspberry) are also prominent. Grass projective coverage totals 100%, while mosses are absent, except for few small patches of *Hylocomium splendens* and *Pleurozium schreberi*. Mineral soil patches are covered by sprouts of reed grass, millet grass (*Milium effusum* L.), and sedge. Fireweed occurs, along with tall grass sprouts, along skidding trails. The total average amount of sprouts is 612 per square meter, 63% thereof is tall grasses and 17% is fireweed. No conifer regeneration is observed and very few up to 1-m tall birch individuals are found.

A year after prescribed burning, grass projective coverage, along with down deadwood loading, decreased, certain grass species changing in abundance. Grass cover was of mosaic pattern in burned parts of logging sites. Reed grass grew less abundant, whereas fireweed, bird's-tare (*Vicia cracca* L.), and killwort (*Chelidonium majus* L.) increased in abundance. The proportions of tall grasses, such as *Aconitum septentrionale*, *Cirsium heterophyllum*, *Angelica silvestris*, and *Thalictrum minus* are decreased considerably. Abundances of millet grass, sedge, northern bedstraw (*Galium boreale* L.), and stone brake (*Rubus saxatilis* L.) did not changed in abundance (Table 44).

Table 44. Grass species abundance prior to and one year after logging site prescribed burning

Grass species	Abundance according to Drude scale (Schenikov 1964)	
	Prior to fire	One year after fire
Reed grass (<i>Calamagrostis obtusata</i> Trin)	cop2	sp – cop1 gr
Glague (<i>Aegopodium alpestre</i> Ledeb.)	cop1	sp-cop1
Bird's-tare (<i>Vicia cracca</i> L.)	cop1	sp-cop1
Millet grass (<i>Milium effusum</i> L.)	sp	sp
Stone brake (<i>Rubus saxatilis</i> L.)	sp	sol
Chickweed (<i>Cerastium</i> L.)	sp	-
Common chickweed (<i>Stellaria media</i>)	sp	-
Fireweed (<i>Chamerion angustifolium</i> (L) Holub)	sol	cop ¹
Wood rush (<i>Luzula pilosa</i> (L.) Willd.)	sol	sol
Fern (<i>Gymnocarpium dryopteris</i> (L.) Newman)	sol	-
Strawberry (<i>Fragaria viridis</i> (Duchesne) Weston)	sol	-
Sedge (<i>Carex macroura</i> Meinsh.)	sol	sol
Sylvan horsetail (<i>Equisetum sylvaticum</i> L.)	sol	sp
Meadow horsetail (<i>Equisetum pratense</i> Ehrh.)	sol	sol
<i>Pleurospermum uralense</i> Hoffm.	sol	-
Lungwort (<i>Pulmonaria obscura</i> Dumort.)	sol	sol
Interrupted club moss (<i>Lycopodium annotinum</i> L.)	un	-
Prickly-toothed fern (<i>Dryopteris carthusiana</i> (Vill.) H.P. Fuchs)	un	-
Geranium (<i>Geranium albiflorum</i> Ledeb.)	sol	-
Killwort (<i>Chelidonium majus</i> L.)	-	sol
Sow-thistle (<i>Cirsium heterophyllum</i> (L.) Hill.)	sol	-
Tall bear's foot (<i>Aconitum septentrionale</i> Koelle)	-	sol
Northern bedstraw (<i>Galium boreale</i> L)	sol	sp
Sylvan angelica (<i>Angelica sylvestris</i> L.)	sol	-
Meadow rue (<i>Thalictrum minus</i> L.)	sol	-

Grass cover floristic diversity was estimated on prescribed burned logging sites using a species composition similarity coefficient (K) (Vasilevich 1969):

$$K = [2c/a+b],$$

where c is number of species occurring both prior to and after fire; a is number of species prior to burning; and b is number of species after burning.

This coefficient was calculated to be 0.65 between burned and unburned parts of a logging site to suggest they were floristically close.

Prescribed burned logging sites can recover through either reed grass, or fireweed, the latter species dominating after high-intensity fire resulting in high duff depth of burn.

Our investigation revealed that mountain dark-conifer forest sites burned by low-intensity fire are usually colonized by tall grasses, whereas high-intensity fire consuming the entire duff layer on logged sites enhances fireweed (Figure 58).

The prescribed burned logging sites were revisited three years after burning to show the sites to regenerate through fireweed. Although fireweed stalks were pressed down to ground by the previous winter snow cover, they were observed not to suppress conifer seedlings. To count fireweed individuals on a prescribed burned logging site, ten 1x1-m sample plots were laid out. Fireweed amount was found to range 32-65 individuals per square meter, the average number being 46 individuals/m². The depth of the cured fireweed stalk layer did not exceed 10 cm. Grasses covered 80% of the total logging site, and previous-year fireweed accounted for over half of the area (Figure 59). No dead fireweed individuals 2-3 years old were recorded to suggest their rapid (during a single growing season) decomposition.

8.3. Forest Regeneration on Logging Sites

Prescribed burning of logging sites is aimed at forest fire hazard reduction. Prescribed fire, however, is also important regarding forest regeneration. Logging site clearing by prescribed fire has always been a heatedly argued issue. Forest restoration on logging sites remains a controversial point among foresters (Valendik 2000).

Fire-related literature has a lot of contradictory evidence about influence of soil heating by fire on natural forest regeneration and plantations. Some authors (Chernyshev 1962; Gulisashvili 1963; Kolesnikov 1963; Vaskov and Patrikeyev 1986) are rejecting the concept of prescribed burning and planting forest on burned sites, since fire impacts duff layer, consumes a part of humus, and reduces the upper soil nitrogen content. There exists, however, an opposite view of fire influence on forest regeneration, particularly on well-drained loamy sand (Tkachenko 1931; Molchanov and Shimanuk 1949; Melekhov 1954; Dekatov 1961; Pobedinsky 1964).

The arch objective of our logging site prescribed burning was to reduce fire hazard through “extracting” logging slash as potential forest fuels by fire. Creation of conditions favoring conifer seed germination and seedling establishment by clearing slash out of logging sites by prescribed fire constituted our forest management sub objective.

All prescribed fires were conducted either in the second half of summer, or in early fall. One year after burning, ground vegetation exhibited wide diversity and no dominant species. Fireweed began to dominate this layer only in the second post-fire year. The amount of conifer seedlings under fireweed canopy appeared to be 2.2 times that under reed grass canopy.

A logging site prescribed burned in 1996 was revisited in 2000. Conifer seedlings appeared to be distributed in a non-uniform pattern across the burned site and were limited to the most heavily burned patches. Ten 5x2-m plots were laid out at distances of 50, 100, and 150 m from the surrounding forest to sample conifer seedlings. At a distance of 50 from the forest, which consisted of Scots pine (70%), Siberian pine (10%), spruce (10%), and fir (10%) (i.e., 7SP1SibP1S1F), conifer seedlings amounted to about 2000 per ha. The respective amounts at the distance of 100 m (5SP3F1SibP1S) and 150 m (9SP1SibP) from forest were 1500 and 200 individuals per hectare.

The dependence of conifer seedling occurrence on unburned duff depth was also investigated. Scots pine, larch, spruce, and fir seedlings were found to occur mostly on micro sites where post-fire duff depth did not exceed 3 cm, while Siberian pine seedlings preferred natural shelters, such as under coarse down deadwood and among exposed tree roots.

Therefore, duff reduction should be sought when conducting prescribed fire in order to enhance forest regeneration. On the other hand, duff protects soil from overheating, post-fire erosion, and performs other beneficial functions. Complete duff consumption by prescribed fire should thus be excluded. Post-fire duff 1-3 cm deep is considered optimal, since it does not hamper conifer seedling establishment and development and, simultaneously, prevents soil erosion.

The prescribed burned logging sites were investigated again in 2006, i.e., seven years after prescribed fire (Valendik et al. 2007c). Ground vegetation species composition and structure had grown stable and the majority of conifer seedlings had established by that time. While fireweed and reed grass dominated a prescribed burned logging site, an adjacent unburned logging site was colonized by reed grass and sedge.

New woody seedling amount is one of the main indicators of forest regeneration level. The dynamics of forest regeneration on burned sites can be divided into several amount phases (Ilyichev et al. 2003). A drastic increase in woody regeneration is observed during the first 1-3 post-fire years. The regeneration then slows down from post-fire year 3 to 5 and keeps relatively stable during the period between post-fire years 5 or 6 to 14 or 15. This stability phase is followed by a slowdown from post-fire years 15 or 16 to 20. Forest regeneration was found to be more successful and contain mainly conifer species on a prescribed burned logging site as compared to an unburned logging site (Table 45).



Figure 58. A logging site dominated by fireweed after prescribed burning

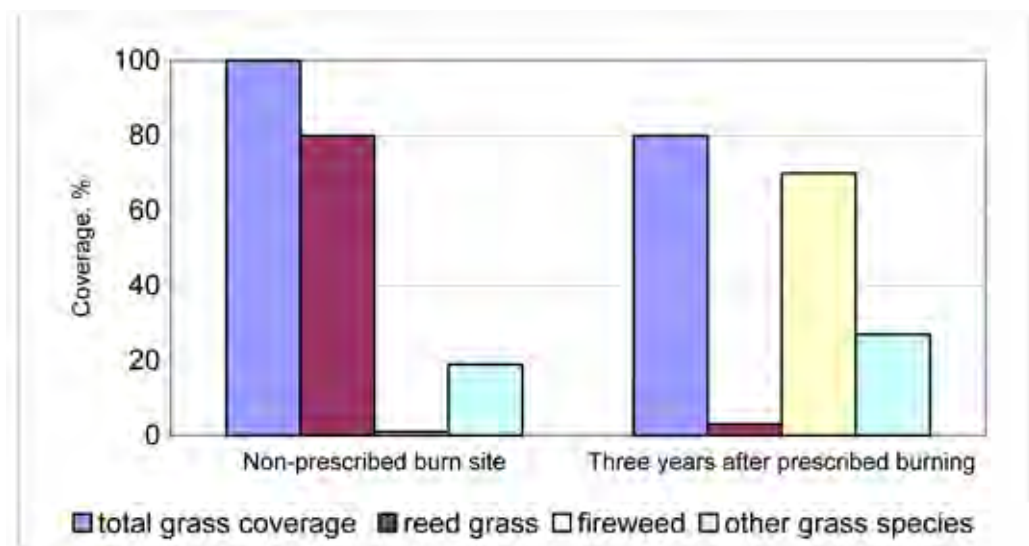


Figure 59. Comparison of logging site grass covers

Woody regeneration distribution across a logging site is, along with its amount, a major indicator of the regeneration success. Woody regeneration was estimated to occur on 88% and 77% of the total areas of burned and unburned logging sites, respectively. Both coniferous and deciduous woody regeneration exhibited more uniform distribution on prescribed burned logging sites (Table 45).

Table 45. Forest regeneration on prescribed burned vs. control logging sites

Indicator	Logging site	
	Prescribed burned	Control
Young woody regeneration amount, X1000/ha:		
Conifers	25	8.7
Deciduous	9.2	23.1
Occurrence across site, %:		
Young forest generation	88	77
Conifers	49	37
Deciduous	72	67
Ratio between young woody species, %:		
Conifers	59	25
Deciduous	41	75

Young tree generation development is stochastic by character and depends on interaction of many factors. Site forest type and logging-caused disturbance level are the two major factors controlling forest regeneration on unburned logging sites. Coincidence of a prescribed burning year with a good seeding year is also critical for prescribed burned logging site recovery.

Woody regeneration species composition appeared to be 3F3B4A + few SibP and S on an unburned logging site and 3S3SP1SibP1B2A + F and L on a prescribed burned logging site. As is clear from these compositions, the proportion of typical dark conifers is higher in the latter case, while deciduous woody species dominate in the former case.

Our analysis of woody regeneration distribution by height showed that individuals up to 1 m high prevailed among conifers and the majority of deciduous regeneration was 1-1.5 m high on the prescribed burned site (Figure 60). Deciduous species exhibited more uniform distribution by height on the control site compared to the prescribed burned site. The majority of deciduous woody seedlings appeared to be 1.0 to 1.5 m high, the total proportion of other deciduous seedling height groups accounting for 10-12% (Figure 61).

As was mentioned above, natural regeneration level is estimated based on amounts of young seedlings. The majority of young seedlings appeared to be 2-5 years old on the logging sites under comparison. Young regeneration age structure found on prescribed burned logging sites differed considerably from that on unburned sites. Prescribed burned logging sites were determined to contain young seedlings of all major woody species, while Scots pine and larch seedlings were absent in unburned logging sites. Scots pine was found to dominate young conifer regeneration on burned logging sites and fir on control sites. Among deciduous woody seedlings, aspen dominated over other species (Table 46). It can be thus concluded that natural woody regeneration species composition changed on prescribed burned logging sites. These changes allow us to assume that commercially valuable young conifer forest will eventually occur on prescribed burned logging sites.

Table 46. Young woody regeneration age structure on prescribed burned and control logging sites

Woody species	Logging site					
	Prescribed burned			Control		
	<2-yr-old seedlings	2–5-yr-old seedlings	6–10-yr-old seedlings	<2-yr-old seedlings	2–5 yr-old seedlings	6–10-yr-old seedlings
Scots pine	4.6	6.0	-	-	-	-
Siberian pine	0.6	1.1	-	-	0.7	-
Spruce	4.3	5.0	-	-	0.7	-
Fir	0.7	1.5	-	1.0	5.4	0.9
Larch	0.8	0.4	-	-	-	-
Aspen	2.3	2.9	-	3.4	7.8	1.7
Birch	1.7	2.3	-	2.3	6.4	1.5

Young woody regeneration condition is a critical factor controlling logging site recovery. Vigor of 2-10-yr old seedlings appeared to differ markedly between prescribed burned and unburned logging sites. The amount of healthy 6-10-yr-old conifer regeneration was determined to be 2.4 times that on the control site. Conversely, the amount of healthy 6-10-yr old deciduous regeneration was 3.1 times that on the control logging site (Table 47). The proportions of slightly and highly weakened 6-10-yr old conifer seedlings were largely similar on both logging sites.

Deciduous seedling distribution by vigor category was different compared to conifers. The total proportion of slightly and highly weakened 6-10-yr old deciduous regeneration was calculated to be 43% and 17% of the total amount of deciduous regeneration of this age category on prescribed burned and unburned logging sites, respectively (Table 47).

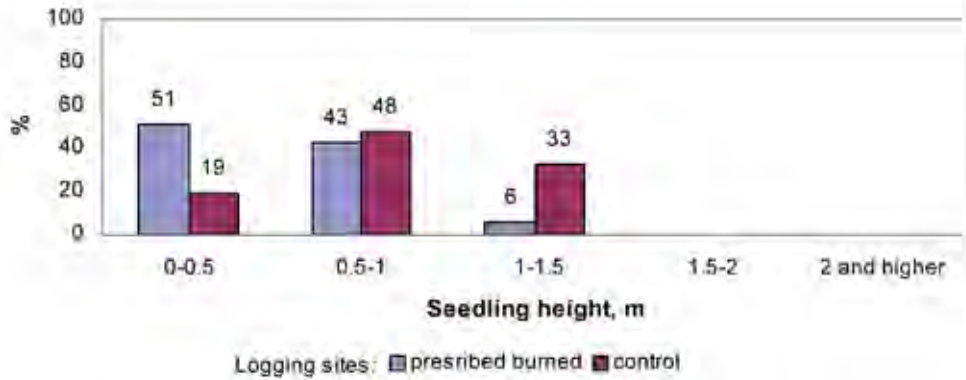


Figure 60. Ratio between conifer woody species height groups on logging sites

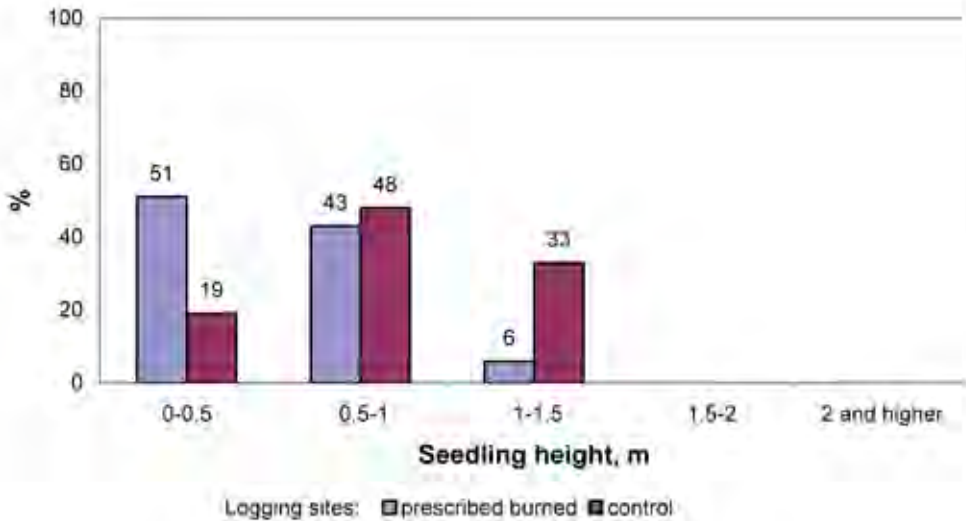


Figure 61. Ratio between deciduous woody species height groups on logging sites

Table 47. Amounts (x1000/ha) of 6-10-yr old woody seedlings by vigor category on prescribed burned and control logging sites

Woody species	Logging site					
	Prescribed burned			Control		
	Healthy	Slightly weakened	Highly weakened	Healthy	Slightly weakened	Highly weakened
Scots pine	5.9	3.7	1	-	-	-
Siberian pine	1	0.4	0.3	1.1	-	-
Spruce	5.7	2.5	1.1	1.2	-	-
Fir	1.5	0.5	0.2	3.8	2.6	0.9
Larch	0.7	0.3	0.2	-	-	-
Conifer total, %	59	30	11	60	30	10
Aspen	2.9	2	0.3	10.0	2.9	-
Birch	2.4	1.2	0.4	9.2	1	-
Deciduous total, %	57	35	8	83	17	-

Forest regeneration was successful on logging sites cleared using prescribed fire. A study by Ilyichev et al (2003) found that woody plants decrease in amount in the course of regeneration. However, the amount of <2-yr-old conifer seedlings appeared to be 11,000 / ha on our prescribed burned logging sites versus 1000 / ha on unburned logging sites. Also, prescribed fire was found to improve species composition and increase vigor of woody seedlings. Unlike on unburned logging sites, prescribed burned logging sites provide conditions favorable for rapid development of a new healthy conifer forest.

Conclusions

Prescribed fire is being gradually introduced into the Siberian forest management system. Forestry specialists no longer consider fire as an absolutely negative factor. They are beginning to understand that fire can be beneficial for forest functioning. Prescribed burning is beginning to be used more often as a wildfire prevention and suppression tool, since it was proved to be the most effective and inexpensive method of logging site fire hazard reduction and forest regeneration enhancement. Logging site prescribed burning was found to result in full consumption of slash of up to 2.5 cm in diameter by fire and 25-30% consumption of down deadwood of bigger diameters. Prescribed fires on logging sites produced 2-3 tons of ash per hectare and disturbed neither the upper fertile soil layer, nor microfauna due to high duff moisture content.

Woody species can be sown or planted on logging sites treated by prescribed fire without additional soil preparation. Conifer seedlings aging less than two years were observed to have high vigor on ash-enriched soil of prescribed burned logging sites. Today's prescribed burning technologies allow us to prevent logging site colonization by reed grass, bunch-like root system of which hampers seed germination and young woody seedling establishment and promote fireweed which cannot compete with woody plants and provides a good shelter for both self-sown and planted young conifers.

Logging slash removal by prescribed fire prevent wildfire occurrence for 2-3 years following the treatment, until new young forest generation is established. If a prescribed burned logging site is colonized by fireweed, a wildfire-free period can be as long as 5-6 years, since post-prescribed fire cured fireweed loading is insufficient for carrying wildfire.

Prescribed fire proved to be effective for clearing forest areas defoliated by Siberian moth. Using other methods appeared to technically unfeasible. Processes observed on prescribed burned Siberian moth sites are fairly similar to the post-prescribed burning situation on logging sites.

Ground fuels can be reduced to the minimum loading insufficient for fire spread over light-conifer logging sites by appropriate prescribed fire scheduling and achievement of a desirable burning regime. Full young light-conifer regeneration consumption by prescribed fire, with the overstory tree layer left intact, prevents surface fire crowning.

Broadcast burning of logging sites in plain and mountain dark-conifer forests, as well as Siberian moth forest sites, was permitted based on the multi-year scientific and practical experience gained by V.N. Sukachev Institute of Forest, the Russian Academy of Sciences. The Russian Federal forest management authorities permitted to burn treeless forest sites

and to create wildfire breaks along forest and agricultural land boundaries using prescribed fire. Further improvement of prescribed burning technologies will ensure their full-scale practicing in Siberian forest management in the near future.

References

- Anonymous (2007) Forest fire safety rules. Russian Federation Government Regulation No. 417, approved 30 June 2007; with amendments No. 343 of 5 May 2011, No. 26 of 26 January 2012, and No. 1128 of 1 November 2012. Web source: <http://base.consultant.ru/cons/cgi/online.cgi?req=doc;base=LAW;n=137514>
- Amosov, G.A. (1958) Certain forest fire-specific combustion characteristics. LenNIILH Publishing; Leningrad.
- Andreyev, Yu.A. (1999) Local population and forest fires in the Lower Angara region. VNIPO Publishing, Krasnoyarsk.
- Artsybashev, E.S. (1984) Forest fire science priorities. In: Combustion and forest fire, 5-7. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Atlas of Krasnoyarsk Region and Republic of Khakasia (1994). Roskartografia Publishing, Moscow.
- Babintseva, R.M. (1965) Living ground vegetation dynamics on Siberian pine logging sites in the northern part of western Sayan. In: Forest regeneration in Siberia, 148-162. Krasnoyarsky Rabochy Publishing, Krasnoyarsk.
- Babintseva, R.M., Cherednikova, Yu.S. (1983) Woody species regeneration under southern taiga forest stand canopy. In: Forest regeneration in southern taiga forest subzone, 5-13. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Baisan, C.H., Swetnam, T.W. (1990) Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Can. J. For. Res. 20, 1559-1569.
- Balbyshev, I.N. (1963) Comparison of forest fire resistance between different woody species. In: Forest fires and their suppression, 114-126. USSR Academy of Sciences Publishing, Moscow.
- Bazhenov, I.K. (1934) Western Sayan. USSR Academy of Sciences Publishing, Leningrad.
- Beadle, N.C.W. (1940) Soil temperatures during forest fires and their effect on the survival of vegetation. J. Ecology 28, 180-192.
- Belov, S.V. (1973) Controlled forest fire as a tool to restore taiga Scots pine and larch stands. In: Combustion and forest fires, 213-232. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Belov, S.V. (1982) Forest fire science. LTA Publishing, Leningrad.
- Brown, J.K. (1974) Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station (Ogden, UT).
- Brown, J.K., Oberheu, R.D., Johnston, C.M. (1981) Handbook for inventorying surface fuels and biomass in the Interior West. Gen. Tech. Rep. INT-129. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

- Bulletin of forest stands damaged by Siberian moth (as of September 1, 1996). East Siberian Forest Inventory Enterprise Publishing, Krasnoyarsk.
- Buzykin, A.I. (1964) Scots pine stands and forest regeneration processes in Barguzin and Turka river basins. Doctor Thesis, V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Buzykin, A.I. (1975) Surface fire influence on Scots pine forests of the central Angara region. In: Siberian forest resource protection, 141-153. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Byram, G.M. (1959) Combustion of forest fuels. In: Forest fire: control and use (K.P. Davis, ed), 61-89. McGraw-Hill Book Co. Inc., New York.
- Campbell, A.J., Tanton, M.T. (1981) Effects of fire on the invertebrate fauna of soil and litter of a eucalypt forest. In: Fire and the Australian biota (A.M. Gill, R.H. Groves, I.R. Noble, eds.), 217-242. Australian Academy of Science, Canberra.
- Caprio, A.C., Swetnam, T.W. (1993) Historical fire regimes in elevational gradient on the west slope of the Sierra Nevada, California. In: Proceedings of Symposium of Fire in Wilderness and Park Management: Past Lessons and Future Opportunities, 79-90. Univ. Montana, Missoula, MT.
- Cherednikova, Yu.S. (1963) Siberian pine-dominated forest types on the north-facing slope of Mana Belogorie Mountain Ridge. In: Siberian forest types, 133-140. Nauka Publishing: Moscow.
- Chernyshev A.I. (1962) Logging site clearing without using prescribed fire. Forest Management 4, 62.
- Crutzen, P.J., Goldammer, J.G. (1993) Fire in the environment: the ecological, atmospheric, and climatic importance of vegetation fires. John Wiley and Sons: New York.
- Davis, K.P. (1959) Forest fire: control and use. McGraw-Hill Book Co. Inc., New York, Toronto, London.
- Davydov, A.V. (1934) Estimation of contemporary methods of commercial logging site clearance. Goslestekhzdat Publishing, Leningrad.
- Dekotov, N.E. (1961) Measures to restore forest after forest harvesting by heavy machinery. Goslesbumizdat Publishing, Moscow-Leningrad.
- Dichenkov, N.A. (1997) Guidelines on constructing firebreaks by cured grass prescribed burning. VNIITSlesresurs Publishing, Moscow.
- Falaleyev, E.N. (1956) On characteristics of mixed Scots pine/deciduous woody species stands of North-Yenisei District, Krasnoyarsk Region. In: Proceedings of Siberian Technological Institute, Collection XII.
- Flannigan, M.D., Wotton, B.M. (1990) Lightning-ignited forest fires in northwestern Ontario. Canadian Journal of Forest Research 21, 277-287.
- Forest fire protection problems (1996) Appendix 2 to *Forest News Journal* June 1996. Ales Publishing, Moscow.
- Furyaev, V.V. (1966) Taiga Siberian moth sites and their prescribed burning. Nauka Publishing, Moscow.
- Furyaev, V.V. (1974) Use of prescribed burning for preventing wildfires and increasing Scots pine stand fire resistance. In: Forest fire science issues, 241-261. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Furyaev, V.V. (1996) Role of fire in forest development. Nauka Publishing: Novosibirsk.

- Gaikovskiy F.A. (1885) Forest fire protection. In: Forest Jurisprudence, 39-44.
- Galakhov, N.N. (1964) Climate. In: The USSR environmental conditions and natural resources. Central Siberia (I.P. Gerasimov, ed.), 83-118. Nauka Publishing, Moscow.
- Gerasimov I.P. (ed.) (1964). The USSR environmental conditions and natural resources. Central Siberia. Nauka Publishing, Moscow, 483 pp.
- Gerasimov, I.P., Preobrazhensky, V.S., Pomus M.I., Sochava V.B. (1965) The USSR environmental conditions and natural resources in the Pre-Baikal and Trans-Baikal regions. Nauka Publishing, Moscow.
- GFMC (Global Fire Monitoring Center) (2010). White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia. Edited and published on behalf of the participants of the Symposium on Fire Management in Cultural and Natural Landscapes, Nature Conservation and Forestry in Temperate-Boreal Eurasia and members of the Eurasian Fire in Nature Conservation Network (EFNCN) by the Global Fire Monitoring Center / Fire Ecology Research Group, Freiburg, Germany, 10 February 2010 (see Part IV of this volume).
- Girs, G.I. (1982) Weakened tree physiology. Nauka Publishing, Novosibirsk.
- Goldammer, J.G., Furyaev, V.V. (eds.) (1996) Fire in ecosystems of boreal Eurasia. Kluwer Academic Publ., Dordrecht, Netherlands, 528 pp.
- Goldammer, J.G., Price, C. (1998) Potential impacts of climate change on fire regimes in the tropics based on MAGICC and a GISS GCM-derived lightning model. *Climatic Change* 39, 273-296.
- Goldammer, J.G. (2010) Preliminary Assessment of the Fire Situation in Western Russia in 2010 by the Global Fire Monitoring Center (GFMC), 15 August 2010. Report presented at the parliamentary hearing of the *State Duma* of Russia, Committee for Natural Resources, Nature Use and Ecology, on 23 September 2010. *Int. Forest Fire News* No. 40, 20-42.
- Golovin, V.F. (1960) Krasnoyarsk region. *Krasnoyarsk News* Vol. 30 (1), 61-74. All-Union Geographic Society Publishing, Krasnoyarsk.
- Gorbachev, V.N., Popova E.P. (1992) Soil cover of central Siberian southern taiga. Nauka Publishing, Siberian Publishing House, Novosibirsk.
- Gossow, H. (1996) Fire-vegetation-wildlife interactions in the boreal forest. In: Fire in ecosystems of boreal Eurasia (J.G. Goldammer, V.V. Furyaev, eds.), 431-444. Kluwer Academic Publishers, Dordrecht.
- Grodnitsky, D.L., Raznobarsky, V.G., Shabalina, O.M., Pavlichenko, E.A., Soldatov, V.V. (2001) Siberian moth-damaged forest regeneration. In: Ecological issues of forest restoration and use" (R.M. Babintseva, A.I. Buzykin, V.N. Gorbachev, eds.), 127-143. Russian Academy of Sciences Publishing, Novosibirsk.
- Gudoshnikov, S.V. (1963) Siberian pine forests of Eastern Sayan. In: Problems of nature protection in Siberia and the Russian Far East, 112-118. USSR Academy of Sciences Publishing, Novosibirsk.
- Gulisashvili, V.Z. (1963) Sustainable use of the USSR mountain forests. *Forest Management* 12, 4.
- Humphreys, F.R., Craig, F.G. (1981) Effect of fire on soil chemical, structural and hydrological properties. In: Fire and the Australian biota (A.M. Gill, R.H. Groves, I.R. Noble, eds.), 177-202. Australian Academy of Science Publishing, Canberra.

- Ilyichev, Yu.N., Bushkov, N.T., Tarakanov, V.V. (2003) Recovery of burned forest sites in central Siberia. Nauka Publishing, Novosibirsk.
- Ivanov, V.V. (1952) On the role of steppe fire. Bulletin of Moscow Nature Research Society: Biological Series Vol. 57 (1), 62-69.
- Ivanov, N.I. (1965) Use of prescribed fire to clear forest logging sites and its implications to forest management. PhD Thesis, ULI Publishing, Sverdlovsk.
- Ivanova, G.A. (1996) Extreme forest fire seasons in Evenkia. Siberian Ecological Journal 3, 29-34.
- Ivanova, G.A., Ivanov, V.A., Kukavskaya, E.A., Conard, S.G., McRae, D.J. (2007) Fire influence on carbon emissions in Scots pine forests of central Siberia. Siberian Ecological Journal 6, 885-895.
- Ivanova, G.A., Perevoznikova, V.D. (1994) Forest logging site types and fire hazard in the low-mountain part of eastern Sayan. Geography and Natural Resources 1, 54-60.
- Ivanova, G.A., Perevoznikova, V.D. (1996) Post-fire living ground vegetation development in Scots pine stands of central Angara region. Siberian Ecological Journal 3, 109-116.
- Kasischke, E.S., Christensen, N.L., Stocks, B.J. (1995) Fire, global warming, and the carbon balance of boreal forests. Ecological Applications 5(2), 437-451.
- Kazansky, N.A. (1931) Experiments on fire influence on Scots pine regeneration. In: Experimental studies in general forestry (M.E. Tkachenko, ed.), 3-78. Selkolkhozgiz Publishing, Moscow-Leningrad.
- Kharinsky, M.I., Nepomnik, E.V., Filimonov, E.G., Martyshchenkov, V.V. (1991) Large and catastrophic fire fighting machinery. In: Forest fires and their suppression, 82-92. VNIIPOMleskhoz Publishing, Krasnoyarsk.
- Kolesnikov, B.P. (1963) Principles of the Ural mountain forest use. Forest Management 12, 8.
- Komarova, T.A. (1992) Post-fire forest succession in southern Sikhote-Alin. The Far East Science Center Publishing, Vladivostok.
- Korchagin, A.A. (1954) Conditions favoring fire occurrence and forest fire activity in the European Russia. In: Studies of the USSR vegetation cover, 182-322. Leningrad University Research Proceedings 166, Issue 9. Leningrad University Publishing, Leningrad.
- Korotkov, I.A. (1994) Forest vegetation zones in Russia and the former USSR republics. In: Carbon in forest and bog ecosystems of Russia, 29-47. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Korovin, G.N. (1996) Analysis of the Distribution of Forest Fires in Russia. In: Fire in ecosystems of boreal Eurasia (J.G. Goldammer, V.V. Furyaev, eds.), 112-128. Kluwer Academic Publishers, Dordrecht.
- Korzhuyev, S.S. (1975) Central Siberia. In: Plains and mountains of Siberia, 122-244. Nauka Publishing, Moscow.
- Kozlowski, T.T., Ahlgren, C.E. (eds) (1974) Fire and ecosystems. Academic Press, New York-San Francisco-London.
- Krasilnikov, P.K. (1961) Central Sayan forest types and their commercial importance. Transactions of the Institute of Botany, Russian Academy Issue 9, 49-150.

- Krasnoshchekov, Yu.N., Valendik, E.N., Bezkorovainaya, I.N., Verkhovets, S.V., Kisilyakhov, Ye.K., Kuzmichenko, V.V. (2007) Influence of Siberian moth site prescribed burning on soil properties in southern taiga found near Yenisei river. In: Regional-scale sustainable forestry problems (A.A. Onuchin, ed.), 251-261. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Krauklis, A.A. (1975) Region-specific features of taiga forest of Angara region. In: Natural Regimes and topogeosystems of Angara regional taiga, 14-27. Nauka Publishing, Novosibirsk.
- Kulikov, M.I. (1971) Siberian moth-damaged forest site types in western Siberian taiga. In: Western Siberian forest productivity and regeneration dynamics, 159-178. Nauka Publishing, Novosibirsk.
- Kurbatsky, N.P. (1962) Methods and tactics of forest fire suppression. Goslesbumizdat Publishing, Moscow.
- Kurbatsky, N.P. (1964) Forest fire problems. In: Forest fire occurrence, 5-60. Nauka Publishing, Moscow.
- Kurbatsky, N.P. (1970) Investigating forest fuel loading and properties. In: Forest fire science problems, 5-58. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Kurbatsky, N.P. (1975) Natural and human factors accounting for high forest fire hazard. In: Forest fire science problems, 9-18. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Kurbatsky, N.P., Ivanova, G.A. (1987) Forest-steppe Scots pine fire hazard and its reduction. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Kuznetsov, Yu.A. (1990) Forest protection from agricultural fires in the Trans-Baikal region. Abstract of PhD Thesis. Krasnoyarsk.
- Kuznetsov, Yu.A. (2001) Forest protection from agricultural fires in Trans-Baikal region. Newspaper and Magazine Complex Publishing, Ulan-Ude.
- Lapshina, E.I., Gorbachev V.N., Khramov A.A. (1971) Vegetation and soils of the Yenisei Mountain Ridge (the southern part). In: Vegetation of the right bank of Yenisei, 21-66. Nauka Publishing, Novosibirsk.
- Lubimova, E.L., Khotinsky N.A. (1960) On certain characteristics of southern forests of central Siberia. *Forest Management* 9, 23-25.
- Lukina, N.V., Nikonov V.V. (1995) Approaches to estimating diversity of northern undisturbed and disturbed by technogenic factors forest ecosystems. In: Biodiversity of forest ecosystems (Isaev A.S., ed.), pp. 271-274. Rosselkhozacademy Publishing, Moscow.
- Madany, M.N., Swetnam, T.W., West, N.E. (1982) Comparison of two approaches for determining fire dates from tree scars. *Forest Science* 28, 856-861.
- Matveyev, P.M., Bezrukikh, S.M., Filatov, E.N., Matveyev, A.M. (1987) Methods of prescribed burning for forest regeneration. Proceedings of a scientific-technical conference, Krasnoyarsk.
- Mälikonen, E., Levula, T. (1996) Impact of prescribed burning on soil fertility and regeneration of Scots pine. In: Fire in ecosystems of boreal Eurasia" (J.G. Goldammer and V.V. Fyryaev, eds.), 453-464. Kluwer Academic Publishers, Dordrecht.
- McRae, D.J. (1979) Prescribed burning in jack pine logging slash: a review. Rep. O-X-289. Sault Ste. Marie, ON, Can. For. Serv., Great Lakes For. Cent.

- McRae, D.J. (1986) Prescribed Burning for Stand Conversion in Budworm-killed Balsam Fir: An Ontario Case History. *Forestry Chronicle* 62, 96-100.
- McRae, D.J., Alexander, M.E., Stocks, B.J. (1979) Measurement and description of fuels and fire behavior on prescribed burns: a handbook. Rep. O-X-287, Sault Ste. Marie, Ontario, Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent.
- Melekhov, I.S. (1947) Forest characteristics and fire. Arkhangelsk Forestry Institute Publishing, Arkhangelsk.
- Melekhov, I.S. (1954) Forest regeneration on clearcuts in the north. Arkhangelsk Publishing House, Arkhangelsk.
- Melekhov, I.S. (1983) Forest fire Science: Forestry student manual. Moscow Forestry Institute Publishing, Moscow.
- Molchanov, A.A. (1940) Forest fire spread rate depending on weather conditions and forest stand characteristics. *Forest Management* 6, 64-67.
- Molchanov, A.A. (1957) Conditions of crown fire occurrence and spread in Scots pine stands. *Forest Management* 8, 50-53.
- Molchanov, A.A. (1976) Dendrochronological basis for weather forecasts. Nauka Publishing, Moscow.
- Molchanov, A.A., Shimanuk, A.P. (1949) Vegetation regeneration on clearcut forest sites. USSR Academy of Sciences Publishing, Moscow.
- Nazarov, D.D., Sabinin, L.Kh. (1913) Forest use regulations, issued in 1905 and reviewed by the Russian Senate in 1906, 1908, and 1910", Vol. 1-2, Second revision (non-official) (Revin's Topolitografia Publishing; St-Petersburg).
- Nefedyeva, L.G. (1970) Above-ground biomass distribution in the main landscape units of Onon-Argun steppe. In: Topological dependence of heat, moisture, and organic matter in geosystems, 90-92. Institute of Siberia and Far East Geography SB RAS Publishing, Irkutsk.
- Nesterov, V.G. (1949) Forest fire activity and methods of its estimation. Goslestekhizdat Publishing, Moscow-Leningrad.
- Odum, Yu. (1986) Ecology, Vol. 1. Mir Publishing, Moscow.
- Pobedinsky, A.V. (1955) Forest regeneration of clearcut sites. Goslesbumizdat Publishing, Leningrad.
- Pobedinsky, A.V. (1964) Commercial forest harvesting. Lesnaya Promyshlennost Publishing, Moscow.
- Pobedinsky, A.V. (1965) Scots pine forests of central Siberia and Trans-Baikal region. Nauka Publishing, Moscow.
- Popova, E.P. (1979) On duration of fire influence on forest soil properties. In: Combustion and forest fire, 110-117. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Prozorov, S.S. (1956) Pine looper in forests of western Siberia. In: Transactions of Siberian Forestry Institute, 13-84, Paper Collection 12, Issue 2.
- Rabotnov, T.A. (1978) On fire importance for vegetation cover development. *Botanical Journal* 11 (63), 1605-1611.
- Rodin, L.E. (1946) Vegetation prescribed burning to improve steppe grazing areas. *Soviet Botany* 3, 147-163.

- Rodin, L.E. (1981) Fire and arid zone vegetation. *Botanical Journal* 12, vol. 66, 1573-1683.
- Sampson, A.W. (1944) Plant succession on burned chaparral lands in Northern California. *Univ. Cal. Agr. Expt. Sta. Bul.*
- Sannikov, S.N. (1978) Approaching the problem of enhancing conifer woody species regeneration in the taiga zone. In: *Forest management improvement in the Urals*, 36-43. Ural Science Center Publishing, Sverdlovsk.
- Sannikova, N.S. (1977) Surface fire as a factor accounting for Scots pine seed germination and seedling development. In: *Forest fire detection and analysis*, 110-128. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Serebrennikov, P.P., Matreninsky V.V. (1937) *Forest fires and their suppression*. Goslestekhzdat Publishing, Moscow-Leningrad.
- Schenikov, A.P. (1964) *Introduction to Geobotany*. Leningrad University Publishing, Leningrad.
- Shilov, D. (1889) *Collection of private and public forest protection regulations*. Lesnoi Department Publishing, St. Petersburg.
- Shumilova, L.V. (1962) *Botanical geography of Siberia*. Tomsk University Publishing, Tomsk.
- Smagin, V.N. (1978) Forest management zoning in Siberia. In: *Forest vegetation resources of Siberia*, 5-23. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Smagin, V.N. (Ed) (1980) *Forest types of southern Siberian mountains*. Nauka Publishing, Novosibirsk.
- Sofronov, M.A. (1967) *Forest fires in southern Siberian mountains*. Nauka Publishing, Moscow.
- Sofronov, M.A. (1970) On forest fuel drying under forest canopy. In: *Forest science issues*, 59-104. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Sokolov, G.A., Bogush O.A. (1999) Logging slash prescribed burning influence on small mammals. In: *Proceedings of the 6th Teriological Society Congress*. Russian Academy Publishing, Moscow.
- Standard forest fire prevention measures (1993) Adopted by the Russian Federal Forest Service, Order 289 of 29 October 1993.
- Stelmachovich, S. (1998) Forest fires on the island of Sakhalin: A chronicle of the disaster. *Wildfire* Vol. 7 (12), 35-39.
- Stocks, B.J. (1987) Fire potential in the spruce budworm-damaged forests of Ontario. *Forest Chronicles* 63, 8-14.
- Sushkina, N.N. (1931) On forest soil microbiology in the context of fire influences. In: *Experimental studies in general forestry* (M.E. Tkachenko, ed.), 137-169. Selkolkhozgiz Publishing, Moscow-Leningrad.
- Swetnam, T.W. (1993) Fire history and climate change in giant sequoia groves. *Science* 262, 885-889.
- Swetnam, T.W. (1996) Fire and climate history in the central Yenisei region, Siberia. In: *Fire in ecosystems of boreal Eurasia* (J.G. Goldammer, V.V. Furyaev, eds.), 90-104. Kluwer Academic Publishers, Dordrecht.

- Timoshkina, O.A., Timoshkin, V.B., Sokolov, G.A. (2001) Wildlife complexes on logging sites and prescribed burned areas in the western part of eastern Sayan. *Botanical studies in Siberia* 9, 172-181. Krasnoyarsk.
- Tkachenko, M.E. (1911) Forests of the North. *Proceedings of forestry experiments in Russia* 25, St. Petersburg.
- Tkachenko, M.E. (1931) Forest logging site clearance. Selkolkhozizdat Publishing, Moscow-Leningrad.
- Tkachenko, M.E. (1952) Forestry fundamentals. Goslesbumizdat Publishing, Moscow-Leningrad.
- Tsvetkov, P.A., Ivanov, V.V. (1985) Logging slash loads on forest sites harvested by heavy forest logging machines. In: *Forest fires and their effects*, 124-132. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Turin, A.V. (1925) Scots pine forestry fundamentals. Novaya Derevnnya Publishing, Moscow.
- Vaganov, E.A., Arbatskaya, M.K., Shashkin, A.V. (1996) Climate history and fire frequency in the central part of Krasnoyarsk region: Dendrochronological analysis of tree increment-climate-fire frequency interaction. *Siberian Ecological Journal* 30 (1), 19-28.
- Valendik, E.N. (1963) Fire hazard scales for forests of Krasnoyarsk region and Tuva Republic. In: *Forest fires and their suppression*, 31-57. USSR Academy of Sciences Publishing, Moscow.
- Valendik, E.N., Isakov, R.V. (1978) On forest fire intensity. In: *Forest fire prediction*, 40-51. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Valendik, E.N., Matveyev, P.M., Sofronov, M.A. (1979) Large forest fires. Nauka Publishing, Moscow.
- Valendik, E.N. (1990) Large forest fire suppression. Nauka Publishing, Novosibirsk.
- Valendik, E.N., Ivanova, G.A. (1996) Extreme fire seasons in boreal forests of central Siberia. *Forest Science* 4, 12-19.
- Valendik, E.N. (1998) Controlled fire in Siberian forestry. *Forestry* 1, 51-52
- Valendik, E.N., Vekshin, V.N., Verkhovets, S.V., Zabelin, A.I., Ivanova, G.A., Kisilyakhov Ye.K. (2000) Controlled fire on dark conifer logging sites, Russian Academy of Sciences Publishing, Novosibirsk.
- Valendik, E.N., Vekshin, V.N., Ivanova, G.A., Kisilyakhov, Ye.K., Perevoznikova, V.D., Bryukhanov, A.V., Bychkov, V.A., Verkhovets, S.V. (2001) Prescribed burning of mountain forest logging sites. Russian Academy of Sciences Publishing, Novosibirsk.
- Valendik, E.N., Ivanova, G.A. (2001) Fire regimes in Siberian and Russian Far East forests. *Forest Science* 4, 69-76.
- Valendik, E.N., Verkhovets, S.V., Kisilyakhov, Ye.K., Lantukh, A.Yu. (2004) Contribution of Siberian moth-damaged forest areas to wildfire activity in the Lower Angara region. *Forest Management* 6, 27-29.
- Valendik, E.N., Sukhinin, A.I., Kosov, I.V. (2006) Surface fire influence on conifer woody species tolerance. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.

- Valendik, E.N., Verkhovets, S.V., Kisilyakhov, Ye.K., Kosov, I.V., Tulpanov, N.A., Lantukh, A.Yu. (2007a). Siberian moth site prescribed burning technology. In: Regional-level sustainable forestry problems (A.A. Onuchin, ed.), 246-251. V.N. Sukachev Institute of Forest Publishing, Krasnoyarsk.
- Valendik, E.N., Rybnikov, V.Yu., Perevoznikova, V.D. (2007b) Forest regeneration on prescribed burned dark conifer logging sites. *Forest Management* 4, 23-25.
- Valendik, E.N., Lasko, R.J., Kisilyakhov, Ye.K., Ivanova, G.A., Perevoznikova, V.D., Verkhovets, S.V. (1997) Prescribed fire for managing Siberian Forests. *Wildfire* 6 (8), 29-32.
- Valendik, E. N., Brissette, J. C., Kisilyakhov, Ye. K., Lasko, R. J., Verkhovets, S. V., Eubanks, S. T., Kosov, I. V., Lantukh, A. Yu. (2006) An experimental burn to restore a moth-killed boreal conifer forest, Krasnoyarsk region, Russia. *Mitigation and Adaptation Strategies for Global Change* 11, 883-896.
- Vallette, J.C., Gomendy, V., Maréchal, F., Houssard, C., Gillon, D. (1994) Heat transfer in the soil during very low-intensity experimental fires: the role of duff soil moisture content. *Int. Journal of Wildland Fire* 4 (4), 225-238.
- Van Wagner, C.E. (1968) The line intersect method in forest fuel sampling. *For. Sci.* 14, 20-26.
- Vasilevich, V.I. (1969) Statistical methods in geobotany. Nauka Publishing, Leningrad.
- Vaskov, S.P., Patrikeyev E.I. (1986) Changes of physical and chemical soil properties on burned sites. In: Developing approaches to sustainable use of forest resources of central Volga region, 50-53. Mari-El Polytechnical Institute Publishing, Yoshkar-Ola.
- Viro, P.J. (1974) Effects of forest fire on soil. In: Fire and ecosystems (T.T Kozlowski and C.E. Ahlgren, eds.), 7-44. New York-San Francisco-London, Academic Press.
- Volobuyev, M.I. (1960) On geological structure of the southern Angara-Kansk part of the Yenisei Mountain Ridge. In: Collection of articles on Krasnoyarsk region geology. Gosgeoltekhizdat Publishing, Moscow.
- Weber, M.G., Flannigan, M.D. (1997) Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. *Environmental Reviews* 5, 145-166.
- Wittaker, R. (1980) Communities and ecosystems. Progress Publishing, Moscow.
- Yelpatievsky, M.P., Rumyantsev, S.P., Yarmolovich, B.K. (1935) Forest type-specific methods of logging site clearing. Goslestekhzdat Publishing, Leningrad.
- Yerokhina, A.A., Kirillov, M.V. (1964) Soils. In: The USSR environmental conditions and natural resources. Central Siberia (I.P. Gerasimov, ed.), 189-226. Nauka Publishing, Moscow.
- Zhukov, A.B., Korotkov, I.A., Kutafyev, V.P., Nazimova, D.I., Rechan, S.P., Savin, E.N., Cherednikova, Yu.S. (1969) Forests of Krasnoyarsk region. In: Forests of the USSR, Vol.4. Nauka Publishing, Moscow.
- Zvereva, G.A. (1966) Taiga around Poima riverhead (eastern Sayan). *Proceedings of Siberian Branch of the Russian Academy: Biology and Medicine Series Issue 1* (4), 7-13.

Part II: The Bor Forest Island Fire Experiment

FIRESKAN Science Team

Fire Research Campaign Asia-North (FIRESKAN)

Preface of the 2013 Publication

The initiation of East-West cooperation in wildland fire science and management goes back to the first visit of two wildland fire scientists from the U.S.A. and Germany in the Soviet Union in 1991 (Pyne 1992) and follow-up exchange arrangements under the frame of the International Boreal Forest Research Association (IBFRA) (Fosberg 1992). Subsequently in 1993 the first East-West conference on „Fire in Ecosystems of Boreal Eurasia“ and the Fire Research Campaign Asia-North (FIRESKAN) with its core activity, the „Bor Forest Island Fire Experiment“ were organized, *in tandem*, in Krasnoyarsk Region, Central Siberia.

While the aim of the conference was to compile, discuss and publish the state of knowledge on fire in boreal ecosystems, particularly in Eurasia (Goldammer and Furyaev 1996), the research campaign was designed to investigate hypotheses developed by the International Boreal Forest Research Association (IBFRA), Stand Replacement Fire Working Group. These hypotheses are related to quantitatively understanding boreal ecosystems, the role of fire in boreal ecosystems, and modeling and predicting forest dynamics. The involvement of atmospheric scientists through the structures of the International Global Atmospheric Chemistry (IGAC) Project, a core project of the International Geosphere-Biosphere Program (IGBP) gave additional insights into aspects of fire emissions and atmospheric chemistry. On 6 July 1993 a large forest fire experiment was conducted on Bor Forest Island, Krasnoyarsk Region, Russia. In this paper the results of the first phase of the experiment are given and the medium- to long-term objectives of follow-up research are described.

Abstract

Fire is an important natural and anthropogenic factor in the dynamics of the boreal forest system. The ecological and environmental impacts of boreal fires depend on fire weather, fuel availability, fire behavior, and the history of stand development (frequency and size of fires and other biotic and abiotic disturbances, influence of surrounding landscape on successional developments). About 70% of the global boreal forest is in Eurasia, almost all of it in the Russian Federation. It is estimated that in years with high fire danger up to ca. 10 million hectares (ha) of forest and other land in the Russian Federation are affected by fire. The demand for reliable information on the role of natural and anthropogenic fire, and the necessity of developing adequate fire management systems, is basically due to globally increasing concerns about (1) impacts of boreal wildfires on atmosphere and climate, (2) changing utilization and ecologically destructive practices in boreal forestry, and (3) possible consequences of global climate change on the boreal forest system (Crutzen and Goldammer 1993).

In 1993 a conference on Fire in Ecosystems of Boreal Eurasia, and a subsequent Fire Research Campaign Asia-North (FIRESCAN) were organized, *in tandem*, in the Krasnoyarsk Region, Central Siberia. The aim of the conference was to compile, discuss and publish the state of knowledge on fire in boreal ecosystems, particularly in Eurasia (Goldammer and Furyaev 1996).

The research campaign was designed to investigate hypotheses developed by the International Boreal Forest Research Association (IBFRA), Stand Replacement Fire Working Group. These hypotheses are related to quantitatively understanding boreal ecosystems, the role of fire in boreal ecosystems, and modeling and predicting forest dynamics. The involvement of atmospheric scientists through the structures of the International Global Atmospheric Chemistry (IGAC) Project, a core project of the International Geosphere-Biosphere Program (IGBP) gave additional insights into aspects of fire emissions and atmospheric chemistry. On 6 July 1993 a large forest fire experiment was conducted on Bor Forest Island, Krasnoyarsk Region, Russia. In this paper the results of the first phase of the experiment are given and the medium- to long-term objectives of follow-up research are described.

1. Fire in Ecosystems of Boreal Eurasia

The worlds total boreal forests and other wooded land within the boreal zone cover 1.2×10^9 ha of which 920×10^6 ha are closed forest. The latter number corresponds to ca. 29% of the worlds 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*) of 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 43-65% share of the worlds closed boreal forest.

1.1. 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 intensity have different effects on the ecosystem. High-intensity fires lead to the replacement of forest stands by new successional sequences. Low-intensity surface fires favor the selection of fire-tolerant trees such as pines (*Pinus* spp.) and larches (*Larix* spp.) and may repeatedly occur within the lifespan of a forest stand without eliminating it.

Large-scale forest disturbances connected with drought and fires are familiar from recent history. The Tunguska Meteorite Fall near Vanavara (Krasnoyarsk Region, Russia) (ca. $60^{\circ}54'N$ - $101^{\circ}57'E$) on 30 June 1908 a cometary nucleus explosion at ca. 5 km altitude,

was one of the more exceptional events which caused large-scale forest fires in the region of impact.¹

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 52-70°N and 69-112°E. The main center of fires was between Angara River and Nijnya Tunguska, and the total area burned was estimated at 14.2×10^6 ha. However, the smoke of these fires covered the region between 64-72°N and 61-133°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, humans or a combination of the two were the primary cause of the extended fires of 1915. In Eurasia fire has been for a long time an important tool for land clearing (conversion of boreal forest), silviculture (site preparation and improvement, species selection), and in maintaining agricultural systems, e.g. 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 of Eurasia. In the early 20th 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-sized fire systems (treatment of vegetation by free burning) was replaced by mechanized systems (use of fossil-fuel driven mechanical equipment). Despite the loss of traditional burning practices, however, humans are still the major source of wildland fires; only 15% of the recorded fires 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 less than 4,000 ha. Thus, the major occurrence of Eurasian fires is in the territory of the Russian Federation and other countries of the Commonwealth of Independent States. Statistics compiled by the Russian Aerial Fire Protection Service *Avialesookhrana* show that between 10,000 and more than 30,000 forest fires occur each year, affecting up to $2-3 \times 10^6$ 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 of 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, $1-5 \times 10^6$ ha per year. An exceptional year was 1987 in which 7.4×10^6 of forests were burned in Canada (FIRESCAN Science Team 1994).

1 For more details see http://en.wikipedia.org/wiki/Tunguska_event

1.2. Concerns: Global Change and Fire

Expected global warming over the next 30-50 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). As Wein and de Groot (1996), Fosberg (1996), Stocks (1993), and Stocks and Lynham (1996) underscore, fire may be the most important (widespread) driving force in changing the taiga under climatic warming conditions. The prediction of increasing occurrence of extreme droughts in a $2\times\text{CO}_2$ climate indicates that fire regimes will undergo considerable changes. Increasing length of the fire season will lead to a 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 of vegetation zones, e.g. the boreal forest shifting north ca. 500-1000 km (Kauppi and Posch 1988). The shift of ecosystems will have considerable impacts on the distribution of phytomass. Estimates of carbon 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 Gt ($66\text{--}98\times10^{15}$ g) (US Department of Energy 1983; Apps et al. 1993). Additional large amounts of carbon 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 carbon pool and lead to additional release of carbon into the atmosphere, thus acting as temporary positive feedback loop to global warming.

Changing forestry practices in boreal Eurasia, stimulated by increasing national and international demands for boreal forest products, have resulted in the widespread use of heavy machinery, large-scale clearcuts, and, with this, in the alteration of fuel complexes. The opening of formerly closed remote forests by roads, and subsequent human interferences bring new ignition risks. 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.

1.3. 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 (FIRESKAN) was prepared under the co-sponsorship of 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 cf. 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 post-fire 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. collection of 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 the summer of 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 of Siberia, about 28 km west of the Yenisei 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 1). The study site is a nearly level, slightly elevated, sandy island, about 50 ha in size, which is surrounded by bogs dominated by mixed-grass, sphagnum and tall sedge (Figure 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.

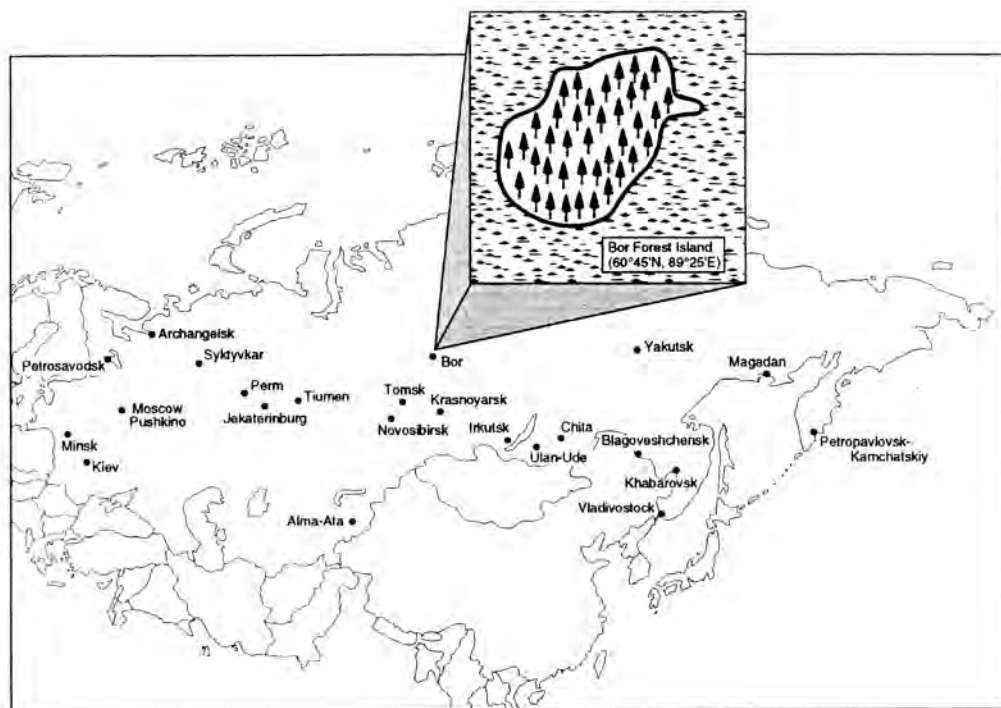


Figure 1. Location of Bor Forest Island near Bor, Krasnoyarsk Region, Russian Federation. All other names of locations are regional headquarters of the Russian Aerial Fire Protection Service Avialesookhrana or relevant services in other countries of the Commonwealth of Independent States.

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 450-500 mm, with wide year-to-year variations. Although most precipitation occurs in the 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 2-3 times per decade).

The fire season lasts from May to September, with most fires in June-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 40-50 years in the north to 25-29 years in the central part of Krasnoyarsk Region. 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 years. As in the rest of Siberia, periodic extreme fire seasons are common. Those seasons are remarkable for long rainless periods (up to 38 days), with relative humidities down to

30%, and air temperatures up to 30-35°C. Until the end of the 19th century, extreme fire seasons in the central Krasnoyarsk Region occurred from 3-4 to 7 times a century. This has increased up to 20-25 events in the 20th century. Most of these fires are human caused, as a result of intense forest exploitation in the area. For the past 50 years, extreme fire seasons associated with mass 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)).



Figure 2. Aerial view of Bor Forest Island immediately prior to the experimental fire

Results of the first two years of investigation from the Bor Forest Island Fire Experiment, including pre- and post-fire studies, are given in the following two sections. Part II reports characteristics of the study site and its vegetation, and presents preliminary results on short-term fire effects. Part III describes fuel characteristics, fire behaviour, and emissions.

2. Fire History, Ecology, and Short-term Fire Effects

2.1. Fire Ecology of *Pinus sylvestris* Forests of the Sym Plain

The Bor Forest Island experimental site is typical of pine-lichen forests of 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, dominant pine stand age is dependent on the time period since the last intense fire. Pine stands on sands are represented primarily by pine-lichen forest types. Species composition of post-fire woody plant regeneration is typically similar to pre-fire composition. The time it takes for a young stand canopy to become closed after fire depends on burned area size, seed sources available, 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 are generally 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 of Central Siberia. These stands occurred on sandy and podzolic soils on high terraces and in river valleys, and experienced periodic fires. They were the same forest type as the Bor Forest Island experimental site. Popov found that grass cover following burns in pine-lichen forests was usually 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 per hectare) after the first year of good seed crop. Popov described the following developmental stages for these stands:

- young pine stands with red whortleberry (*Vaccinium vitis idaea*)-lichen surface cover, and birch as a minor component
- pole pine stands with litter and lichen surface cover;

- middle-aged, pre-mature, mature and old pine stands with the surface cover dominated by red whortleberry; and
- pine-mixed grass-red whortleberry forest.

Popov found that forest regeneration typically occurred without major changes in woody or herbaceous species composition. Some of the typical understory species for this type, along with their importance in the different regeneration stages, are listed in Table 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 Arctic rose (*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 single, scattered individuals.

During pole stand formation, a fragmented understory of alder develops, Arctic rose 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 the formation of a lichen layer under the canopy of thinned pole stands. Rapid drying out of lichens promotes frequent low-intensity fires. Post-fire 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 the age of 80-100 they become rather open. Single individuals of alder, Arctic rose 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 (> 1,000,000 / ha), but underdeveloped. Understory is represented by low growing Arctic rose 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.

Table 1. Understory vegetation typical of different forest development stages in pine stands on sandy podzolic soils in accordance with the classification of Popov (1982). See also Table 3.

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

un = single individual;

sol = up to 10 percent cover;

sp = few individuals, 10 to 30 percent cover;

cop = 30 to 90 percent cover.

Similar patterns have been described for post fire dynamics of 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 of development. Six regeneration (succession) stages differing in fire resistance were described for pine stands on fresh sands, which are mainly 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 due to the presence of downed wood and snags. Recurrent fires can hamper the development of living surface cover and result in destruction of all recent seedlings. Post fire 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 0.6-0.7 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 0.6-0.7 of the area.

To conclude, post fire 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 process of 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 as to the timing of post-fire 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 the duration of regeneration stages or in exact patterns of understory development.

Post-fire 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 of the middle taiga subzone of the Siberian plain. We speculate that there may be some similarities to insect populations in clearcut areas of neighbouring 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 that may be most likely to invade following fire include:

- *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, as it has been observed to fly great distances toward fires during the night by following smoke plumes.
- *Monochamus* species. *M. galloprovincialis pistos* 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 of wood quality.

While information from unburned and cutover 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.

It should be noted that the fire effects research studies referred to in this paper were conducted by comparing burned areas of different ages. Long-term observation of a permanent site burned by a high-intensity fire has never been undertaken in Siberia before.

2.2. Physical Characteristics of Bor Forest Island Study Site

The study site is a nearly level, slightly elevated, sandy island, about 50 ha in size, 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 podsol, 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 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).

Table 2. Characteristics of the soil profile of Bor Forest Island

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
B _s	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

2.3. 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).

(a) 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

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, for purposes of reconstructing 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 Yenisei River. The lake catchment is dominated by *P.sylvestris*, but also includes scattered aspen groves. The catchment was clearcut 1 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 years ago, with a concurrent decrease in *Picea* pollen (Figures 3a and 3b), patterns typical of western Siberia (Peterson 1993). Although changes in the composition of vegetation may have been modest over the last 5000 years, 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 BP (Figure 3c). 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 BP and 3400 to 2800 BP, 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, suggesting that distribution data are relatively unbiased by method. Sieve samples and airborne samples were analyzed by identical methods, and results were identical (Figure 3c). The decline in fire importance over the last 5000 years suggests that boreal fire regimes are sensitive to climate changes such as those that might occur with global warming. Before 4600 BP, 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 over the impacts of such changes on fire regimes in the boreal zone.

(b) 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 of this region. Ultimately, we plan to use the fire history of Bor Forest Island, in combination with fire histories from many other stands in west-central Siberia to investigate the interactions of 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" to the northeast of the island (trees EXB 15 to EXB 101) with a chainsaw. The mainland was located 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 located 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 year dates of fires and the approximate season of occurrence of the fires 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), so the ages of overstory trees and cohorts reported here are preliminary and should be confirmed by further sampling.

Before the experimental burn of 1993 at least six fires burned portions of the island during the past six centuries (AD 1481, 1638, 1753, 1796, 1867, and 1956). Intervals between these fires ranged from 43 to 157 years, with a mean fire interval (MFI) of 95 years. Fire-scarred samples in pine forests adjacent to the island, but separated by wet bog, recorded nearly three times more fire dates during the same time period (Figure 4a). 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 years. Preliminary stand age structure estimates on Bor Island, derived from increment cores taken from mature trees (Figure 4b), suggest that the overstory is composed of at least two major cohorts that established approximately 180 and 130 years ago. We speculate that these cohorts established following the fires of 1796 and 1867, respectively. An earlier cohort, about 320 to 340 years 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 year, microscopic analysis also 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, while the next largest percentage was within the first one-third of earlywood. Although we lack specific knowledge of 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), while 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 of 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.

3. Vegetation and Fuels

3.1. Pre-fire 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 the bottom of the crown for 5 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 of 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 plots (1 m²) 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) (Table 3):

Table 3. Drude Scale classification categories

Scale rating	Description
soc (socialis)	Dominant plant species; coverage is more than 90 percent
cop3 (coptosal)	Very abundant; 70-90 percent cover
cop2 (coptosal)	Many individuals; 50-70 percent cover
cop1 (coptosal)	Thirty to 50 percent cover
sp (sporsal)	Individuals small in number; cover 10-30 percent
sol (solitarie)	Very few individuals; up to 10 percent cover
un (unicum)	A single individual

Vegetation was typical of central taiga forests of 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 years old). 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. The volumes of standing living trees, snags and downed wood were 248, 14.6, 17.3 m³ ha⁻¹, respectively. Downed wood was in various stages of decomposition.

Table 4. Characteristics of pre-fire living ground cover in a pine-lichen forest, Bor Forest Island experimental site

Lichens and mosses	Abundance (Drude Scale)
<i>Cladina stellaris</i>	cop3 soc
<i>Cladonia sylvatica</i>	sol
<i>Cladonia rangiferina</i>	sol
<i>Cladonia uncinata</i>	sol
<i>Cetraria islandica</i>	sol
<i>Pleurozium schreberi</i>	cop3
<i>Hylocomium splendens</i>	sp
<i>Dicranum undulatum</i>	sp
<i>Ptilium cristacastrensis</i>	sp
<i>Politrichum strictum</i>	sol
Sphagnum	sol
Total moss and lichen cover	90%
Shrubs	
<i>Vaccinium vitis-idaea</i>	Cop2
<i>Vaccinium myrtillus</i>	Cop1 Cop2
<i>Vaccinium uliginosum</i>	Sp
<i>Ledum palustre</i>	Cop1 Cop2
Carex	Sp
<i>Calamagrostis langsdorffii</i>	Sol
Total shrub cover	10%

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 4). The heights of the lichen, moss, and low shrub layers were 5-7, 3-5 and 12-35 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.

3.2. First-year Vegetation Recovery and Stand Conditions

Photo points: Ten permanent photo points were established on the island before the fire on sites selected to represent the range of pre-fire stand conditions in terms of tree size distribution, occurrence of snags, regeneration, 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 5a, 5b, and 5c illustrate typical stand conditions at one of these photo points before, immediately after, and one year after the fire. Note 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.

Post-fire vegetation sampling: When member of the Team returned to study forest regeneration processes on the experimental site, one year after the fire, no resample of pre-fire plots to determine vegetation cover was done since living ground cover was virtually nonexistent. Isolated individual pine seedlings were observed in the interior of the island as well as newly emerged small sedge and wild rosemary (*Ledum*) sinusia in places where the fire burned into the edges of the bog. Otherwise there was no visible regeneration of either herbaceous or woody species.

This updated report provides the photographic inventory of re-visits of Bor Forest Island between 1993 and 2012. Examples of the observation plots monitored until 2012 are provided in Annex II.

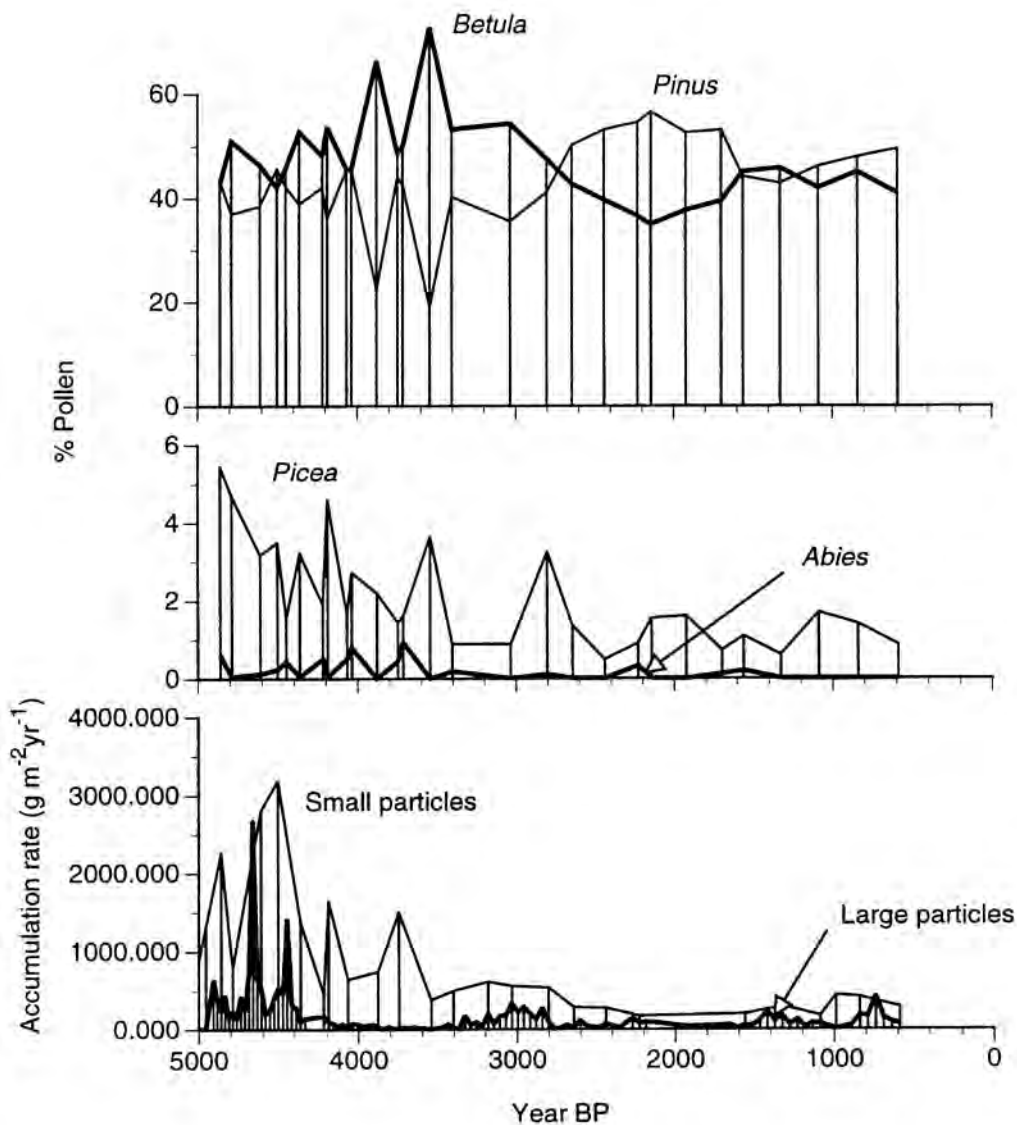


Figure 3. Pollen counts (% of total pollen) from Bor Lake core for (a) *Betula* and *Pinus*, (b) *Picea* and *Abies*, and (c) accumulation rates of carbon particles in sediment core. The period covered is 5000 to 600 years BP.

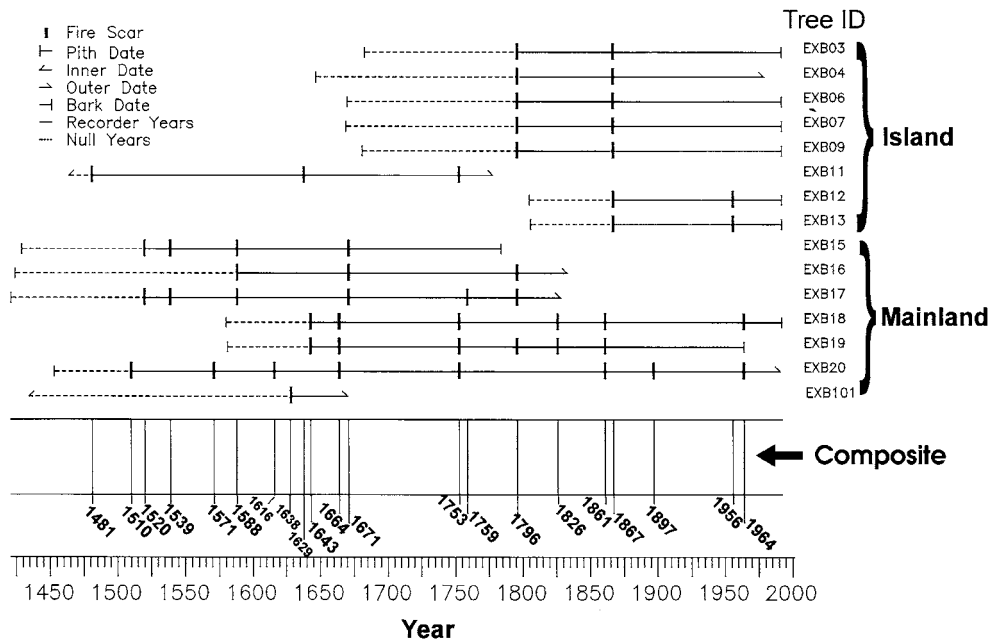


Figure 4a

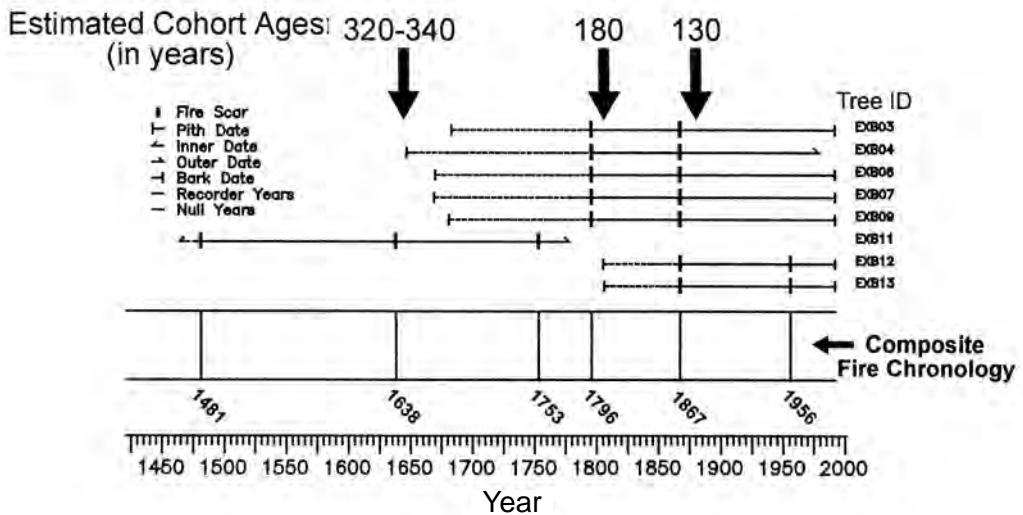


Figure 4b

Figure 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.

3.3. 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 10 1 m^2 plots (one every 10 m) for determining pre-fire lichen, litter, and small branch loads. Forest floor organic matter was measured in 0.5 m by 0.5 m subplots. Samples were oven dried to constant weight and then weighed. Before sampling, we measured depths of lichens and litter and of the forest floor organic layer. After the fire we established 10 additional 20 by 25 cm plots next to the pre-fire plots to measure the organic matter remaining after fire. Twenty by 25 cm plots were also established next to these plots the year after the fire to determine post-fire litter volume. The Canadian team also measured pre-burn and immediate post-burn fuel loads at 12 sites throughout the burned area, primarily to quantify fuel consumption in the fire. Their methods are described in Section III.

Pine-lichen stands are remarkable for rapid development of flammability after a fire and their high flammability over a long period during the fire season. A considerable load of ground fuels on the forest island (Table 5) promoted the occurrence of high fire intensity, even in the absence of significant ladder fuels. The pre-fire surface fuel loads of 33.6 t ha^{-1} were decreased by 50 percent a year following the fire. The Canadian team estimated pre-fire ground and small ($<3 \text{ cm}$) 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 pre-fire 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 a 88% reduction in depth (all the lichen layer plus an average of 1.3 cm of duff). Ivanova (Table 4) reported 79% reduction in the loose surface litter and 21% reduction in the forest floor (duff) layer one year after fire. Except around the bases of trees, there were few places where the fire burned to mineral soil. Essentially all of the loose litter measured in 1994 had accumulated since the fire. This litter consisted primarily of needles (77.6 percent) and bark (8.6 percent) shed from injured and dying trees following the fire. The pre-fire research allowed us to estimate pre-fire fuel loads and biomass consumption, and to investigate post-fire processes of forest restoration in this area.

Table 5. Russian measurements of pre-fire and post-fire (1 year after fire) structure and load of fuels in a pine-lichen forest (dry weights) at Bor Forest Island. Miscellaneous litter includes lichens (pre-fire), needles, bark, etc. Small branches are branches up to 2 cm diameter. Forest floor is the compacted forest floor organic layer.

Fuel Type	Pre-fire		Post-fire
	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

To measure the effects of the fire on the carbon and nutrient contents of the soil organic layer, and to monitor post-fire accumulation of soil organic matter, two 30 m x 30 m plots were established. Pre-fire and post-fire samples were collected on 5 and 7 July, 1993. The chemistry of the humus layers before and after the fire is described in Table 6. Fire intensity on Plot 2 was higher because of a greater amount of downed woody material.

Table 6. Element content and standard deviations (kg ha⁻¹) of the humus layer of 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 ± 3,890	20,030 ± 1,300	20,040 ± 3,010	15,170 ± 3,260	19,870 ± 3,290	17,600 ± 3,470
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

3.4. 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 based on foliage color (light green or brown in areas where crowns were scorched, dark green where they were not). A 30 m by 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 the percent of crown with dried foliage were recorded for each tree. Trees were classified as alive, dead, or dying. The plot was located on the northwest corner of the island in 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 percent of the area of the island burned as a crown fire (see Figure 15). All of the trees in these parts of the stand died. In another 25 percent 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 percent were 6-11 cm in diameter, 53 percent 12-17 cm DBH, and 30 percent 18-23 cm DBH (Figure 6). Fifty-five percent of the trees in the plot had maximum char heights of greater than 2 meters (Figure 7). Except for the smallest size class, there was generally a positive correlation between tree diameter and char height. A similar relationship has been 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% dry foliage. At the time of sampling in July 1994, 75 percent of the trees were dead or dying (Figure 7). Most trees 20-24 cm DBH are expected to survive. We anticipate additional mortality as insect damage increases and trees of low 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 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.

Modelling: We also measured fire injury to individual trees for the purpose of beginning to develop models for predicting mortality of *P. sylvestris* following wildfires. Immediately following the fire, we established 5 plots of twenty 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. An attempt was made to distribute plots in areas of varying fire severity. However, this initial sampling resulted in a very high proportion of sample trees in medium to high fire severity areas, and most of these trees had died



a)



b)



c)

Figure 5. View from photo point 5 of typical stand condition on the Island. **a.** Before the fire, **b.** Immediately after the fire, **c.** July 1994, one year after fire. For the years up to 2012: See Annex II.

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 purposes. 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 the base of the tree (as a possible indication of impacts of fire on shallow roots). In 1993, we also did visual estimates of percent crown scorch. This was not possible in 1994 because dead needles resulting from post-fire insect damage and decreases in tree vigor could not be distinguished from scorch, and many needles had already been shed. In 1994 we also noted 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 post-fire tree mortality as a function of tree size and fire damage variables. The model used is of the form:

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

where $P(m)$ is the probability of post-fire 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 percent 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 using the Homer and Lemeshow goodness of fit statistic (SAS Institute 1989; Saveland and Neuenschwander 1990).

Of the 201 trees sampled for development of mortality models, 57 percent were dead by a year after the fire. Ninety-nine percent of dead trees sampled, as well as 85 percent of the living trees, were infested with bark beetles. Although infestation levels 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 percent 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 in Table 7. 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 by 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.

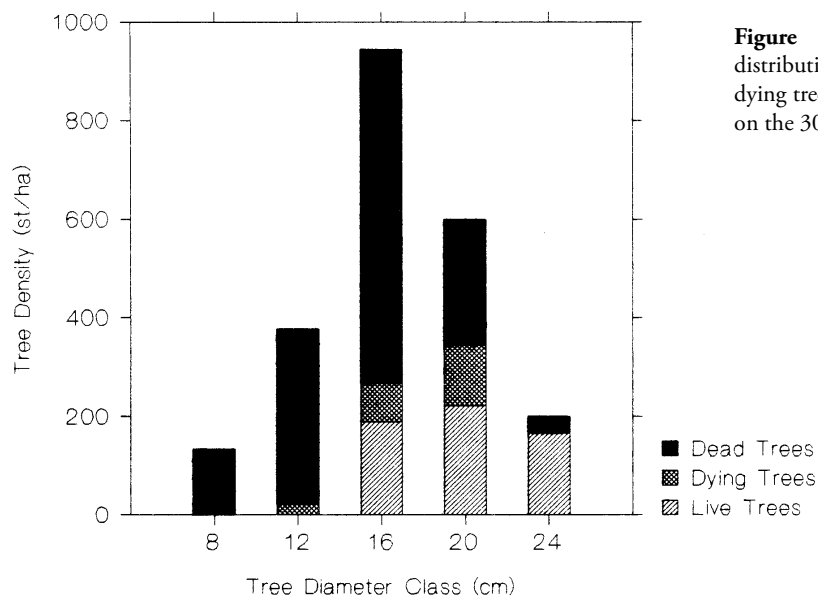


Figure 6. Diameter class distribution of live, dead, and dying trees one year after the fire on the 30 by 30 m sample plot

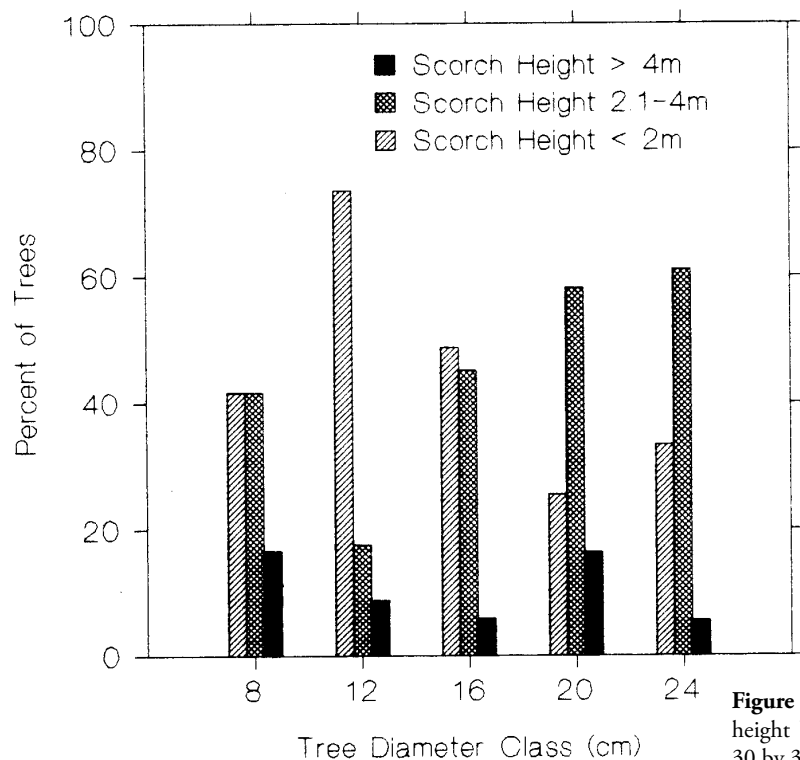


Figure 7. Distribution of scorch height by diameter class on the 30 by 30 m sample plot

Table 7. 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

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 excellent fit, with 97 percent concordant pairs, and a Hosmer and Lemeshow goodness of fit statistic with $p=0.9937$ (Table 7). We also attained good fit with a model incorporating crown scorch and DBH (94.7 percent concordant pairs, goodness of fit $p=0.9518$; Table 8). The best model for all trees together incorporated relative average char height and DBH². This model had 83.3% concordant pairs, with $p=0.7702$ for the goodness of fit statistic (Table 8). 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 model parameter estimates are very dependent on how soon the measurements are made after the fire. 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. However, all models presented here are preliminary, as we expect continuing mortality.

Table 8. Parameter estimates for the best fitting mortality models for 1993 and 1994 data sets

Sampling date (n):	Model Parameter Estimates					
	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

Insect damage: The year following the fire, insect damage was evaluated in early July on trees in the 30 m by 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 of approximately 0.2 m² was removed from each of five trees, and counts were made of the number of living larvae under the bark, the number of mother passages in the bark, and the number of 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 m by 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 one could hear the sounds of bark insects in the tree stems throughout the forest. All of the five sample trees showed evidence of heavy insect infestation in the bark plates sampled (Table 9).

Table 9. Insect populations in the sample trees, in July 1994 at Bor Forest Island

Tree No.	Diameter (cm)	Bark sample (m ²)	Living larvae (#/m ²)	Mother passages (#/m ²)	Larval passages (#/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)		

Although there was considerable variation in the level of insect infestation from tree to tree, the levels were in general quite high, both in dead trees and in those that were still living. All of 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 grey capricorn beetles (*Acanthocinus edulis* L.), brown capricorn beetles (*Criocephalus vesticees* L.), and big pine weevils (*Hylobius abietis* L.). The small plot area makes it likely that important species were not observed.

4. Fuel Assessment, Fire Weather and Fire Behavior

4.1. Pre-burn Fuel Sampling

For fuel sampling and fire behavior documentation purposes, 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 using the line-intersect method (McRae et al. 1979). Mean pre-burn oven-dry fuel weights were determined to be 0.198 kg m^{-2} for fuels 0-3 cm in diameter, 0.417 kg m^{-2} for fuels 0-7 cm in diameter, and 1.088 kg m^{-2} for fuels >7 cm in diameter. The total pre-burn 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 in order 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.

In order to determine the bulk density of the forest floor a series of 3 randomly located 0.25 m^2 ($0.5 \times 0.5 \text{ m}$) 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 total 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/data logger system was installed in order to determine the spread rate and residence time of the fire. The thermologgers are designed to measure and record flame zone temperatures and their durations, 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.

4.2. Fire Weather

Daily fire weather data, recorded at the *Avialesookhrana* (Aerial Forest Fire Protection Service) Base at the Bor airport, was used to track the 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 indices 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 dew-point 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 in early 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, windspeeds generally above 10 km h⁻¹, and very scant precipitation. Fire danger conditions were generally extreme by late June, but moderated substantially after more than 25 mm of rain fell during the 28 June-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 levels 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, while the Fine Fuel Moisture Content (FFMC) and Initial Spread Index (ISI) levels also indicated moderate to high spread rates. Bor fire weather data for the 1 June to 6 July period is listed in Table 10. Weather measurements taken on Bor Forest Island on 5 and 6 July were generally consistent with observations in Bor, with the exception of slightly lower windspeeds.

Table 10. Canadian FWI System codes and indices for Bor Airport (temperature in °C, windspeed 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).

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

4.3. Fuel Moisture

As 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 collected immediately prior to ignition of the Bor Forest Island Fire. These samples were subsequently oven-dried, and the average moisture contents of selected fuel strata determined as a function of overstory weight. Fine downed and dead woody fuel moisture contents were consistent at about 7.5% for material under 3 cm in diameter. Forest floor fuel moisture content levels showed a 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 indices, and indicate a high level of fuel consumption could be expected during the experimental burn.

4.4. Fire Behavior

(a) Ignition Procedure

Since the primary purpose of the Bor Forest Island Fire Experiment was the creating of 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 1300h were similar to those observed at the Bor airport weather station. With light winds ($\sim 7 \text{ km h}^{-1}$) from the SE, ignition began along the east side of Bor Forest Island at 1420h, using hand-held torches. By the time this ignition line was complete (1436h), 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 west side of the Island in order to obtain a headfire effect. This line (approximately 500 m) was ignited between 1515h and 1520h, and the two ignition lines began slowly moving together. Winds were still light and variable in direction, however, and a decision was made 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 process began at 1530h, being completed along the southern edge at 1535h, and along the northern edge at 1550h (Figure 8). The complete ignition phase was monitored and documented by helicopter-mounted cameras.

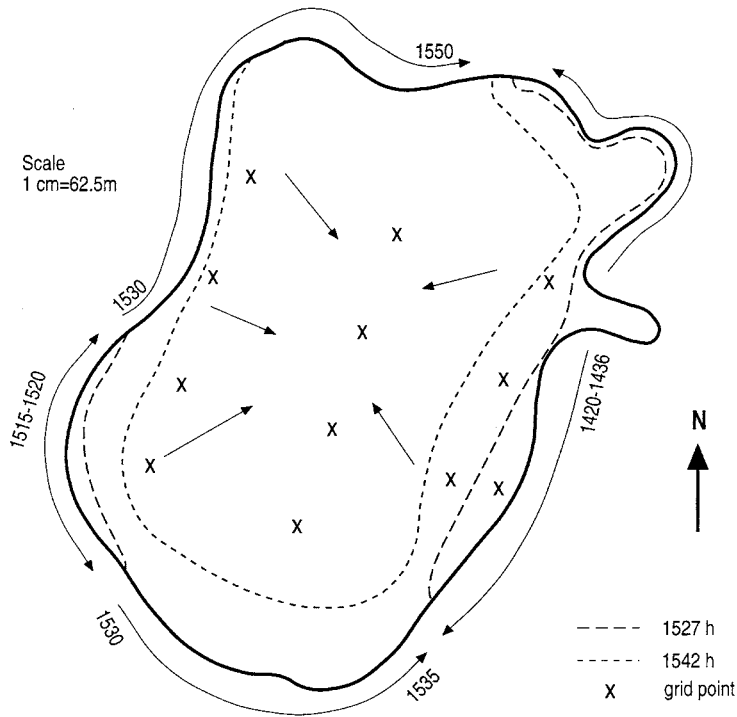


Figure 8. Ignition sequence of Bor Forest Island Experimental Fire (6 July 1993)

(b) 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 9-14), particularly when the fire reached the crest of the sloped sides of the Island. As the fire progressed, however, an increasingly stronger convective influence took place as the fire lines accelerated inward. Crowning became more continuous, with a fire storm developing in the final phase of the burn. Although it was impossible to observe visually, thermo logger measurements indicated the active phase of the burn was complete by approximately 1550 h. The fact that the Bor Forest Island Fire did not burn as a running headfire complicated the use of thermo logger data as an aid to quantifying spread rate. However, an average spread rate was determined from points 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} or 0.42 m s^{-1} .

(c) Residence Times

The thermologger data provided a clear picture of the combustion rate and residence time of the Bor Forest Island Fire, as usable data was retrieved from 11 of the 12 loggers. Figure 16 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 Bor Forest Island Fire thermologger data represents primarily crown fire originating from a deep but low bulk density surface lichen layer. It can be inferred from Figure 16, 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 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 behind the passage of the flaming front was observed to be minimal, however, with little residual smoke.

(d) Fuel Consumption

Following the fire, line intersects transects were re-inventoried 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 translates into consumption of all of the surface lichen layer (1390 kg m⁻²) and an additional 1.46 cm (1051 kg m⁻²) of the underlying duff (organic) layer. Thus, total ground fuel consumption was 2441 kg m⁻².

The short duration 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. Using the diameter distribution of the Bor Forest Island stand, along with crown fuel weights measured in jack pine (*Pinus banksiana*) in Canada (Stocks and Walker 1975), and assuming 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



Figures 9, 10. Ignition of Bor Forest Island experimental fire: Development of a surface fire in the initial stage.



Figures 11, 12. Transit of the surface fire to crown fire and ground view of typical high-intensity surface / intermittent crown fire behavior on north side of Bor Forest Island (1545h). Figure 11 (left) provides an aerial view of the west side of Bor Forest Island at 1522h. Figure 12 is a ground view of a typical high-intensity surface/intermittent crown fire behavior on north side of Bor Forest Island at 1545h.



Figures 13, 14. Aerial view of the high-intensity surface / intermittent crown fire behavior and development of the second fire front



Figure 15. Aerial view of the fire storm developing at the stage of merging of the two fire fronts

(ground, surface, and aerial) during the Bor Island Fire was therefore determined to be 3712 kg m^{-2} (37.12 t ha^{-1}).

(e) 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 ($\sim 18,000 \text{ kJ kg}^{-1}$), 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 $28,062 \text{ kW m}^{-1}$ was estimated for the Bor Forest Island 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, in combination with the strong convective fire activity generated by the ignition pattern of the Bor Forest Island Fire. This extreme intensity was reflected in the strong vertical development of the convection column above the fire, which was estimated to have reached 6000 m during the most intense stage of the fire (Figure 18). The development of this most intense phase of the Bor Island Fire is evident from the high levels of crown fuel consumption evident in the center portion of the Island (Figures 19 and 20).

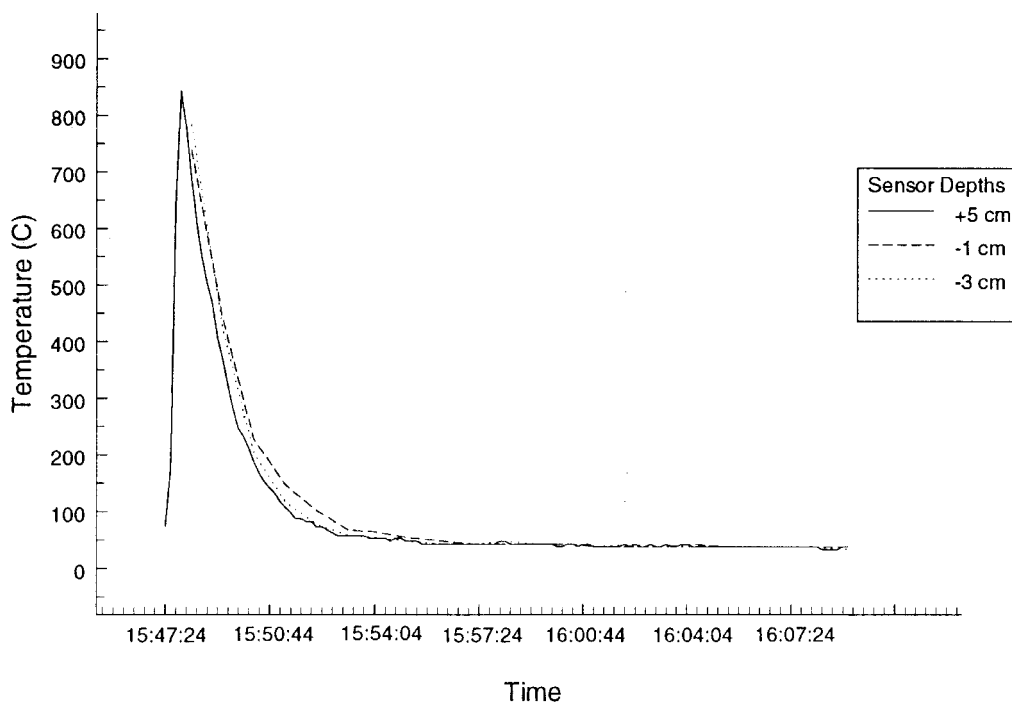


Figure 16. Typical temperature-time profile for Bor Forest Island Experimental Fire



Figure 17. Pre-fire ground fuel profile showing well-developed lichen layer (~7 cm) and underlying organic material (~4 cm) over mineral soil

5. Atmospheric Emissions

5.1. 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 Bor Forest Island Fire. Particle-filtered samples were drawn through a probe mounted on the nose of the 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/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 11. 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 presented 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.

Of major interest from Table 11 is the fact that samples collected during the high-intensity phase (F2) of the Bor Island Fire revealed elevated carbon monoxide emission ratios, suggesting lower combustion efficiency than previously inferred from results obtained from Canadian boreal logging slash fires during flaming combustion (Cofer et al. 1990). Methane and hydrogen emission ratios, however, were similar to measurements obtained in the Canadian fires. During the smoldering combustion phase (S3) carbon monoxide emission ratios were almost three times higher than on Canadian logging slash fires.

It had been previously suggested that very high-intensity flaming combustion may significantly change the emissions chemistry associated with the flaming stage of combustion,

leading to more incomplete combustion and correspondingly higher proportions of incompletely oxidized combustion products such as carbon monoxide (Cofer et al. 1989). The enhanced proportion of CO emissions during the vigorous flaming stage of the Bor Forest Island Fire seems to support this thesis, although additional data will be required to verify this. Trace gas emissions from this fire are analyzed in greater detail in Cofer et al. (1995.).

Table 11. Mean CO₂-normalized emission ratios and standard deviations (in %) determined for the Bor Forest Island Fire

Type and Stage of Fire, Number of Samples *	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

* Combustion Phase (F=Flaming; S=Smoldering), Stage of Fire (1,2,3), and number of Samples ()

5.2. Compounds Affecting Stratospheric Ozone

To compliment the NASA trace gas emissions measurements, both helicopter and ground-based grab sampling (using stainless steel vacuum canisters) of emissions for specific analysis of methyl bromide (CH₃Br) and methyl chloride (CH₃Cl) was also carried out during the Bor Forest Island Fire. Decay products of these compounds are, like the longer-lived chloro-fluorocarbons (CFCs), known to induce depletion of stratospheric ozone. It should be noted here that bromine 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 CH₃Br and CH₃Cl measured in the Bor Forest Island Fire were in the range of 1.1-31x10⁻⁷ and 0.2-12x10⁻⁵ respectively. This 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 can be explained by the lower combustion efficiency of the smoldering process when compared to the prevailing flaming combustion of grass-type fuels.

Estimates of global pyrogenic emissions of CH₃Br from all vegetation fires and other plant biomass burning falls in the range of 10-50 Gg yr⁻¹, or 10-50% of the total source strength (Manö and Andreae, 1994). An accurate determination of the contribution of boreal fires to the atmospheric budget of methyl bromide requires further analysis of boreal fire emissions.



Figure 18. Well-developed convection column (height: 6000 m) above Bor Forest Island (1555h)



Figure 19. Post-fire ground-level view within high-intensity portion of Bor Forest Island Fire



Figure 20. Aerial view of Bor Forest Island one day after the fire. Note the heavily crowned-out center portion of the Island, where convection-driven firelines converged

5.3. Aerosols

In connection with the lake sediment coring investigation discussed earlier, a study of the dispersion of particles emitted from the Bor Island Fire was also undertaken. A series of twenty-one 400 cm² traps were arrayed along three transects radiating away from the burn into the surrounding fen, in order to estimate the production and transport of “large” (10 μm) 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 the following day when smoldering emissions had ceased. Total particle fluxes and particle size distributions were determined using 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 (3712 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 the fact that it was obtained for large particles trapped at the ground surface. Settling is an important removal mechanism for these large particles, so they are rapidly depleted within a plume and generally not considered in aerosol measurements. The ground-level traps collected particles just slightly elevated from the ground surface.

Particle deposition declines sharply within 5 m of the burn edge (Figure 21). Although there is scatter 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 21 that traps are required at greater distances from the burn in order to adequately characterize the pattern of deposition. The high intensity level and well-developed convection column of the Bor Island Fire probably lofted particles sufficiently 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 (Fig. 22). The largest (>10¹ μm) particles are restricted to traps from within the burn. Maximum particle size was lowest (10^{0.8} μm) 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 of the particle size range (Fig. 22). 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.

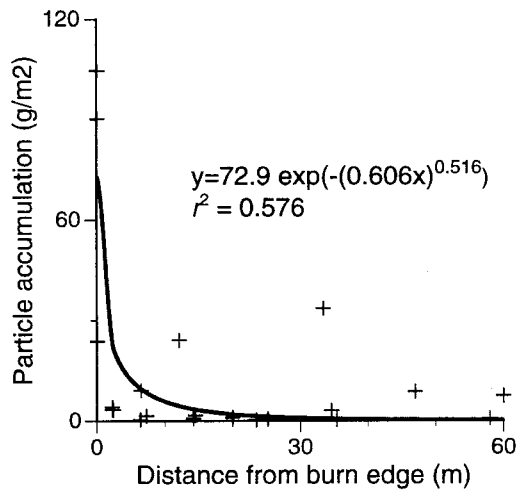


Figure 21. Particle accumulation in traps/ distance from the edge of the Bor Forest Island Fire

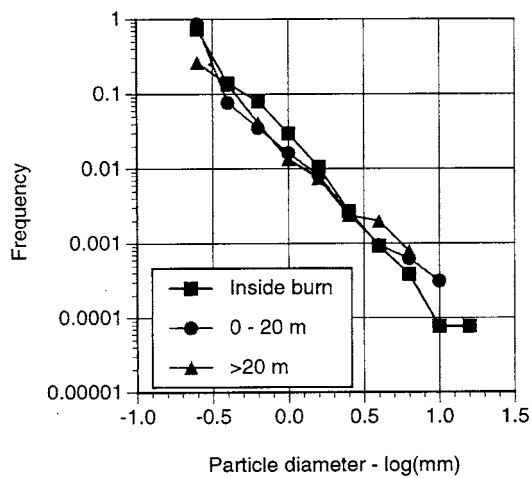


Figure 22. Particle size distributions for all Bor Forest Island traps

6. Summary

The major objective of the Bor Forest Island Fire Experiment was the conducting of a high-intensity, stand replacement fire that would permit the 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 windspeeds 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 was accomplished, and fire behavior was 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 purposes, Figure 23 shows a 1991 Siberian wildfire near Yakutsk, which exhibits patterns of fire intensity similar to the Bor Forest Island Fire.



Figure 23. Aerial view of a coniferous forest affected by a high-intensity fire in Yakutsk Region, August 1991. Photo: S. Pyne

This Experiment also demonstrated that it is possible to accommodate a number of experimental approaches within a single 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 of this region of Siberia.

The Bor Forest Island site provides an ideal location for long-term fire ecology investigations. The site is well protected from human influences, being isolated from population centres, and protected by surrounding bogs and marshland. However, many more long-term sites, covering a broad range of fuel types and ecosystems burned under a variety of conditions, are required in order to fully understand boreal fire regimes. This 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.

Acknowledgements

The Bor Forest Island Fire Experiment, an activity of the Fire Research Campaign Asia-North (FIRESCAN), and the international conference "Fire in Ecosystems of Boreal Eurasia" was financed by the Volkswagen Foundation (Germany) and the Max Planck Institute for Chemistry (Germany). Additional funding for participation of researchers was provided through national funds for the International Boreal Forest Research Association (IBFRA) provided by the U.S.A., Canada, Sweden, and Finland. The Russian Academy of Sciences, Siberian Branch, Sukachev Institute of Forest, Forest Fire Laboratory, Krasnoyarsk, provided infrastructure and organization for the conference and selecting and preparing the experimental site at Bor Forest Island. The director of the Russian Aerial Forest Protection Service *Avialesookhrana*, Mr. Nikolai Andreev, and the responsible manager for research and technology transfer, Mr. Eduard P. Davidenko, and the staff of Krasnoyarsk Aviabase under Mr. Nikolai Kovalev provided all logistical and infrastructural support for conducting the experiment. Safe and reliable aerial service for personnel transport and smoke sampling was provided by Aeroflot. English-Russian and vice-versa translation by Irina S. Savkina ensured the success of the conference and the experiment. Laboratory work for trace gas analyses at the Max Planck Institute for Chemistry was conducted by Stein Manö (Norway). James H. Speer conducted the dendrochronological analysis of fire scars at the Tree Ring Laboratory in Arizona. The Experiment was documented by Schubert Film Production (Munich, Germany) and broadcast first by the French-German TV Channel Arte, in cooperation with the German TV Channel Two (ZDF), on 20 December 1993. This film is available on the GFMC repository and can be made available upon request.

References

The first complete version of this paper has been published by the FIRESCAN Science Team (1996). This updated version includes several additional references, which had not been included in the 1996 version of the paper.

- Alexander, M.E., Euler, D.L. (1981) Ecological role of fire in the uncut boreal mixedwood forest, in Canadian Forestry Service, Department of the Environment, editor, Boreal Mixedwood Symposium, CODJFRC Symp.Proc. O-P-9, 42-64.
- Apps, M.J., Kurz, W.A., Luxmore, R.J., Nilssohn, L.O., Sedjo, R.A., Schmidt, R., Simpson, L.G., Vinson, T.S. (1993) The changing role of circumpolar boreal forests and tundra in the global carbon cycle. *Water, Air, and Soil Pollution*, 70, 399.
- Bolin, G., Döös, B.R., Jäger, J., Warrick, R.A. (1986) The greenhouse effect, climate change and ecosystems. SCOPE 29. J. Wiley and Sons, Chichester, England.
- Byram, G.M. (1959) Combustion of forest fuels, in K. P. Davis, editor, *Forest Fire Control and Use*, 61-89, McGraw-Hill Co., New York, NY.
- Cahoon, D.R., Levine, J.S., Cofer, W.R. III, Miller, J.E., Minnis, P., Tennille, G.M., Yip, T.W., Stocks, B.J., Heck, P.W. (1991) The Great Chinese Fire of 1987: A view from space, in J. S. Levine, editor, *Global biomass burning*, 61-66, The MIT Press, Cambridge.
- Cahoon, D.R., Stocks, B.J., Levine, J.S., Cofer, W.R., Pierson, J.M. (1994) Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia. *J. Geophys. Res.* 99(D9), 18627.
- Clark, J.S., Hussey, T.C. (1996) Estimating the mass flux of charcoal from sediment records: the effect of particle size, morphology, and orientation, *The Holocene* 6, 129-144.
- Cofer, W.R. III, Levine, J.S., Sebach, D.I., Winstead, E.L., Riggan, P.J., Stocks, B.J., Brass, J.A., Ambrosia, V.G., Boston, P.J. (1989) Trace gas emissions from chaparral and boreal forest fires, *J. Geophys. Res.* 94, 2255-2259.
- Cofer, W.R. III, Levine, J.S., Winstead, E.L., Stocks, B.J. (1990) Gaseous emissions from Canadian boreal forest fires, *Atmos. Environ.* 24A, 1653-1659.
- Cofer, W.R. III, E.L., Winstead, E.L., Stocks, B.J., Goldammer, J.G., Cahoon, D.R., Levine, J.S. (1995) Gaseous crownfire emissions from the Bor Forest Island Fire. IUFRO XX World Congress, Tampere, Finland, 6-12 August 1995. Abstract Vol., p.91.
- Cofer, W.R., E.L., Winstead, E.L., Stocks, B.J., Overbay, L.W., Goldammer, J.G., Cahoon, D.R., Levine, J.S. (1996) Emissions from boreal forest fires: are the atmospheric impacts underestimated? In: *Biomass burning and global change* (J.S. Levine, ed.), 834-839. MIT Press, Cambridge, MA.

- Crutzen, P.J., Goldammer, J.G. (eds.) (1993) Fire in the environment. The ecological, atmospheric chemical, and climatic importance of vegetation fires. Environmental Sciences Report 13. John Wiley and Sons, Chichester, England.
- Dieterich, J.H., Swetnam, T.W. (1984) Dendrochronology of a fire scarred ponderosa pine, *Forest Science* 30, 238-247.
- Dusha-Gudym, S.I. (1992) Forest fires on areas contaminated by radionuclides from the Chernobyl power plant accident. *Int. Forest Fire News (ECE/FAO)* No.7, 4.
- ECE/FAO (Economy Commission for Europe/Food and Agricultural Organization of the United Nations) (1985) The forest resources of the ECE region (Europe, the USSR, North America). ECE/FAO/27, Geneva.
- FIRESCAN Science Team (1994) Fire in Boreal Ecosystems of Eurasia: First results of the Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESCAN). *World Resource Review* 6, 499-523.
- FIRESCAN Science Team (1996) First results of the Fire Research Campaign Asia-North (FIRESCAN): Implications on the fire component in the IGBP Northern Eurasia Study. EGS XXI General Assembly, The Hague, The Netherlands, 6-10 May 1996. *Annales Geophysicae* 14, Supp. II, C 597.
- FIRESCAN Science Team (1996) Fire in ecosystems of boreal Eurasia: The Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESCAN). In: Biomass burning and global change. Vol.II (J.S.Levine, ed.), 848-873. The MIT Press, Cambridge, MA. Modified version available online: http://www.fire.uni-freiburg.de/other_rep/research/rus/rus_re_1.htm
- Fosberg, M.A. (1992) International Boreal Forest Research Association, Stand Replacement Fire Working Group. *Int. Forest Fire News* No.7, 6.
- Fosberg, M.A. (1992) Agreement signed between the United States and the Republic of Russia on fire management and fire research. *Int. Forest Fire News* No. 6, 14-16.
- Fosberg, M.A., Stocks, B.J., Lynham, T.J. (1996) Risk analysis in strategic planning: fire and climate change in the boreal forest. In: Fire in ecosystems of boreal Eurasia (J.G. Goldammer and V.V. Furyaev, eds.), 495-504. Kluwer Acad. Publ., Dordrecht.
- Furyaev, V.V., Kireyev, D.M. (1979) Landscape-based investigation of post fire forest dynamics, Novosibirsk, Nauka Publ. 160 pp. (In Russian).
- Furyaev, V.V., Zlobina, L.P. (1995) Regeneration of pine-lichen forests under cyclic fires, in *Forest Fires and Their Effects*, Krasnoyarsk, Institute of Forest, Siberian Branch, USSR Academy of Sciences., pp.83-92 (in Russian).
- Furyaev, V.V. (1994) The Role of Fire in Forest Formation Processes, *Int. Assoc. Wildland Fire*, 1994.
- Goldammer, J.G., Di, Xueying (1990) The role of fire in the montane-boreal coniferous forest of Daxinganling, Northeast China: A preliminary model. In: Fire in ecosystem dynamics. Mediterranean and northern perspectives (J.G. Goldammer and M.J. Jenkins, eds.), 175-184. SPB Academic Publishing, The Hague, 199 pp.
- Goldammer, J.G., Furyaev, V.V. (1995) Global change, the boreal forest, and fire: Search for new strategies in science policies and research mechanisms. In: Science Policy: New Mechanisms for Scientific Collaboration between East and West (V. A. Koptug and J. Klerkx, eds.), 45-61. NATO ASI Series 4, Science and Technology Policy Vol.1. Kluwer Academic Publishers, Dordrecht-Boston-London, 256 p.

- Goldammer, J.G. (1995) Introduction to the objectives and design of the Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESKAN). IUFRO XX World Congress, Tampere, Finland, 6-12 August 1995. Abstract Vol., p.86.
- Goldammer, J. G., Furyaev, V.V. (eds.) (1996) Fire in Ecosystems of Boreal Eurasia. Kluwer Acad. Publ. Dordrecht, 528 p.
- Graybill, D.A. (1979) Revised programs for tree-ring research, Tree-Ring Bulletin 39, 77-82.
- Heinselman, M.L. (1981) Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. In: Fire Regimes and Ecosystem Properties (H.A. Mooney et al., eds.), 7. USDA For. Ser. Gen. Tech. Rep. WO-26, 1981.
- Johnson, E.A. (1992) Fire and Vegetation Dynamics. Studies from the North American Boreal Forest. Cambridge University Press, Cambridge, UK.
- Kauppi, P., Posch, M. (1988) A case study of the effects of CO₂-induced climatic warming on forest growth and the forest sector: A. Productivity reactions of northern boreal forests. In: The impact of climatic variations on agriculture, Vol 1: Assessments in cool temperature and cold regions, 183-93. Reidel, Dordrecht, The Netherlands.
- Komin, G.E. (1967) Influence of fire on age structure and growth of swampy northern taiga pine stands of Trans-Ural region. In: Types and Dynamics of Forests of the Urals and Trans-Ural Region, Sverdlovsk, Ural Dpt. USSR Acad. Sci., pp.207-222 (in Russian).
- Korchagin, A.A. (1954) Conditions of fire occurrence and annual forest fire coverage in the north of the European part of USSR. In: Studies in Vegetation Cover in the USSR, Collection 1, Leningrad University, pp. 182-322 (in Russian).
- Korovin, G. N., (1996) Analysis of the distribution of forest fires in Russia. In: Fire in Ecosystems of Boreal Eurasia (J.G. Goldammer and V.V. Furyaev, eds.), 112-128. Kluwer Acad. Publ. Dordrecht.
- Kurbatsky, N.P. (ed.) (1985) Forest fires and their consequences. Sukachev Institute of Forest and Wood, Krasnoyarsk (in Russian).
- Kuusela, K. (1990) The dynamics of boreal coniferous forests. The Finnish National Fund for Research and Development (SITRA), Helsinki, Finland.
- Kuusela, K. (1992) Boreal forestry in Finland: a fire ecology without fire. *Unasylva* 43 (170), 22.
- Manö, S., Andreae, M.O. (1994) Emission of methyl bromide from biomass burning, *Science* 263, 1255-1257.
- Maxwell, B. (1992) Arctic climate: potential for change under global warming. In: Arctic ecosystems in a changing climate (F.S. Chapin, R.L. Jefferies, J.F. Reynolds, G.R. Shaver and J. Svoboda, eds.), 11-34, Academic Press, New York.
- McRae, D.J., Alexander, M.E., Stocks, B.J. (1979) Measurement and description of fuels and fire behavior on prescribed burns: a handbook, Dep. Environ., Can. For. Serv., Sault Ste. Marie, ON, Inform. Rep. O-X-287.
- Nesterov, V.G. Combustibility of the forest and methods for its determination, USSR State Industry Press.

- Peterson, G.M. (1993) Vegetational and climatic history of the western former Soviet Union. In: Global Climates Since the Last Glacial Maximum (H.E. Wright jr., J.E. Kutzbach, T. Webb III, W.F. Ruddiman, F.A. Street-Perrott, and P.J. Bartlein, eds.), 169-193, University of Minnesota Press, Minneapolis, MN, 1993.
- Pisarenko, A.I., Strakhov, V.V. (1993) Global role of the Russian boreal forests: A viable assessment, World Resources Review.
- Popov, L.V. (1982) Southern taiga forests of Central Siberia. Irkutsk University Publ. 330 pp.
- Pyne, S.J. (1992) The Russian fire establishment. Impressions from a study tour. Int. Forest Fire News No. 6, 3-5.
- Pyne, S.J. (1996) Wild hearth. A prolegomenon to the cultural fire history of northern Eurasia. In: Fire in Ecosystems of Boreal Eurasia (J.G. Goldammer and V.V. Furyaev, eds.), 21-44. Kluwer Acad. Publ. Dordrecht.
- Regelbrugge, J.C., Conard, S.G. (1993) Modeling tree mortality following wildfire in *Pinus ponderosa* forests in the Central Sierra Nevada of California. Int. J. Wildland Fire 3(3), 139-148.
- Sannikov, S.N. (1992) Ecology and Geography of the Natural Regeneration of Pine Habitats, Nauka, Moscow (in Russian).
- SAS Institute, Inc. (1989) SAS/STAT User's Guide, Version 6, Fourth Edition, Vol. 2, SAS Institute, Inc., Cary, NC, 846 p.
- Saveland, J.M., Neuenschwander, L.F. (1990) A signal detection framework to evaluate models of tree mortality following fire damage, Forest Science 36, 66-76.
- Schenikov, A.P. (1964) Introduction to geobotany. Leningrad University, Leningrad. 446 p. (in Russian).
- Shanin, S.S. (1965) Structure of pine and larch forests of Siberia, Moscow, Timber Industry Publ., 106 p. (in Russian).
- Sherbakov, I. P. (ed.) (1979) Forest fires in Yakutia and their Influence on the nature of forests, Nauka (in Russian).
- Shostakovitch, V.B. (1925) Forest conflagration in Siberia. With special reference to the fire of 1915. J. For. 23, 365-371.
- Shugart, H.H., Leemans, R., Bonan, G.B. (eds.) (1992) Boreal forest modeling. A systems analysis of the global boreal forest. Cambridge University Press, Cambridge, UK.
- Shugart, H.H., Smith, T.M. (1992) Modelling boreal forest dynamics in response to environmental change. Unasylva 43 (170), 30.
- Slaughter, C.W., Barney, R.J., Hansen, G.M. (eds.) (1971) Fire in the Northern Environment. A Symposium, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.
- Sofronov, M.A. (1967) Fires in forests of Southern Siberia. Nauka, Moscow, 1967 <in Russian>.
- Stocks, B.J., Global warming and forest fires in Canada, The Forestry Chronicle 69, 290-293, 1993.
- Stocks, B.J., Walker, J.D. (1975) The fuel complex of mature and immature jack pine stands in Ontario, Dep. Environ., Can. For. Serv., Sault Ste. Marie, ON, Inform. Rep. O-X-229.

- Stocks, B.J., Lawson, B.D., Alexander, M.E., Van Wagner, C.E., McAlpine, R.S., Lynham, T.J., Dubé, D.E. (1989) Canadian Forest Fire Danger Rating System: An overview. *The Forestry Chronicle* 65, 450-457.
- Stocks, B.J., Korovin, G.N., Sukhinin, A., Cahoon, D.R., Goldammer, J.G. (1995) Forest fire occurrence in Russia and Canada: Ground, aerial, and satellite measurements. IUFRO XX World Congress, Tampere, Finland, 6-12 August 1995. Abstract Vol., p.87.
- Stocks, B.J., Goldammer, J.G., Cofer III, W.R. (1995) International crown fire experiment in Northern Canada. IUFRO XX World Congress, Tampere, Finland, 6-12 August 1995. Abstract Vol., p.93.
- Stocks, B.J., Lynham, T.J. (1996) Fire weather climatology in Canada and Russia. In: *Fire in Ecosystems of Boreal Eurasia* (J.G. Goldammer and V.V. Furyaev, eds.), 481-487. Kluwer Acad. Publ. Dordrecht.
- Swetnam, T.W., Dieterich, J.H. (1985) Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. In: *Proceedings, Symposium and Workshop on Wilderness Fire* (J.E. Lotan, B.M. Kilgore, W.C. Fischer, and R.W. Mutch, Tech. Coords.), 15-18 November 1983, Missoula, Montana. USDA Forest Service, General Technical Report INT-182:390-397.
- Tkachenko, M.E. (1952) General introduction to forestry, Moscow-Leningrad, Goslesbuzmizdat Publ, 599 pp. (in Russian).
- Tsvetkov, P.A. (1993) Fire effects on larch forests of Central Evenkia. In: *Fire in Ecosystems of Boreal Eurasia* (J.G. Goldammer and V.V. Furyaev, eds.), 387-392. Kluwer Acad. Publ. Dordrecht.
- US Department of Energy (1983) Carbon in live vegetation of major world ecosystems. DOE/NBB-0037.
- Valendik, E.N., Ivanova, G.A. (1990) Extreme fire hazard seasons and their reconstruction. In: *5th All Union Conference, Abstracts and Papers* (S.G. Shiyatov, ed.), Sverdlovsk, Russia (in Russian).
- Van Wagner, C.E. (1987) Development and structure of the Canadian Forest Fire Weather Index System, Can. For. Serv., For. Tech. Rep. No. 35.
- Viereck, L.A., Schandelmeier, L.A. (1980) Effects of fire in Alaska and adjacent Canada. A literature review. BLM-Alaska Tech. Rep. 6 (BLM/AK/TR-80/06), Anchorage.
- Viro, P.J. (1969) Prescribed burning in forestry, *Comm. Inst. For. Fenn.* 67 (7).
- Walker, S.H., Duncan, D.B. (1967) Estimation of the probability of an event as a function of several independent variables, *Biometrika* 54, 167-179.
- Wein, R.W., MacLean, D.A. (eds.) (1993) The role of fire in Northern circumpolar ecosystems. SCOPE 18, John Wiley & Sons, Chichester, UK.
- Wein, R.W., de Groot, W.J. (1996) Fire-climate change hypotheses for the taiga. In: *Fire in Ecosystems of Boreal Eurasia* (J.G. Goldammer and V.V. Furyaev, eds.), 505-512. Kluwer Acad. Publ. Dordrecht.
- WMO (World Meteorological Organization) (1992) Scientific Assessment of Ozone Depletion. WMO Rep.25. Geneva.
- Zackrisson, O. (1977) Influence of forest fires on the North Swedish boreal forest, *Oikos* 29, 22.

Annex I

Photographic Documentation of the Long-Term Observation Plots and Aerial Views
1993-2012

Plot 1

1993 - pre-fire



1993 - post-fire



1994



1995

Plot 1

1999



2003



2008



2012



1993 - pre-fire



1993 - post-fire

Plot 2

1994



1995



1999



2003

Plot 2

2008



2012

Plot 3

1993 - pre-fire



1993 - post-fire



1994



1995

Plot 3

1999



2003



2008



2012

Plot 4

1993 - pre-fire



1993 - post-fire



1994



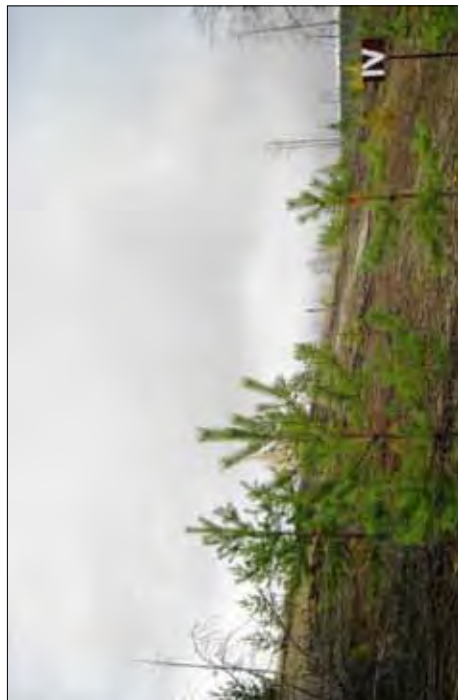
1995

Plot 4

1999



2003



2008



2012

Plot 5

1993 - pre-fire



1993 - post-fire



1994



1995

Plot 5

1999



2003



2008



2012

Plot 6

1993 - pre-fire



1993 - post-fire



1994



1995

Plot 6

1999



2003



2008



2012

Plot 7

1993 - pre-fire



1993 - post-fire



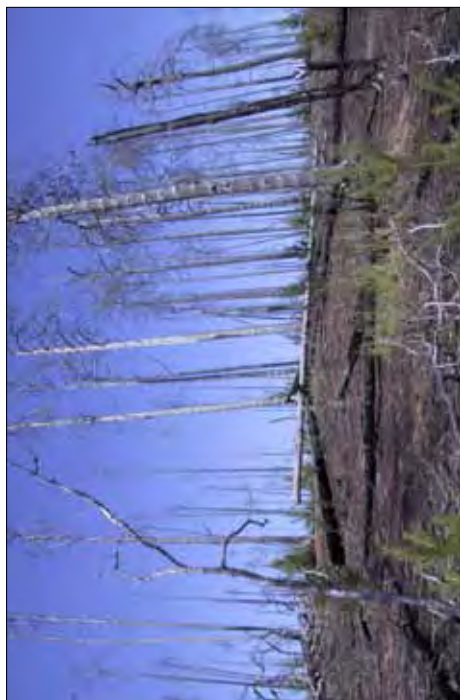
1994

not recorded

1995

Plot 7

1999



2003



2008



2012



1993 - pre-fire



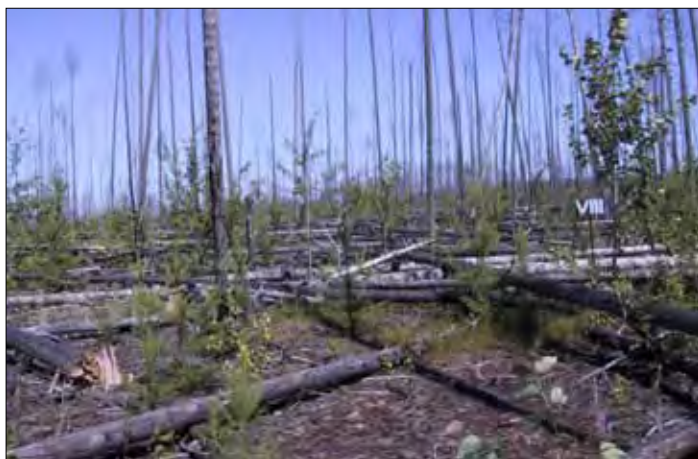
1993 - post-fire

Plot 8

1995



1999

Plot 8

2003



2008



2012



1993 - pre-fire



1993 - post-fire

Plot 10

1994



1995



1999

Plot 10

2003



2008



2012

Aerial Views of Bor Forest Island (1993-2012)

1993 - pre-fire



1993 - post-fire

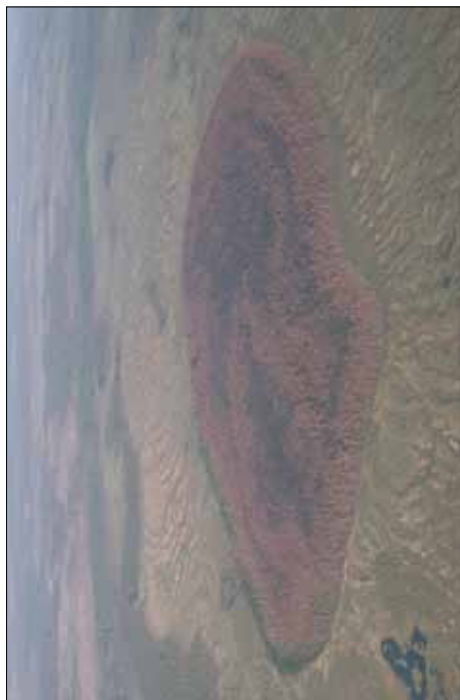


1993 post-fire



1993 post-fire

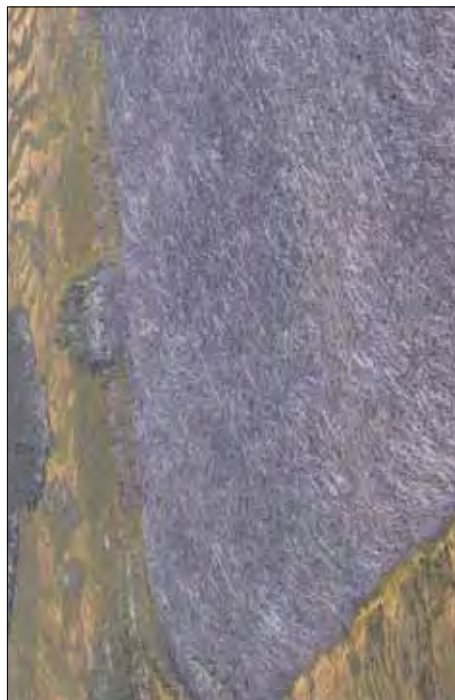
Aerial and Space Views of Bor Forest Island (1994-2003)



1994



2003



2003

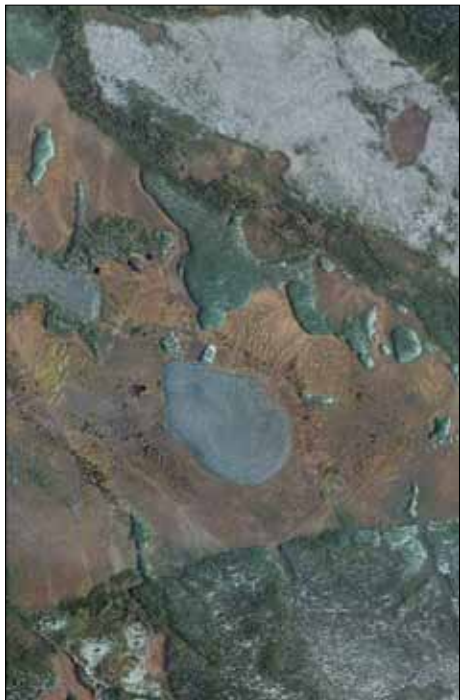


2003

Ground and Space Views of Bor Forest Island (2003 and 2005)



2003



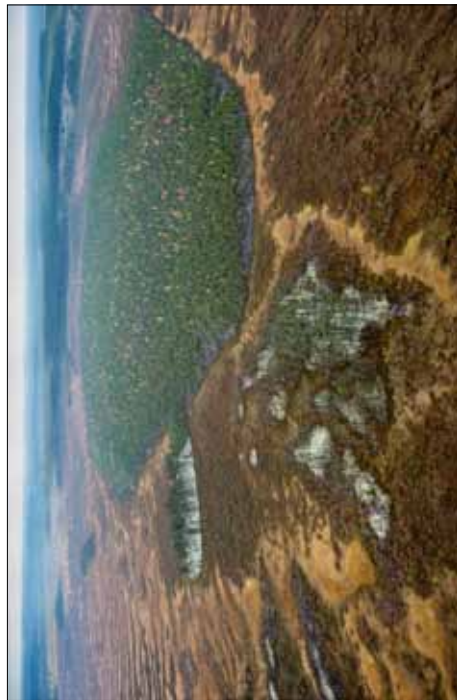
Bor Forest Island and its surrounding Sym Plain see from space in 2005.
Source: NASA

Aerial Views of Bor Forest Island (2008 and 2012)

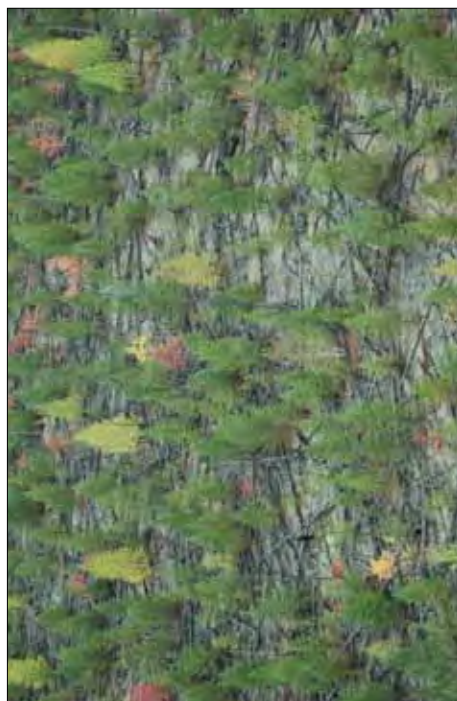
2008



2008



2012



2012

Annex II

The FIRESCAN Science Team (1993)

The Bor Forest Island Fire Experiment was a joint effort of the science team of the first phase of the Fire Research Campaign Asia-North (FIRESCAN). Coordinators of the experiment were Johann G. Goldammer, Brian J. Stocks, Valentin V. Furyaev, and Erik N. Valendik. The introductory part of this manuscript was compiled by Johann G. Goldammer. Lead author of Part II of the manuscript was Susan G. Conard (with James S. Clark, Valentin V. Furyaev, Johann G. Goldammer, Galina A. Ivanova, E. Mäkönen, and T.W. Swetnam), while lead author of Part III was B.J. Stocks (with J.S. Clark, Wesley R. Cofer, Bruce D. Lawson, and Johann G. Goldammer). Addresses and affiliations of participants actively involved in preparing, conducting and evaluating the field research are given in the list below. Affiliations are given without details. At the time of the update of this report (July 2012) several FIRESCAN Team members have moved to new assignments or are retired.



FIRESKAN Team Members (in alphabetic order)

Christopher H. Baisan
Laboratory of Tree Ring
Research
The University of Arizona
USA

James S. Clark
Duke University
Department of Botany
USA

Wesley R. Cofer III
Atmospheric Sciences Division
NASA Langley Research
Center
USA

Susan G. Conard
Riverside Forest Fire
Laboratory
USDA Forest Service
USA

Valentin V. Furyaev
Sukachev Institute of Forest
Russian Academy of Sciences
Russia

Johann G. Goldammer
Global Fire Monitoring Center
(GFMC)
Max Planck Institute for
Chemistry
Germany

Hartmut Gossow
University of Agricultural
Sciences
Vienna
Austria

Gary Hartley
Canadian Forest Service
Canada

Galina A. Ivanova
Sukachev Institute of Forest
Russian Academy of Sciences
Russia
Yegor K. Kisilyakov
Sukachev Institute of Forest
Russian Academy of Sciences
Russia

Bruce D. Lawson
Canadian Forest Service
Canada

Eino Mälkönen
The Finnish Forest Research
Institute
Finland

Loyd W. Overbay
Atmospheric Sciences Division
NASA Langley Research
Center
USA

Jon C. Regelbrugge
Riverside Forest Fire
Laboratory
USDA Forest Service
USA

Brian J. Stocks
Canadian Forest Service
Natural Resources Canada
Canada

Thomas W. Swetnam
Laboratory of Tree Ring
Research
The University of Arizona
USA

Erik Valendik
Sukachev Institute of Forest
Russian Academy of Sciences
Russia

Ross W. Wein
Forest Science and Canadian
Circumpolar Institute
University of Alberta
Canada

Edward L. Winstead
Science Application
International Corporation
USA

Annex III

The Expeditions 2008 and 2012

In 2008 routine field work on the Bor Forest Island took place 18-21 September. With the following participants:

- Leonid G. Kondrashov UNISDR Regional Northeast Asia Wildland Fire Network / Pacific Forest Forum, Khabarovsk, Russia
- Yegor Kisilyakov, Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk
- Alexander Selin, Krasnoyarsk Aviabase, Russia
- Johann G. Goldammer, Global Fire Monitoring Center (GFMC), Freiburg, Germany

The opportunity should be taken to acknowledge the work of Dr. Leonid Grigorievich Kondrashov, who over many years served as the leader of the UNISDR Regional Northeast Asia Wildland Fire Network and the Pacific Forest Forum. His main work was to bring the state-of-the-art knowledge in wildland fire science to the fire management community and to policy makers. Three years after the expedition Leonid Kondrashov passed away on 29 April 2010.



In memory of Leonid G. Kondrashov (left)



Toast to the escape from bear attack
From left: Goldammer, Selin, Kisilyakov



In memory of Leonid G. Kondrashov (left)



Farewell at Yartsevo air field



Group photo of the 2012 expedition

The last expedition before the publication of this book volume was realized in the frame of the “International Fire Management Week” in Krasnoyarsk Krai, Russian Federation, 1-10 September 2012 (see Part V of this volume). The field work took place on 5 September 2012 and involved a larger group of participants, including two film teams from *Avialesookhrana* and the public Russian TV channel Vesti. A full documentation produced by these film teams is available on the Vesti.ru and GFMC on-line repositories:

- TV report produced by Vesti.ru: <http://www.vesti.ru/videos?vid=446529&cid=1320> and <http://www.fire.uni-freiburg.de/intro/Krasnoyarsk-Int-FM-Week-Vesti-ru-15-Sep-2012-short.mp4> (mp4, 56 MB)
- Film produced by *Avialesookhrana*: <http://www.fire.uni-freiburg.de/intro/Krasnoyarsk-International-Fire-Management-Week-2012.mp4> (mp4, 0.7 GB)

From left to right (back row, standing): Alexey Narishkin (Head, Department of Fire Prevention and International Cooperation, Aerial Forest Fire Center *Avialesookhrana*), Yulia Gavrikova (Reporter, Newspaper Forestry News), Antonina Kramskih (Reporter, Newspaper Forestry News), Johann Georg Goldammer (Director, Global Fire Monitoring Center), Andrey Eritsov (Deputy Chief, Aerial Forest Fire Center *Avialesookhrana*), Sergiy Zibtsev (Head, International Programs, Institute of Forestry and Landscape Park Management, Na-

tional University of Life and Environmental Sciences of Ukraine), Alexey Kolegov (Helirapeller, Krasnoyarsk Aerial Forest Fire Center, Yartsevo outstation), Aleksandr Selin (Director, Krasnoyarsk Aerial Forest Fire Center), Elena (Reporter, TV Rossia-2), Fedor Zebzeev (Instructor, Team of Helirapellers of Krasnoyarsk Aerial Forest Fire Center, Yartsevo outstation)

From left to right (first row, sitting): Aleksandr Stepchenko (Deputy Director, St. Petersburg Forestry Research Institute), Battugs Gendenjav (National Emergency Management Agency, Mongolia), Oleg Arban (smokejumper, *Avialesookhrana* Yoshkar-Ola outstation, and camera operator).

This group photo of the 2012 expedition does not include all participants. Photographs of Yegor Kisilyakov (Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk) and Oyunsanaa Byambasuren (GFMC) are found on the following page.



The international participants (from left):
Oyunsanaa Byambasuren, Johann G.
Goldammer, Sergiy Zibtsev, Battugs Gendenjav



Unloading the MI-8 helicopter



Helicopter rotor downwash



On-site briefing



Yegor Kisilyakov



Alexey Narishkin and Alexey Kolegov setting up
an inventory plot

Part III: Forest and Steppe Fires in Mongolia

Oyunsanaa Byambasuren and Johann Georg Goldammer

1. Introduction

The Central Asian region including Mongolia for the last two decades is experiencing an increase in occurrence, area burned and environmental impacts caused by wildland fires. In Mongolia the damages from wildland fires, as well as their influence on human health and wellbeing, are increasing. The scale of wildland fire sometimes has transboundary effects (e.g. fires and fire-smoke pollution crossing the borders with Russia and China), demanding regional / international and cooperative efforts to address the problem.

Reasons for the escalation of destructive wildfires are, among other, result of the rapidly changing socio-economic conditions, a limited public budget for forest and fire management, and side effects of illegal logging. Projected trends of climate change impacts on vegetation cover and fire regimes, as well as observed demographic and socio-economic trends suggest that wildland fire may continue to play a major role in the destruction of vegetation cover in Mongolia, resulting, among other, in accelerating steppization, permafrost thawing and desiccation of peatlands / wetlands.

Every landscape has a specific fire regime, and the adaptation methods of vegetation types are diverse. In the Taiga- und Sub-taiga forests, fire is a natural ecological factor which, in conjunction with climatic and edaphic factors, influences species composition and the spatial distribution of forest ecosystems (Goldammer 2002; Mühlenberg et al. 2000). The main natural cause of forest fires in the Taiga ecosystems during the summer months is lightning (Chuluunbaatar 2001). Since the transition to a market economy at the beginning of the 1990s, the duration, frequency and intensity of forest fires have increased significantly. The seasonal outbreak of fires correlates with socio-economic activities resulting in a main fire season from March to June (80% of forest fires), and a smaller fire season during the autumn months (5 to 8% of forest fires) from September to October (Goldammer 2002). Forest fires are one of the main causes of the drastic degradation of Mongolian forest resources over the past two decades. Fire regimes may vary in space and time at both regional and local scale (Johnson and Van Wagner 1985). At the regional scale, latitudinal and longitudinal gradients in fire regime have been observed (Heinselman 1981; Payette et al. 1989) and the response of fire regimes to short and long-term climate change has been reported (Clark 1988, 1990). At the local scale, different topography and vegetation types may be characterized by specific fire behavior (Romme and Knight 1981; Fowler and Asleson 1982; Engelmark 1987) and fire regimes may vary from one landscape to another in relation to the specific proportion and arrangement of their topographical units and forest cover (Heinselman 1981; Knight 1987). Thus, understanding of ecology and dynamics

of different forest ecosystems is essential to implement sustainable forestry and forest fire management planning.

In this chapter we present the socio-economic changes, which influences on forest resources and wildland fire situations in Mongolia. Also, general characteristics of Mongolian forest ecosystems, historical fire conditions in different forest ecosystems and results the First Central Asian Forest Fire Experiments were presented.

2. Physical and geographical characteristics of Mongolia impacting the fire risk

The Mongolian environment is hosting a range of diverse landscapes that include forested mountain ranges in the north, and desert, desert-steppe and steppe areas with low mountains and sparse vegetation in the south. High mountains and glaciers are concentrated in the west while the east of the country is characterized by vast plains and wild heathlands. The average elevation of the country is 1580 meters above sea level (Tsedendash 1995).

Natsagdorj et al. (1998) estimate that during the last five decades sandy areas have increased by 47,500 ha due to the progression of the Gobi Desert and the northern part of the country. The observed and the predicted changes in annual precipitation across Mongolia have been variable. Recent global climate model simulations have predicted declining precipitation in all parts of Mongolia, which would cause decreased soil moisture and increased drought duration (Batima et al. 2005). Mongolia has 3811 rivers and streams stretching for 67,000 km, over 3000 lakes containing 500 km³ of water, about 6900 springs with steady flows, over 190 glaciers taking about 540 km² and over 250 mineral water springs. However, less than 43% of people have access to a safe water supply. 18% of the annual water reserves available for use in Mongolia are groundwater resources. Surface water is located in northern and central regions, but for the Gobi Desert and steppe areas in the southern parts of Mongolia the only source is groundwater (MNE 2006).

The principal soil type is dry-steppe chestnut soil that covers some 40% of Mongolia. Other major soil types are brown desert-steppe and grey brown desert soils. Arable soils are generally dark chestnut and chestnut soils, which are typically light, fine-silty, around 20-30 cm deep with an organic matter content of 3-4% and pH of 6-7. Due to above mentioned climatic factors the soil ecosystems are comparatively vulnerable, highly susceptible to degradation by human activities.

The rates of humus production and vegetative regeneration and growth are very low throughout the country and agricultural productivity is not high comparing to other countries of the same latitude. Land degradation and desertification are the problems of great significance in Mongolia since, according to the Land Administration Authority, approximately 11 million ha or 7% of the total land area is degraded to some extent. The principal factors leading to degradation and desertification are considered to be: climate change

(especially increased drought); overgrazing due to livestock location near populated settlements, wells and along the main roads; wind erosion of cultivated areas and abandonment of cultivated land; fires; degradation due to rodent and insect damage to pastures; damage caused by vehicles (MNE 2006).

2.1. Climate and climate change

Severe Mongolian climate determines the total amount of fuel and the length and rigidity of the fire season. At the same time atmosphere state (temperature, humidity, stability, pressure, wind speed and direction, clouds and precipitation) impacts fire behaviour and spread and the level of moisture in the fuel controlling ignition and combustion.

Mongolia is a land of temperature extremes. Temperatures in Gobi desert can reach +40°C in summer and -40°C in winter. In Khovsgol Province (northern Mongolia) the temperatures can go down to -50°C. The fluctuations in annual average temperatures are between -9°C and 5°C. Spring comes in the mountainous areas at the beginning of April and continues to the end of June. In the steppe, semi-desert and desert zones, spring governs for 55 to 70 days though in the lowlands it is even shorter. At that time the mountainous areas have dry atmosphere, strong winds and occasional freezing until June. Summers here are usually short and begin in mid June and continue until the end of August. In the steppe and desert zones, the summer stretches over 3 months. July temperature of the Mongolian Altai Khangai, Khentii and the Khovsgol mountainous regions averages less than 15°C. The maximum summer temperature can reach anywhere from 35°C to 39°C in the north and 38°C to 41°C in the south. The highest temperatures are experienced in the mountainous and forest steppe regions for 7 to 10 days while in the desert zone it is felt for about 30 to 39 days. In the mountainous areas, the cold spring air mass disperses around the mid of June and reforms around the end of July. It is always cool in summer at elevations of over 2000 m above sea level. But, annually in the forest steppe there are 80 to 90 warm days and the number of warm days increases southwards, reaching 140 warm days in the Gobi Desert. Autumn is short starting in mountainous regions at the end of August and ending during the last days of September; in steppe, semi desert and desert zones autumn begins at the end of October / early November, lasting about 65 days.

It becomes evident that climate warming is leading to progressive melting of permafrost grounds in Mongolia along the entire southern forest border where island forests are occurring. Since these forests depend directly on permafrost as an important source of water supply, its melting and disappearing can start quick and uncontrolled declining of the forests in Northern Mongolia and Southern Siberia. After that one cannot exclude a possibility for the Central Asian deserts expanding to the north. Thus the problem of state and dynamics (both natural and anthropogenic) of the island forests in Mongolia concerns another problem, namely maintenance of stability of the whole structure of ecosystems along southern boundaries of the taiga biome of the eastern part of Asia (Dugarjav and Tsogt 2008).

2.2. Forest and other vegetation resources

Mongolia is considered as a country with poor forest reserves. Forests here due to their fragile characteristics relating to hard continental climate are very vulnerable to wildland fires, pests' invasions and human activities. The Mongolian forests are mainly located in the northern parts of the country, basically within the Khangai and Khentii ranges and Khovsgol region functioning as a separator of great taiga and steppe, and protect them of drying effect and having significant international ecological duties. Various signs (altitude, rainfall distribution and soil type) allow selecting six vegetation zones: alpine tundra (3.0% of the total area), mountain taiga (4.1%), mountain steppe (25.1%), steppe (26.1%), desert steppe (27.2%) and desert (14.5%). The greater part of area used for agricultural production is used for extensive grazing. Not more than 2.5% of the total area is considered to be suitable for arable use (1.7 million ha) and for production of hay (2.0 million ha). Total cropland is put at 1.3 million ha with some 0.8 million ha under crops each year. Sandy areas are estimated at about 4.4 million ha (3% of land) and roughly 4.3 million ha are occupied by settlements, ploughed farmland and infrastructure. The remainder is covered by water, glaciated and rocky areas. Mongolian forests contain about 140 species of trees, shrubs and woody plants.

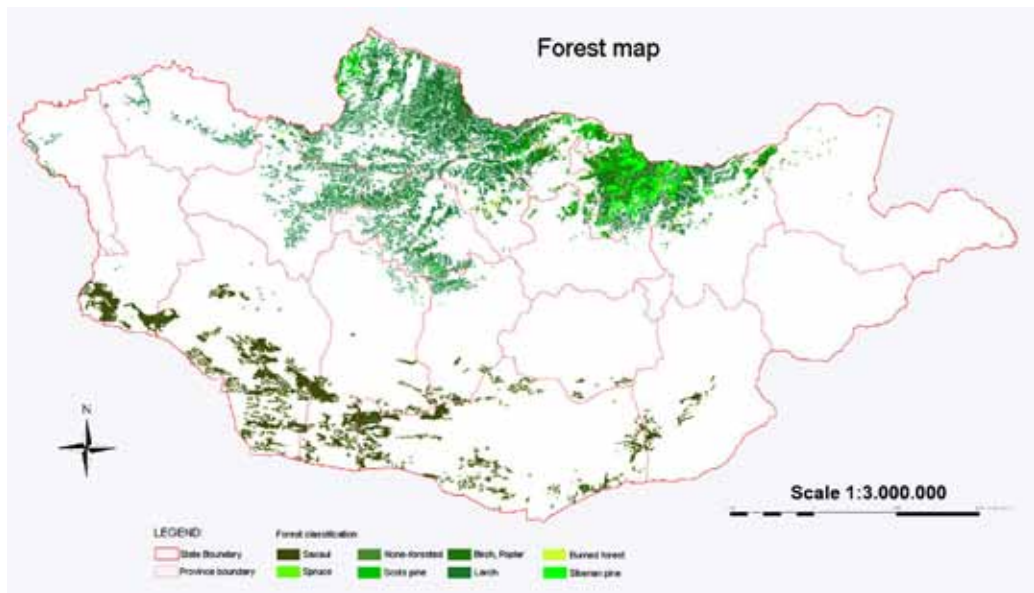


Figure 1. Forest map of Mongolia. Source: Information and Computer Center (ICC), Mongolia (ICC 2010)

About 124.3 million ha (79% of land area) are covered by grassland and 15 million ha (9.5%) are covered by forest and shrub. The leading species are larch (73.6%), cedar (13%),

pine (8%), birch (5%) and other species (fir, aspen etc.) and saxaul (*Haloxylon ammodendron*) forests. Most forests are considered to be critical for watershed protection. In the river floodplains poplar (*Populus laurifolia*), various species of willows and birches, and in the mountain valleys and on the banks of the temporal canals elm (*Ulmus pumila*) are encountered. Pine (*Pinus sylvestris*) takes significant areas in the East, Khentii, Selenge and partially in central Aimags and also is met as an admixture to larch. Larch and pine are widely spread in the mid part of the slopes while in the lower part the secondary deciduous forests are prevailing dominated by birch (*Betula platyphylla*) and aspen. In the upper part of the slopes of high ranges on the level 2000-2100 m *Pinus sibirica* is admixing with reaching the upper border of the forest forms pure pine forests. On the level 2200-2300 m in the mountains Khentii *Pinus pumila* is encountered. The banks of small rivers and branches are bordered by thick bushes of birches (*Betula humilis*, *B. rotundifolia*) and willows (with height of 2-3 m), and upper in the mountains in the river hollows there are valleys of spruce forests (*Picea obovata*) in some places with the admixture of fir (*Abies sibirica*). In the river valleys of Khangai-Khentii mountain region as well as in the west of the country in intra-mountain basins and valleys there encountered a comprehensive inundated complex – riparian forest. It contains various species of high willows, bird cherry, hawthorn, sea-buckthorn (*Hippophae rhamnoides*) and scattered poplars (*Populus laurifolia*).

The average standing volume of the northern closed forest is estimated to be 103 cubic meters per hectare, giving a total standing volume of around 1300 million cubic meters (Table 1).

Table 1. Area and standing volume of Mongolian forests. Source: Crisp et al. (2004)

	Area (ha x 1000)	Standing volume (million cubic meters)
Larch (<i>Larix sibirica</i>)	7,527	1,030
Pine (<i>Pinus sylvestris</i>)	662	71
Cedar (<i>Pinus sibirica</i>)	985	161
Other conifers	29	4
Broadleaf Species (<i>Betula</i> , <i>Populus</i> , <i>Salix</i>)	1,199	86
Saxaul (<i>Haloxylon ammodendron</i>)	2,029	1
Total	12,431	1,335

The total area of forest in the country is 17.9 including around 1.8 million ha are non-forested areas, 4.5 million ha are the southern saxaul scrub forests, and the remainder are the 11.5 million ha of northern coniferous forests (Crisp et al. 2004). The latest information presented at the First international Central Asian Wildland Fire Joint Conference and Consultation revealed that forest stock of Mongolia today is 18.3 million ha and covers 12% of

the total territory. 13,776,500 ha or 75.3% are coniferous and deciduous species and shrubs. 4,515,300 ha or 24.7% are occupied with Haloxylon forest. 58.8% of forest stock is Siberian larch (*Larix sibirica*), 5.2% - Scots pine (*Pinus sylvestris*), 7.7% - Siberian cedar (*Pinus sibirica*), 8.8% - birch (*Betula* spp.) and 16.0% - Haloxylon respectively. However Siberian spruce (*Picea obovata*), poplar (*Populus tremula*), elm (*Ulmus* spp.) and willow (*Salix* spp.) occupy a small area (Dugarjav and Tsogt 2008).

More than a half of the total forest resources of the country belong to special and protected forest area. In last century Mongolia lost about 4 million ha of forest but the pace of average annual forest destruction increased from 40,000 ha to about 60,000 ha in the last decade of the 20th century (World Bank 2003). For the last 30 years the natural forest area has been reduced by 953,400 ha (Dugarjav and Tsogt 2008).

Most of the forested area is unavailable for wood production under the existing system that distinguishes strict, protected, and utilization zones. Commercial harvesting area is 1.2 million ha but there is a rapid increase of illegal logging. The legal harvest in 2002 was 40,000 cubic meters of roundwood and 580,000 cubic meters of fuelwood, which is more than allowable cut and about one fourth of actual consumption (World Bank 2003). The center of wood harvesting is Selenge Aimag.

The total amount of wood in Mongolian forests is 1.379 billion m³, according to species, the amounts are: Siberian larch (*Larix sibirica*) 1.027 billion m³, Scots pine (*Pinus sylvestris*) 92.6 million m³, Siberian pine (*Pinus sibirica*) 164 million m³, spruce (*Picea obovata*) 3.7 million m³, fir (*Abies sibirica*) 375,700 m³, birch (*Betula platyphylla*) 86 million m³, poplar (*Populus* spp.) 2.1 million m³, aspen (*Populus tremula*) 1.4 million m³, willow (*Salix* spp.) 544,700 m³ (Tsogtbaatar 2002). It is important to note that the steppe-forest and taiga ecosystems in Mongolia are very fragile and therefore require special care and protection. Forest restoration started in 1970 but only very small areas were reforested successfully and sustainably.

2.3. Socio-economic development and forest utilization

Mongolia remained a nation of mainly rural population until the late 1970s when for the first time more than 50 percent of Mongolians were residing in urban areas. At the turn of the millennium, 56.6 percent of the overall population of Mongolia lived in urban areas. By 2010, this proportion is estimated to have increased to 63.3 percent (UNDP 2011). Which supports pressure on natural ecosystems surrounding the urban areas, on the other hand fire risk may increase in an abandoned rural areas. The World Bank (2012) study reveal that Mongolia is at the threshold of a major transformation driven by the exploitation of its vast mineral resources and the share of mining in GDP stands at 20 percent, twice the ratio of

a decade ago. The economy grew by 17.3 percent in 2011, compared to 6.4 percent GDP growth in 2010.

Sustainable forestry and forest utilization has been affected by various developments. The annual volume of logging, which was about 2.2 million m³ in the mid 1980s, fell to about 0.86 million m³ in 1992, and the harvest in the year 2000 was only 0.5 million m³. This fall in harvest levels is partly due to the influence of institutional and policy changes involving the privatization of production enterprises and the decentralization of decision-making power. But partly it is also due to the supply constraint as a consequence of the reduction in the area of designated utilization forest from about 5.8 million ha in 1985 to around 1.2 million ha in 2007. This is due to reclassification of some of the utilization forests as protected areas.

Clear cutting is second important disturbance factor after wildfire. Results of the inventory of forest ecosystems in the Mongolian part of the Lake Baikal basin show that territories with strong and severe disturbance cover 14,550 km², or 20% of the total forests cover. For the last 15 years 250,000 ha of felled forest plots have accumulated without any natural regeneration. Some disturbed forest lands are covered only with birch and aspen (Goldammer 2006; Dugarjav and Tsogt 2008). Such high rates of forest cover decline suggest possible future changes in the regional ecology resulting from the alteration of the water-regulating functions of the deforested areas. Recent research reveals that a decrease of forest cover due to clearcuts by 10% leads to an increase of annual surface runoff to 15-25 mm (Dugarjav and Tsogt 2008).

Statistics reveal that one-quarter of Mongolia's total forest land has been affected by human activities such as illegal cutting, forest fires, and harmful insects and pests. A World Bank study of 2006 confirmed that the wood supply in Mongolia is mostly from illegal sources. At present, annual timber logging in the country has reached 700,000 m³. The government of Mongolia has established quotas for sawn timber and fuel wood on the level of 0.04 and 0.6 million m³ respectively. This is approximately half of the wood used in the country. Currently about 65 percent of logged wood is used by the poorest of the Mongolian population in agricultural and urban regions for heating and cooking. The government introduced some measures to decrease the illegal wood turnover including the certification code for transportation of commercial and fuel wood between Aimags and cities; revised licenses to cut commercial and fuel wood; revised law articles connected with planning and allowable cut volumes; inspection of illegal cuttings; NGOs and citizens involvement in monitoring of logging; state support of community based forest management approaches. These measures are directed to combine the power efforts with the activities of the civil society beginning to understand that the forests and their sustainable development is one of the main economic pillars of the country.

Forest fires cause major economic losses. Not only do timber yields per hectare decrease, but also wood quality is negatively affected in large areas of economically significant forests. In addition, the induced mortality to natural forest regeneration or forest plantations is a special problem in areas where tree regeneration or artificial reforestation is especially dif-

ficult due to highly-specific ecological conditions. Thus, forest fires, in addition to livestock grazing that is often exceeding the carrying capacity of steppe ecosystems, have a direct effect on forest land distribution by transforming forests into steppe ecosystems. This process might be irreversible if climate change will significantly alter precipitation patterns and reduce the total annual rainfall.

3. Fire situation in Mongolia

Wildland fires become one of the most influential factors changing the situation in the environment and people livelihoods. Extremely large fires occurred in Mongolia in the following periods: 1968-1969, 1977-1978, 1985-1987, 1991-1992, 1996-1998, 2000-2002 (Enkthur et al. 2005). According to studies, 55.3% of the country's territory is referred to a forest and steppe fire-risk zone. Frequent and large-scale vegetation fires led to recorded wide devastation of forests (GFMC 2008). Fire-prone fuels, low humidity, strong winds in the dry season, economic activities causing disturbances make conditions for wildland fires. As a result, more than a half of the country is considered a fire-risk zone, and 98.5 percent of forests are classified as high fire risk areas.

Table 2. Wildfire database 1980-1989. Sources: GFMC database; Bayartaa (2006)

Year	Total No. of Fires on Forest, Other Wooded Land, & Other Land	Total Area Burned on Forest, Other Wooded Land, & Other Land	Area of Forest Burned	Area of Other Wooded Land and Other Land Burned
	No.	ha	ha	ha
1980	162	395 800	107 200	288 600
1981	94	169 200	4 600	164 600
1982	109	1100 000	156 300	943 700
1983	95	245 400	87 400	158 000
1984	116	513 900	156 200	357 700
1985	99	1 896 700	3 400	1 893 300
1986	204	3 187 000	30 600	3 156 400
1987	233	1 228 000	143 300	1 084 700
1988	142	243 000	2 300	240 700
1989	192	1 281 000	51 000	1 230 000
Mean	145	986 460	63 521	922 938

The wildfires constitute a major factor that determines spatial and temporal dynamics of forest ecosystems. 4 million ha (23% of total forested area) are disturbed to varying degrees, either by fire (95%) or by logging (5%). Wildland fire impacts are vividly characterized by the examples of the period 1996-1998 when winters and springs were extremely dry in the majority of Aimags. Mongolia experienced large-scale forest and steppe fires (Table 3) that devastated large parts of the country. Fire episodes caused the death of 29 people, 82 people were injured and 11,700 livestock were killed. Also, 218 family houses, 1066 communication facilities, 750 fences and 26.3 million ha of pasture and forest burned. The total costs of property losses amounted to 820.2 million tugriks. Ecological and economical damage were estimated as 1.85 billion tugriks (December 1999 value: ca. \$US 1.8 million).

Table 3. Wildfire database 1990-1999. Sources: NEMA; GFMC database; Bayartaa (2006)

Year	Total No. of Fires on Forest, Other Wooded Land, & Other Land	Total Area Burned on Forest, Other Wooded Land, & Other Land	Area of Forest Burned	Area of Other Wooded Land and Other Land Burned
	No.	ha	ha	ha
1990	129	2 577 000	55 000	2 522 000
1991	101	6 099 000	639 000	6 035 100
1992	171	1 541 000	390 700	1 123 300
1993	63	2 763 000	202 000	2 561 000
1994	126	3 600 000	165 000	3 435 000
1995	120	168 570	34 200	134 370
1996	417	10 194 400	2 363 600	7 830 800
1997	239	12 440 000	2 710 00	9 730 000
1998	132	5200 000	700 000	4 500 000
1999	76	5120 000	25 000	5 095 000
Mean	157	4 970 297	484 550	3 591 877

Table 4. Wildfire database 2000-2011. Sources: NEMA (2011); GFMC database; Bayartaa (2006)

Year	Total No. of Fires on Forest, Other Wooded Land, & Other Land	Total Area Burned on Forest, Other Wooded Land, & Other Land	Area of Forest Burned	Area of Other Wooded Land and Other Land Burned
	No.	ha	ha	ha
2000	264	1090 000	660 000	430 000
2001	127	380 000	87 000	293 000
2002	323	860 000	582 000	277 000
2003	60	3 800 000	3 700 000	100 000
2004	79	7 800 000	100 000	7 700 000
2005	115	4 364 800	310 900	4 053 900
2006	164	5 593 900	391 700	5 202 200
2007	228	1 335 300	512 300	823 000
2008	178	198 537	32 479	198 537
2009	120	409 389	160 750	248 642
2010	104	1 014 518	39 770	974 748
2011	161	4 138 338	17 964	4 120 374
Mean	160	2 582 065	549 572	2 035 117

3.1. Fire occurrence

Statistics reveal that the majority of fires burn on the areas of concentration of pine and larch stands and human economic activity. Forest cover, mainly pine stands with mixed herbaceous ground cover, is characterized by high fire danger in spring and autumn. Steppe vegetation and surrounding pine stands attain high flammability practically simultaneously. Fires are frequent in pine and larch stands of the forest-steppe and sub-taiga zones, while they are rare in larch and Siberian pine stands of the mountain taiga (Chuluunbaatar 2001). In addition to that, the extreme fire seasons are caused by long droughts creating the conditions for fires from April to July. However, the average fire season usually has two peaks. One peak occurs during spring (from March to mid June) accounting for 80 per cent of all fires. The other fire peak falls within a short period in autumn (September to October) with its 5 to 8 percent of all fires. In summer, fires are very rare (only 2 to 5 percent of the total) because of the high summer precipitation. Fire start and spread is assisted by the rapid drying of vegetation on southern and western slopes. Steppe and forest under certain

weather conditions often exchange fires. Strong winds of a continental-cyclonic character, whose average speed amounts to 5m/s in spring time, also contribute to fast drying of forest fuel. Intensive solar radiation removes thaw water from the topsoil by evaporation, and the remaining thaw water flows from elevated sites downhill and accumulates in depressions because it cannot penetrate deeply into frozen soils. Spring fires are thus most common in stands on these elevated dry landscape elements (slopes) and in those where herbs and small shrubs form a loosely compacted living ground cover layer. The number of fires reaches its maximum in May and June which are the hottest and driest months. In summer, abundant green vegetation reduces the fire start risk considerably. In exceptionally dry years, however, fires remain active during summer period. Most of the lightning fires are registered in the mountain forest belt, especially in the high elevations. Lightning storm activity increases considerably at the end of May and early June.

3.2. Fire causes

Accurate information on fire causes in Mongolia are sparse. However, it is established that during the main fire seasons (spring and late fall), there are very few to none lighting fires. The recent increase in the number of fires is related to the increasing economic activities and opening of markets that were once highly controlled or restricted (Goldammer et al. 2004). Fires are mainly attributed to carelessness. One example is the presence of people in the forests collecting elk antlers for sale to European and Chinese markets. This activity had been monopolized and strictly controlled during the previous regime. Nowadays, it is open to virtually anyone. In this context wildfires are ignited due to three reasons: (1) antler collection starts in February when fire is a survival tool in the cold winter weather. Camp fires set for warming and cooking are not properly taken care and result in spread of wildfires; (2) sparks from vehicle exhaust pipes in remote forests; and (3) tracer bullets used for hunting that ignite forest fuels (the bullets were left by the Russian military and have entered the game hunting market).

The 2005 country report from Mongolia (Enkhtur et al. 2005) summarizes the causes of forest fires in the period 2000-2004 as follows: lightning – 12%; campfires – 16%; cigarettes and matches – 15%; sparks from vehicle exhaust pipes – 6%; border-crossing fires from neighbouring countries – 7%; other – 43%.

Using fire to transform forests into pastures and to repeatedly burn established pastures to improve grazing was a common and widespread practice by nomads in Mongolia. Recently pasture burning has been banned in many counties. Yet a successful ban of burning resulted in widespread re-growth of shrubs resulting in higher fuel loads. This policy is not very popular among pastoralists, since they are losing high-quality grazing lands. Repeated fires have been responsible for converting the shrub areas into grasslands.

3.3. Fire environment, fire regimes and the ecological role of fire

Fire plays a significant role in forming forest ecosystems in Mongolia. Typical fire regimes found in the steppe and forest ecosystems, including the transition types of grass forests, are provided in Table 2 to 4. In the majority of the forest lands of Mongolia – with a few exceptions of less accessible forests in the North of the country – fire regimes have been moderately or significantly altered.

A significant proportion of Mongolia's land area is occupied by the mountain forest-steppe zone, which historically could have burned as frequently as the pure steppe areas adjacent to it. Fuels would be consistent between the two with the same rate of drying and exposure to wind. This fire regime has likely experienced the greatest changes over the course of the last century. The most profound changes would be in stand structure (density by age-class) and could be attributed mostly to grazing removing grass fuels plus organized fire suppression during the Soviet-influenced regime.

The ultimate effect of overgrazing-induced stand density increases is resulting in higher fire severity than was historically the case, plus a higher incidence and intensity of insect attack. Fires are now heavily thinning the younger cohorts and even killing the historically more resilient older cohorts as well. This leads to an altered forest structure that is not as resilient as the historic structure. Post-wildfire salvage is also exacerbating the situation by removing the older, large-diameter trees (whether alive or dead), and leaving the dense, dead, younger trees. Dead trees on the site eventually will rot at the base and fall over, accumulating on the site as large diameter surface fuel. With such dry cold conditions in Mongolia the decay rate of this "fuel" is very slow meaning the fuel hazard will persist for a long time. When this material burned in a wildfire tends to smoulder at high temperatures and long residence times. Subsequent consequences include surface erosion and excessive surface runoff.

3.4. Fire history of different type of forest stands in West Khentii Mountains, Mongolia

During the last decade the radial growth responses of trees to climate have been extensively studied for climate sensitive trees in Mongolia (Jacoby et al. 1996, 2003; D'Arrigo et al. 2000, 2001; Baatarbileg et al. 2001; Pederson et al. 2001; Davi et al. 2006). However, the understanding of the forest ecology and disturbance regime based on dendrochronological analysis has been less studied. Thus, understanding of the history and natural role of fire,

the effects of fire suppression, and fire behavior under various conditions is essential tool to develop and implement a fire management program.

The objective of this study is to determine the fire regimes within different forest types. More specifically, our work aims to understand the effects and relationship of forest fire and stand dynamics within different types of stands.

Materials and methods

In order to examine the fire history, *Pinus sibirica*-*Abies sibirica*, *Picea obovata*-*Abies sibirica*, *Larix sibirica*-*Betula platyphylla* and *Pinus sylvestris*-*Larix sibirica* forest stands were selected in Khonin nuga region of north-west Khentii Mountains. To characterize the stand structure ten (40 x 40m) quadrat plots were established within each forest type. In each of the plots, the number of living trees, species and diameter at breast height (DBH; measured at 1.3 m) were recorded. The number of snags (standing dead trees) and its species (if distinguishable) were recorded to document structural features, disturbance history, and decay dynamics.

Fire scarred specimens were taken from stumps, downed logs, snags and live trees, not farther than ≈ 100 m radius from the plots. Large diameter live trees were sectioned using the methodology described by Arno and Sneek (1977). In some cases, large diameter, solid snags were sectioned in a similar manner to large-diameter live trees in order to avoid felling them. This was done if the snag had high potential value for wildlife and if it was – (a) safe to leave it standing, or (b) too dangerous to let it fall. In most of these cases, the samples were represented by dominant tree species within the forest type. A total of 266 cross-sections/specimens were collected.

After the tree rings from all fire-scarred cross sections were cross-dated, calendar years were assigned to all fire scars. Then all data was entered to the FHx2 software (Grissino-Mayer 1995). For the analysis of the historical range of variability of fire regimes standard statistics were used. (Grissino-Mayer 1995, 2001b; Georgina 2007).

The seasonality of fires was determined by recording the intra-annual position of the scar within the tree ring (Dieterich and Swetnam 1984; Baisan and Swetnam 1990; Grissino-Mayer et al. 2004). The seasonality of fire events may show temporal shifts in fire season, and these shifts could be linked to forest structure changes and human activity in a region (Seklecki et al. 1996; Lewis 2003; Grissino-Mayer et al. 2004).

The seasonality of fire events is a critical component of the fire regime because managers can use this information for the development of fire management plans in order to mimic the effects of past fires (Lewis 2003). We used five categories of fire seasonality established by previous studies: dormant, early-early season, middle-early season, late-early season, and late season. Dormant season fires are located between the latewood of the previous ring and the earlywood of the following ring (Figure 2). Recent fire (NEMA 2011) records in Mongolia indicate that fires which started in spring are more common than fires in late-summer or fall. Any tree-ring samples that could not be cross-dated were not used in subsequent analysis.

Table 5. Fire statistics (in years) for all sampling sites.

Classes	Statistics*	<i>Pinus sibirica</i> - <i>Abies sibirica</i> forest (1753-2009)	<i>Picea obovata</i> - <i>Abies sibirica</i> forest (1753-2009)	<i>Larix sibirica</i> - <i>Betula</i> <i>platyphylla</i> forest (1792-2009)	<i>Pinus sylvestris</i> - <i>Larix sibirica</i> forest (1758-2009)
All Scarred	MFI	45.98	38.99	8.50	11.68
	WMEI	35.34	35.65	6.38	8.42
	WMOI	30.23	26.90	4.16	1.89
	SD	18.9	24.50	6.58	11.51
	CV	0.49	0.60	0.75	0.99
	MIN	17.40	15.86	2.10	1.60
	MAX	62.00	68.57	24.70	38.70
	LEI	19.18	16.83	2.54	1.91
	UEI	57.02	63.91	15.43	23.82
Min 2 trees & 25% Scarred	MFI	59.02	54.18	16.00	14.06
	WMEI	45.83	37.98	15.77	11.56
	WMOI	41.57	24.14	13.31	5.60
	SD	25.29	32.97	9.29	11.77
	CV	0.55	0.72	0.66	0.93
	MIN	23.00	17.60	7.70	3.70
	MAX	75.20	84.60	33.00	40.10
	LEI	24.33	16.30	7.73	3.80
	UEI	72.12	76.92	26.52	26.14

*MFI = Mean Fire Interval; WMEI = Weibul Median Interval; WMOI = Weibul Modal Interval; SD = Standard Deviation; CV = Coefficient of Variation; MIN = Minimum Fire Interval; MAX = Maximum Fire Interval; LEI = Lower Exceedance Interval; UEI = Upper Exceedance Interval

In Mongolia, no specific research has been conducted on the phenology of tree species to determine the exact time of cambial growth of trees. To complicate this type of analysis, the length of the growing season can vary depending on the site. We therefore chose to provide fire season information based only on the intra-annual position of the fire scars.

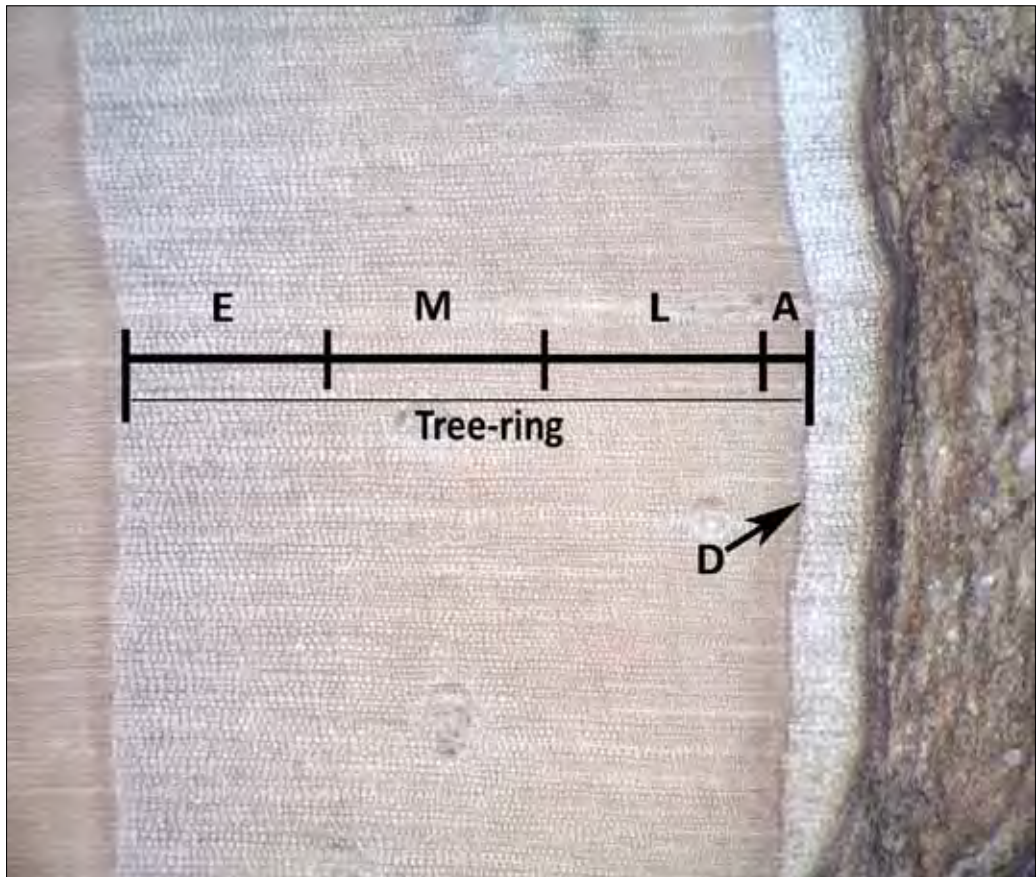


Figure 2. Illustration of fire seasons on a fire-scarred *Pinus sibirica* cross-section. Fire seasons include E = early-early season, M = mid-early season, L = late-early season, A = late season, and D = dormant season fires. *Note:* The white incomplete ring at the right side shows that early-early season fire, which occurred in all study forests on 18 May 2009.

Fire history of *Pinus sibirica*-*Abies sibirica* forest

Between 1753 and 2009, *Pinus sibirica* dominated forests experienced a mean fire interval (MFI) of 45.98 years (Table 5) for the all-scarred class and it was 59.02 for the 25%-scarred class. In general, the fire-free intervals in *Pinus sibirica* forests were found to be of the longest duration amongst the four study sites. For the all-scarred class, the LEI and UEI were 19.18 and 57.02 years, respectively. For the 25%-scarred class, the LEI and UEI were 24.33 and 72.12 years, respectively. Values for LEI and UEI in this forest were similar with *Picea obovata*-*Abies sibirica* forest. Fires at *Pinus sibirica*-*Abies sibirica* forest, which are spatially

large, extending across several ridges, occurred in 1856, 1929, and 2009. The last largest fire occurred in 2009, which had a high intensity and affected large portions of the study area. This forest also experienced numerous spatially-small, patchy fires that scarred only one or few trees within our study area, such as the fires in 1814, 1819, 1823, 1826, 1868, 1875, 1896, and 1954.

Fire history of *Picea obovata*-*Abies sibirica* forest

Fire regime statistics for the *Picea obovata*-*Abies sibirica* forest include a total of 11 separate fires over the period from 1753 to 2009. The first dated fire in this forest occurred in 1823, and the most recent one was the 2009 fire. In this forest, MFI was 38.99 years for the all-scarred class and 54.18 years for the 25%-scarred class (Table 5). The LEI and UEI were 16.83 and 63.91 years, respectively for the all-scarred class, and 16.30 and 76.92 years for the 25%-scarred class. *Picea obovata*-*Abies sibirica* forest did not experience large fires and the relatively large-scale fire occurred in 1872. Smaller or spatially individual fires occurred in 1822, 1866, 1884, 1895, 1929, 1945, and 1970. The last extensive fire in *Picea obovata*-*Abies sibirica* forest occurred in 2009, which was also a major fire year in the other three forest sites. Based on fire history statistics at *Picea obovata*-*Abies sibirica* forest, the MFI was 38.99 years for the all-scarred class and 54.18 years for the 25%-scarred class (Table 5). The LEI and UEI were 16.83 year and 63.91 years, respectively, for the all-scarred class, and 16.3 years and 76.92 years for the 25%-scarred class. As with *Pinus sibirica*-*Abies sibirica* forest, the fires in *Picea obovata*-*Abies sibirica* forest had a much patchier distribution in contrast to the fire regimes at *Larix sibirica*-*Betula platyphylla* and *Pinus sylvestris*-*Larix sibirica* forest.

Fire history of *Larix sibirica*-*Betula platyphylla* forest

The fire scar record at *Larix sibirica*-*Betula platyphylla* forest extended from 1752 to 2009 and included 66 separate fires. The earliest fire occurred in 1793, the MFI was 8.5 years for the all-scarred class and 16.0 years for the 25%-scarred class (Table 5). The LEI and UEI were 2.54 years and 15.43 years respectively for the all-scarred class and 7.73 and 26.52 years respectively for the 25%-scarred class. The *Larix sibirica*-*Betula platyphylla* forest had the most frequent fires and the largest fires did occur in 1929, 1948, 1996, and 2009. Also, in these years *Pinus sylvestris*-*Larix sibirica* forest experienced one of the biggest fires.

Fire history of *Pinus sylvestris*-*Larix sibirica* forest

Fire regime statistics for the *Pinus sylvestris*-*Larix sibirica* include a total of 61 separate fires over the period from 1798 to 2009. The MFI of all-scarred class for this period is 11.68 years with a minimum interval of 1.6 year and a maximum of 38.70 years. The MFI for 25%-scarred class were 14.06 years, with a minimum interval of 3.7 and a maximum of 40.1

years. The LEI and UEI were 1.91 years and 23.82 years respectively for the all-scarred class and 3.80 and 26.14 years respectively for the 25%-scarred class.

In general, the coefficients suggest that the variability for the mean fire intervals were fairly consistent for three forests (Table 5): *Pinus sibirica-Abies sibirica*: 0.49 (all) and 0.55 (25%); *Picea obovata-Abies sibirica*: 0.60 (all) and 0.72 (25%); and *Larix sibirica-Betula platyphylla*: 0.75 (all) and 0.66 (25%). The variability of the lengths of fire-free periods in *Pinus sylvestris-Larix sibirica* was the highest amongst the four sites: 0.99 (all) and 0.93 (25%). This property can be seen in the fire statistics for *Pinus sylvestris-Larix sibirica* forest (Table 5).

Fire seasonality

Fire seasonality analysis showed that the majority of fires within all forest sites were early-season fires or occurred in the dormant season (Table 6), thereby likely indicating fires that occurred in the spring of that year. Dormant season fires occur after the last growing season's coniferous needles fall and before the leafed trees flush in spring (Farrar 1998). In *Pinus sibirica-Abies sibirica* forest, 73.2% of fires were either early season (72.2%) or dormant season (1%) fires, with 26.6% of fires occurring through the middle until the late period of the growing season. In this forest, 85.8% of fire seasonality was determined successfully and 14.2% of fire scars could not be assigned a season because these scars were too degraded or unclear in order to determine the season of the event.

Picea obovata-Abies sibirica forest had 65.5% of fire scars that indicated early growing season and dormant season fires (Table 6), the majority of which were early growing season fires (61.8%). Fire scars that occurred during the middle part of the growing season made up 34.5% of the total. In *Picea obovata-Abies sibirica* forest, 12.7% of fire events could not be assigned a fire season in the tree-ring record because of the degraded state of the wood.

Fire seasonality in *Larix sibirica-Betula platyphylla* forest were also concentrated in the early earlywood (Table 6) with 83.6% and in the dormant season with 0.9% of all scars attributed to those portions of the intra-annual ring. Minor proportions were also found in the middle earlywood (12.9%) and late earlywood (3.4%). The latewood fire scars were not found in this forest. We could not determine the seasonality to 32% of the fire scars in this forest type because of the unclear position of scars. When compared to other forest types, it scored the highest percentage of undetermined seasons.

Table 6. Seasonality of fire events (expressed by percent) for scars where season could be determined.

Study area	Dormant (D)	Early-Early (E)	D+E	Middle-Early (M)	Late Early (L)	Late (A)	M+L+A
<i>Pinus sibirica</i> - <i>Abies sibirica</i>	1	72.2	73.2	12.4	14.4	0	26.8
<i>Picea obovata</i> - <i>Abies sibirica</i>	3.6	61.8	65.5	34.5	0	0	34.5
<i>Larix sibirica</i> - <i>Betula platyphylla</i>	0.9	82.8	83.6	12.9	3.4	0	16.4
<i>Pinus sylvestris</i> - <i>Larix sibirica</i>	2	73.2	75.2	19.9	4.9	0	24.8

The seasonality of past fires in *Pinus sylvestris*-*Larix sibirica* forest was similar to the seasonality observed for past fires in other forest types (Table 6). The majority of fires (75.2%) were concentrated to the early growing season and dormant season fires. Minor proportions were detected in the middle earlywood (19.9%), late earlywood (4.9%) and dormant season (2%). In *Pinus sylvestris*-*Larix sibirica* forest, 70.8% of trees was found to successfully determine the fire season and the undetermined seasonality of fires was 29.2% because of degraded wood or too narrow rings on samples.

Discussion

Fire history. One of the aims of this research was to determine the frequency of forest fires in the north-west Khentii Mountains, Mongolia. Most of the forest fire history studies rely on a series of inferences based on a set of physical evidence left by fire. This includes even-aged, post-fire regeneration cohorts (e.g. Johnson 1992) and anomalies in the tree-ring structure of individuals, such as fire scars (Stephens et al. 2003; Swetnam et al. 2001). In this research the reconstruction of a composite master forest fire chronology for the study area was possible because of remaining trees with traces of fire incidence. Consistent patterns of past forest fire occurrence were emerging as many sites were collected and cross-dated from different forest types in the Khentii Mountains. Mean fire intervals were clearly different between the dark and light taiga forest types. The mean fire interval of 46 years (range 17.4-62 years) in *Pinus sibirica*-*Abies sibirica* forest, and 39 years (15.8-68.5 years) in *Picea obovata*-*Abies sibirica* dark taiga forests indicated that it was longer in contrast to those in *Larix sibirica*-*Betula platyphylla* and *Pinus sylvestris*-*Larix sibirica* light taiga forests. In com-

parison to the forest fire history studies in Siberia, fire return intervals in both the dark and light taiga forest types in the Khentii Mountains, showed shorter intervals. For example, the fire return interval in the light conifer (*Larix spp.* and *Pinus sylvestris*) middle taiga in central Siberia is 20-30 years (Furyaev et al., 2001) as compared to the 80-300 years in dark conifer (*Pinus sibirica* and *Abies sibirica*) southern and mountain taiga in southern Siberia (Polikarpov et al. 1986; Soja et al. 2006). It is not surprising that slow growing dark conifers are not adapted to frequent fires and the ones that burn with high severity fire, typically die. Additionally, they are not light-tolerant, so they are not likely to be the first species to succeed following fire events. On the other hand, *Larix sibirica* and *Pinus sylvestris* are evolutionarily adapted to fire and successfully regenerate through the opening of the cones after fire events (Tchebakova et al. 2009).

Turner (1994) concluded that crown fire ecosystems are probably the best regarded as non-equilibrium systems, because extensive, infrequent fires tend be very large relative to the total landscape area. Smaller fires also occur, perhaps frequently, but they have far less influence on stand age class distribution, and their effects are generally overshadowed by the rare large fires. Crown fires rarely consume the entire forest, and the spatial heterogeneity of burn severity patterns creates a wide range of local effects and is likely to influence plant re-establishment as well as many other ecological processes. In our study *Pinus sibirica*-*Abies sibirica* and *Picea obovata*-*Abies sibirica* dark taiga forests were found to show such a trend.

In context to the fire extent, the most recently known fire was recorded in 2009, which was very intensive and affected almost the entire study area. The fires in 1929 and 1954 were of a similar intensity within the area, however when compared, these fires date to recruitment pattern of trees and stand structure characteristics of *Pinus sibirica*-*Abies sibirica* forest (e.g. composition and density of trees species, abundance of downed logs, saplings and lichens on the trees), suggesting that fire was not highly intensive in this forest. Also, in *Picea obovata*-*Abies sibirica* forest, very few trees recorded fire in 1929 and none in 1954.

For the pure *Abies* stands dendrochronological technique is not generally applicable to determine fire history, since *Abies* species are not resistant to fire and thus generally do not survive to produce fire scars. However, mixed stands of *Abies* with *Picea* or *Pinus* can provide some data on fire frequency, because the latter species often record fires through scarring (Beaty and Taylor 2007). This was the case of *Picea obovata*-*Abies sibirica* forest in the present study. Fire in *Abies*-dominated forests appeared to convert *Abies* stands to other tree species rather than to perpetuate *Abies*. In our study area, we did not have pure *Abies* stands, however *Abies* co-dominated stands could already be present at this stage. Although widespread fires are not always more severe than small ones (Beaty and Taylor 2007), the correspondence between fire extent and severity in *PcOb-AbSI* forest suggests that fires (e.g., fire in 1929) may also have been low- severity events.

Valendik et al. (1998) estimated the mean fire interval (MFI) from 13.9 to 18.8 years in *L. sibirica* stands and 22.8 years in *P. sylvestris* stands in Bulgan province, Mongolia. Similar results were observed on fire history study of Larch forests at the eastern shore of the Lake Khovsgol (Oyunsanaa et al. 2006) revealing that the mean fire interval was 25.6 years. In

Siberia, the mean fire-return interval in larch stands is 15 years, ranging, according to one estimate, from 4 to 43 years (Takahashi 2006), and has not been observed to exceed 50 years (Valendik et al. 1998).

Hessl et al. (2011) observed that 6.8 years of WMFI (10% scarred class) in pure *P. sylvestris* stands at Tuijin Nars, which is located ca. 200 km to the north-west of our research area. In this study WMFI (25% scarred) in *L. sibirica* and *P. sylvestris* forests were 15.7 and 11.6 years, respectively. Mean fire intervals revealed from our study are in the range of other reports in Mongolia and Siberian region. *L. sibirica* and *P. sylvestris* trees are fire tolerant species (Sherbakov 1979; Wirth et al. 1999; Tsvetkov 2004). Mature *L. sibirica* stem is much more resistant to fire than *P. sylvestris* tree because of its relatively thick bark. Generally, *L. sibirica* and *P. sylvestris* trees are affected by forest fires at least several times during a generation (Sherbakov 1979). In the present study it was clearly seen that several *L. sibirica* trees recorded 11 fire scars (from 1792 to 2009), and *P. sylvestris* trees survived from 12 fires between 1752 and 2009.

Fire Seasonality. The seasonality of fires was, for the most period, constant and unchanging within each forest type. Also, the historical fire seasonality between the different forest types was similar. In *Pinus sibirica*-*Abies sibirica* forest, the majority of fire events took place during the spring season (72.2%), with the occasional fire took place during a different season. The most recently known fire date in the study area was the last ten days of May 2009. Different tree species within the different forest types recorded similarly this fire event and the most of the trees produced few cells during this period (an example of fire scar on *Pinus sibirica* tree from this date is shown in Figure 2). However, in *Picea obovata*-*Abies sibirica* forest, compared to other forest types, there was lesser early-early season (65.5%) fires and more of a middle-early season (34.5%) fire events. Generally, radial growth of trees could start later in *Picea obovata*-*Abies sibirica* forests; because they are growing in the north-facing narrow slopes, with the coldest and the longest snow cover period in the valleys.

In *Larix sibirica*-*Betula platyphylla* and *Pinus sylvestris*-*Larix sibirica* forests, the early-early season fire was the dominant and small amount of middle-early and late-early season fire events were recorded. Late-wood fire was recorded in none of the four forests types.

During the early spring before leaved trees flush, fires are common because of increased temperatures and wind speeds and low humidity, which work together to dry the surface fuel. These fuels remain exposed to the sun and wind until leaved trees flush in mid- to late April in low to middle elevations. During the late spring and into the summer, new vegetation growth increases, humidity rises, and wind speeds decline, all of which collectively contribute to reducing the likelihood of fires during the relatively long dry spring (Lafon et al. 2005).

Valendik et al. (1998) studied fire in Mountain sub-taiga pine stands in eastern Khovsgol region and found that the fire activity was the highest during spring, and autumn fires accounted for only 5% of the total number of fires recorded. Hessl et al. (2012) also reported that most of the historical fires occurred in the spring season (67%). Based on fire statistics

data, Mongolia has two fire seasons - a spring fire season (March to early June), and a short, less intense fall season (September to late October). At least 90% of all fires occur during the spring (Goldammer et al. 1996). Compared to modern fire season (last four decade of records), our results revealed that the seasonality of fire has not changed at least for the last 250 years.

3.5. Fire influence on vegetation cover

According to Chuluunbaatar (2008), the forest fuels are divided into following groups that are related to the typical occurrence of fires:

- (1) Plants that grow on freshly burned areas and disappear as succession towards forest is developing (*Chamaenerion angustifolium* L., *Corydalis sibirica* L., *Polygonatum sibiricum* Decker, *Cerastium pauciflorum* Steud., *Chenopodium album* L., *Artemisia marcocephala* J., *Carex amgunensis* ER., and others);
- (2) Plants that are favoured by the influence of fire and are permanent part of the ecosystem (e.g., *Bromus pumellianus* Sc., *Poa sibirica* Roc., *Trisetum sibiricum* Rub., *Artemisia integrifolia* L., *Geranium vlassovianum* F., *Fragaria orientalis* Los.);
- (3) Plants that are occurring permanently under the influence of recurrent forest surface fires. Such fires do not change the vegetation cover (no tree mortality) but affect the grass cover.

The investigation in the area of mountain taiga and mountain subtaiga shows that the surface fuel load in grass-pine forests of Eg-Selenge is 3.9-7.0 tons/hectare (t/ha) and 2.9-7.5 t/ha in grass-larch forest of Central Khentii. The amount of forest mosses is 5 t/ha in grass-pine forests and cowberry is 6.4 t/ha in cowberry ledum pine (*Pinus sibirica*) forest. The amount of forest litter is 14.1-18.6 t/ha (54.9-70.9%) in the pine forest of mountain taiga, 9.3-14.2 t/ha in the larch forest (42.5-61.3%) and 6.9-13.1 t/ha (54.8-61.4%) in birch forest. Its variation coefficient is 32-56%. The amount of the resource of herbs during the vegetation period is 0.3-2.1 t/ha (1.6-11.0%) in the pine forest, 2.8-4.1 t/ha (2.8-4.1%) in the larch forest. Average variation coefficient is 66%.

Thus, the total resource of fuel of soil cover in forb-pine forest of mountain subtaiga of Eg-Selenge is 22.9+3.2-30.0+4.4 t/ha, total resource of fuel of soil cover in grass-larch forest of Central Khentii is 17.2+3.4-24.8+4.2 t/ha, total resource of surface fuels in grass-birch forest is 12.6+1.8-19.2+1.7 t/ha. As assuming the amount of forest floor and litter by excluding the vegetation part of fuel of soil cover, it becomes 16.7-62.1% (3.9-18.6 t/ha) in pine forest, 16.9-57.3% (2.9-14.2 t/ha) in larch forest and 25.4-68.2% (3.2-13.1 t/ha) in birch forest (Chuluunbaatar 2008).

Dorjsuren (2008) noted that the vegetation cover of larch stands affected by a low-intensity surface fire is basically restored within 2-3 year period and in 5-8 years it almost does

not differ from pre-fire vegetation. On those sites where upper soil layer is burned, seedlings appear in 3-4 years, and their number reaches 3000 to 5000 per ha depending on the seed production of the stand. During surface fire with moderate intensity, trees are comparatively more damaged with bark fire scars up to 3-4 m height and damage of some surface roots. These damages result in tree mortality of up to 20-30% and to an almost complete loss of saplings. Dominated layer of the trees in the stand is restored within 7-15 years after such fire. After this type of fire in the pseudotaiga larch forests patches of regeneration of the next generation of larch is becoming established. In the larch forests of the Northeast Khangai and Eastern Khentii birch encroachment is frequently encountered. The further absence of fire allows gradual formation of uneven-aged stands with a clearly distinguishable post-fire generation of trees.

High-intensity surface fires burn almost all ground vegetation, shrubs and bushes, debris and forest floor destroying stands and penetrating for 5-7 cm into the ground damaging lateral and surface roots of the trees creating favourable conditions for insect colonization and mass outbreaks. After high-intensity fire in the pseudo taiga larch forests during the first year the stage of "black burned spots", characterized by the drying of damaged trees, pioneer species of herbaceous plants are appearing on the burned area (e.g., *Corydalis sibirica*, *Chamaenerion angustifolium*) and also some forest herb grasses and cereals. In the second year the new stage – the *Marshantia polymorpha*-*Corydalis sibirica* grass stage of succession begins. This stage is lasting about 4 years. Sixth year onwards burned area of *Rhytidium rugosum* larch forest already starts developing cereal stage of succession which lasts about 15-20 years. The full mineralization of a ground surface of after fire creates favourable conditions for the growth and development of the seedlings. As a result, on the site burned by high-intensity surface fire there is sufficient seed production and the larch stand restores itself by successful seeding. In 4-5 years several thousands of seedling per hectare are noted. However, the large-scale catastrophic fires result in different pictures as they destroy the tree layer and seed sources at a large scale (Dorjsuren 2008).

Steppe ecosystem covers 65% of the territory of Mongolia. According to recent research the steppe ecosystems in Eastern Mongolia is most affected by grazing and fire (Tuvshintogtokh et al. 2007, 2008). The steppe vegetation after fire is almost completely consumed and results in the temporary formation of open, bare land areas. However, the steppe ecosystems restore sufficiently fast sometimes with some composition changes. The steppe fires are becoming subject to more in-depth research that will provide more information on the role of fires in the dynamics of these ecosystems as well as in the economic impacts of fire on pastoralism as fires obviously affect the food resources of animal husbandry.



Figure 3. Forest in North-Central Mongolia degraded by illegal logging and fire. Photo: Oyunsanaa (2007).



Figure 4. Forest patterns in Northeast Mongolia are also shaped by past logging activities involving large-scale clearcuts and fire. Former pine-dominated stands are replaced by pioneer species such as birches and poplars. Photo: GFMC (2003).



Figure 5. Open pine forests with limited impacts of illegal logging are quite resilient to frequent surface fires. The recurrent surface fires reduce the fuel loads and leave behind a forest in which the risk of high-intensity and high-severity is reduced. Photo: GFMC (2003).



Figure 6. Northern Mongolian “moonscape” – a result of accelerating illegal exploitation and fire. Photo: GFMC (2007).

4. Demonstration Experiment Using Prescribed Fire for Wildfire Hazard Reduction

4.1. The Experimental Site

The main study area is a mountain pine tree forest stand located in Ajnai hills, in Mandal Soum of Selenge Aimag (48°44' N, 106°38' E)

Climate ¹

Mongolia is located in the northern hemisphere, surrounded by high mountains, which isolate the territory from seas and oceans. Thus there is less precipitation with much changes of air temperature. However the territory is separated from oceans still the Arctic, Atlantic and Pacific Ocean air flow comes to the area. They are influenced by the continental climate of Mongolia and stays in clockwise cyclone in warm seasons and in counter-clockwise cyclone in cold seasons of the year. Due to this extreme continental climate repeated natural dryness is observed and it happens in spring and autumns and even in summer sometimes. Therefore fire threatens Mongolia around the year except winter. However with certain weather characteristics such as temperature, moisture and wind speed that mostly influence on fire ignition, spread and stretch fire forecast for risky seasons can be determined.

Geography

Total territory of Mandal Soum, Selenge Aimag, is 4788 km². The Soum center is located 160 km north of Ulaanbaatar, the capital of Mongolia and in 201 km south of Selenge Aimag.

1 Source: JambaaJamts (1983, 1989) and Tsegmid (1969)

The fire experiment study site we selected is in ca. 20 km South East of Zuunkharaa village center and 12 km West of Tunkhel center. This forest area is located in the river basins Kharaa and Orkhon and surrounded by mountains Noyon (1527 m) and Khatan, which are relatively low mountain ranges in the far West of Khentii range.

Hydrography

Bayangol, Mekheert, Ajnai and other small rivers of Nariin Davaa mountains flow around the study site. Kharaa is the biggest river in the area. The length of this river is 291 km and the river catchment area is 15,000 km². Sugnugur, Tunkhel, and Bayan rivers that start from Lower Khentii range flow to Kharaa River, so the width of the river extends through the deep bottom and the valley gets wider. The river water is widely used for cultivation.

Weather

Average annual temperature around these branch mountains of Khentii range of this region is -2.0°C degrees. It is not more than +18°C degrees above 0°C in July and not below than -22°C in January. There are approximately 90 days that are not cold. It means that it is relatively cool in summer and less cold in winter if compare to river valleys. However warmth is not enough for vegetation growth. Precipitation is in average 300 mm annually and relatively thick snow layer stays in winter.

Annual average air temperature is -1 to -3°C in areas of 1000 m above sea level and 0 to 1°C in steppes and river basins. January is the coldest month of the year in all areas, monthly mean air temperature ranges between -20.7 to -5.2°C. The warmest month is July and the mean air temperature ranges between 18.2 to 20.8°C.

However the air temperature reaches below zero in the first ten days in October in valleys between Khentii range mountain chains and it gets above 0°C by the mid of April. Here almost 220 days are cold.

The warm season in this area with more than 10 degrees above zero starts in middle of May and lasts for 110-130 days until the third decade of September.

Precipitation is varying between the different areas of the territory. Temporary heavy rains in summer do not penetrate well deep into soil. The soil take 80% of the rainfall of 6-10 mm. Rainfalls with more than 5 mm occur in mid June, and rainfalls of more than 10 mm start in last June and end in late August of the year. In most years the moisture provision during the warm season in this area is 60-70% of the total annual precipitation. The mean annual precipitation is 309 mm.

Wind conditions

Dominating direction of wind is from west or northwest from rivers, high areas and mountains to valleys and lower areas. The mean wind speed is 1.5 m per second. In spring in April to May the mean wind speed reaches 2.4 to 2.5 m/s.

Wind conditions have to be taken into consideration when organizing forest fire fighting. Wind is influenced by atmospheric conditions, airflows, and by regional specific characteristics. The counter clockwise cyclone is based in southern Mongolia and stable in winter, therefore wind is mostly moderate; while in spring and autumn central latitude wind fronts are coming in and out from north and south, so the weather is not stable and affected by winds. Near-ground wind directions are determined by the local topography. For instance, directions of valley winds of rivers located along northwest to southeast are mostly from northwest or southeast, but directions of valley winds of river located along west to east are from west or east. It shows that physico-geographical settings of the area are very important for wind directions. North Western wind dominates around the year. Wind frequency reaches 40-70% and the average wind speed is approximately 2.2 m/sec. Days with snowstorms are in average 2.4 per year, the maximum is 5.1. There are in average of 10 days with dust storm per year. Mean wind speed in Khentii mountainous area reaches 2.1-3.5 m/sec. Wind speed is stronger from the first 10 days of March till June comes and snow or dust storms occur. The maximum wind speed occurs in March and April and it reaches 17-22 m/sec. Days with dust storms are 15-26 days in average and days with snow storms are 5-8 per year in average. The specific weather conditions during the experiment shown in Table 7.

Soils

Mountainous taiga turf soil occurs in pine tree forest with grass and herb in mountainous taiga belt where the study site has been chosen (Ogorodnikov 1981). Mountainous taiga turf soil occurs in the study site along a belt from the outskirt of the forest and dominates in southwestern and northwestern slopes. This area belongs to Khentii region by the Mongolian soil classification. There is a vertical soil zonation in the region: dark brown and brown soil dominates in the height of up to 1400 m; dark mountain soil in 1400-1600 m, and mountainous forest grey and mountainous turf taiga ashy soil seen in up to 1800-2000 to 2200 m. Mountainous meadow peaty thin soil is distributed on flat tops of mountains, and brown and dark brown soil dominates in southern slopes of mountains that are not covered with trees.

Forest and vegetation

The study site is located in west Khentii Mountains according to the Mongolian forest and vegetation zonation map (Figure 1; ICC 2010).

Forest type:	Pine forest with grass and herb in mountainous taiga belt
Forest composition:	7 <i>Pinus</i> 3 <i>Betula</i>
Tree species:	<i>Pinus sylvestris</i> L., <i>Betula platyphylla</i> Sukacz.
Tree age classification & age:	<i>Pinus sylvestris</i> L., – Age class 5 (100 years) <i>Betula platyphylla</i> Sukacz. – Age class 5 (50 years)
Average height:	Pine – 17 m, Birch – 11 m
Average diameter:	Pine – 24 cm, Birch – 12 cm
Bonitet:	4, Thickness – 0.4
Reserve per hectare:	90m ³ ; Total reserve: 2430 m ³
Young adult:	Height: 2 m; 2000 pcs/ha
Composition:	4 <i>Pinus</i> , 3 <i>Populus</i> , 3 <i>Betula</i>
Species:	<i>Pinus sylvestris</i> L., <i>Populus tremula</i> L., <i>Betula platyphylla</i> Sukacz.
Reserve:	<i>Pinus</i> 1701 m ³ ; <i>Betula</i> 729 m ³

Shrubs like *Spiraea media*, *Rosa acicularis* occur in the area. Grassy vegetation cover is 60-70% and *Carex amgunensis*, *Trisetum sibirica*, *Thalictrum minus*, *Artemisia tanacetifolia*, *Calamagrostis obtusata*, *Geranium sibirica*, *Elymus sibirica*, *Lespedeza dahurica*, *Zerna pumpeliana* quite common. *Rhytidium regosum* occur in groups (5-60%) as well as in patches (20-25%). Fuel loads like thin twigs, cones, needles, leaves, and barks are found on ground surface.

4.2. Objectives of the Demonstration Experiment Using Controlled Fire for Wildfire Hazard Reduction

The main objective of the experiment is to demonstrate that the use of controlled fire in feasible to reduce the hazard of a wildfire, which would damage and further degrade a pine forest. The effect of a controlled fire is to consume the surface fuels (needle and grass layer, twigs, branches). A reduced fuel layer will reduce the potential of a high-intensity wildfire.

4.3. Procedures of the Demonstration Experiment Using Prescribed Fire in Tunkhel Soum

Following the international expertise, and particularly the experience of the Global Fire Monitoring Center (GFMC), the fire was set by the GFMC team to demonstrate the safe and efficient use of a controlled fire. Participants were instructed in the technique of controlled burning.

Table 7. Weather conditions in the afternoons of the prescribed burning experiments on 4-5 June 2008

4 June 2008, Mandal experimental site				
Time (GMT +7)	Temperature (°C)	Relative humidity (%)	Wind (km/h)	Wind direction
16.45	21.1	30.3	4.1	S/N
17.00	23.5	30.2	6.6	S/N
17.15	24.5	29.8	4.2	W/E
17.30	23.7	30.7	3.0	S/N
17.45	22.9	36.0	7.3	S/N
18.00	23.0	31.9	1.1	W/S
18.15	22.0	37.6	2.2	S/N
18.30	22.0	38.0	1.6	S/N
18.45	22.7	32.5	3.5	S/N
19.00	21.0	34.2	0.0	-
19.15	21.3	34.8	1.6	S/N
19.30	21.1	36.2	1.8	S/N
19.45	21.2	34.2	2.0	S/W
20.00	20.3	34.0	2.2	W/E
20.15	21.1	37.5	3.0	S/N
5 June 2008, Mandal experimental site				
17.15	25.1	31.5	8.0	W/E
17.30	25.0	31.3	9.1	E/W
17.45	23.2	35.9	3.8	W/E

18.00	22.0	37.3	9.5	W/E
18.15	20.4	38.4	8.9	W/E
18.30	22.4	37.9	6.3	W/E
18.45	21.6	38.7	16.1	W/E
19.00	20.4	39.8	9.5	N/S
19.15	20.1	39.9	7.1	N/S
19.30	19.8	38.4	3.5	W/E
19.45	18.0	41.2	4.4	W/E
20.00	18.1	39.1	3.8	W/E

Annex I: Photographic documentation and satellite images of the experimental site



Figure 7. View from the stand to open hill sites degraded by illegal logging and fire



Figure 8. View of the stand



Figure 9. View of the stand, dominated by grass-shrub understory



Figure 10. View of the stand, with occasional larger woody fuels



Figure 11. View of the ridge between the experimental stand and the neighbouring stand



Figure 12. View of the ridge between the experimental stand and the neighbouring stand

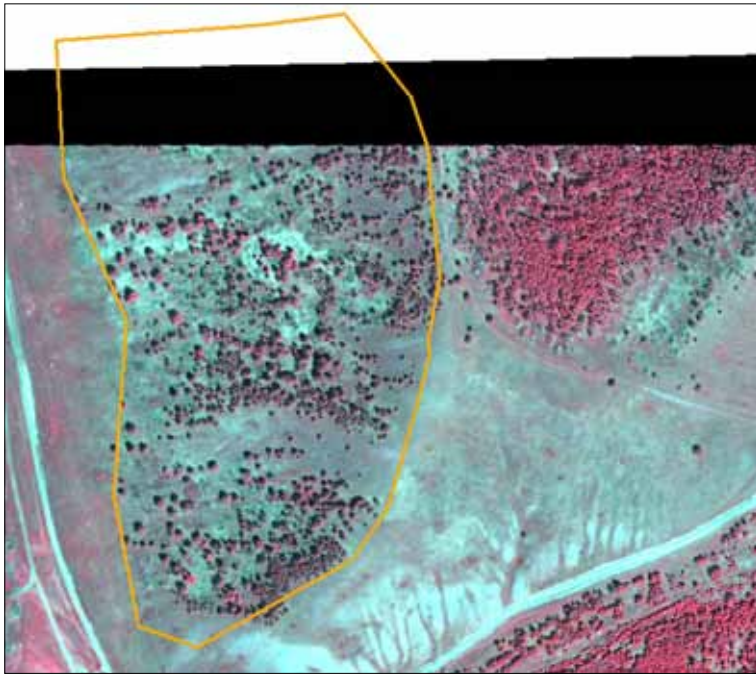


Figure 13. Satellite image (false colours) of the experimental stand. Source: NASA.



Figure 14. Satellite image of the experimental stand. Source: NASA.



Figure 15. Stumps of illegally harvested trees on the experimental site show signs of past fires (fire scars)



Figure 16. Other tree stumps show scars of post-cutting fire



Figure 17. Preparation of “black fire breaks” around the experimental site



Figure 18. Preparation of “black fire breaks” around the experimental site



Figure 19. Fuel load measurement on the transect



Figure 20. Fuel load measurement on 20 x 25 cm² subplots



Figure 21. Instruction of freshly equipped and trained firefighters



Figure 22. Distribution of hand tools to local communities attending the prescribed burn



Figure 23. Starting the prescribed fire by local firefighters



Figure 24. Demonstration of hand tools by local community members



Figure 25. Low-intensity fire burning downhill controlled by the firefighters



Figure 26. Local community members are attending and exercising



Figure 27. Patrolling the fire edge



Figure 28. Demonstration of multiple ignition lines



Figure 29. Merging of downhill and uphill fire lines, creating fire whirls and higher fire intensities



Figure 30. Exercising the use of air blowers for fire suppression



Figure 31. Post-fire view of the experimental site



Figure 32. Post-fire view of the experimental site



Figure 33. Post-fire inventory of fuels burned



Figure 34. Post-fire inventory of fuels burned



Figure 35. The experimental fire team with visitors



Figure 36. View of post-fire development of the experimental site on 31 July 2008

References

- Arno, S.F., Sneck, K.M. (1977) A method for determining fire history in coniferous forests of the mountain west. USDA For. Ser., Intermountain Research Station. Ogden. UT. Gen. Tech. Rep. INT-42.
- Baatarbileg, N., Pederson, N., Jacoby, G., D'Arrigo, R., Dugarjav, C., Mijiddorj, R. (2001) An extended drought and streamflow variability record: Potential forest/steppe implications. Proceedings of Symposium on Climate and Sustainability of Pastoral Land Use Systems in Temperate and Central Asia. Ulaanbaatar. Mongolia, (28 June – 1 July 2001), Interpress Publishing and Printing, Ulaanbaatar.
- Baisan, C.H., Swetnam, T.W. (1990) Fire history on a desert mountain range: Rincon Mountain Wilderness, USA. *Canadian Journal of Forest Research* 20, 1559-1569.
- Bayartaa, N. (2006) Fire environment, fire regimes, and ecological role of fire common to country (or vegetation and fire characteristics of the region in which the country is located). In: Proceedings of I International Northeast Asia Forest Fire Conference and III International Meeting of the Northeast Asia Wildland Fire Network (28-30 September 2006, Khabarovsk, Russia), 105-110. Khabarovsk, Pacific Forest Forum, 202 pp. (on file at GFMC repository).
- Beaty, R.M., Taylor, A.H. (2007) Fire history and the structure and dynamics of a mixed conifer forest landscape in the northern Sierra Nevada, Lake Tahoe Basin, California, USA. *Forest Ecology and Management* 255, 707-719.
- Chuluunbaatar, Ts. (2001) Forest fire danger and its reduction methods. Ulaanbaatar. 128 p.
- Chuluunbaatar, Ts. (2002) Forest fires in northern Mongolian mountains, *Int. For. Fire News* No. 27, 92-97.
- Chuluunbaatar, Ts. (2008) Composition of the forest fuel in Mongolia. Paper presented at the First International Central Asian Wildland Fire Joint Conference and Consultation, Ulaanbaatar, Mongolia. Abstract available at: <http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/ICAWFCC-2008-Programme-Abstracts.pdf>.
- Clark, J.S. (1988) Effect of climate change on fire regimes in northwestern Minnesota. *Nature* 334, 233-235.
- Clark, J.S. (1990) Fire and climate change during the past 750 years in northwestern Minnesota. *Ecological Monographs* 60, 135-159.
- Crisp, N., Dick, J., Mullins, M. (2004) Mongolia forestry sector review. World Bank Report. Victoria. B.C.
- D'Arrigo, R., Jacoby, G., Pederson, N., Frank, D., Buckley, B., Nachin, B., Mijiddorj, R., Dugarjav, C. (2000) Mongolian Tree Rings, Temperature Sensitivity and Reconstructions of Northern Hemisphere Temperature. *The Holocene* 10, 669-672.
- D'Arrigo, R., Jacoby, G., Frank, D., Pederson, N., Buckley, B., Nachin, B., Mijiddorj, R., Dugarjav, C. (2001) 1738 years of Mongolian temperature variability inferred from tree-ring width chronology of Siberian pine. *Geophys. Res. Lett.* 28, 543-546.

- Davi, N.K., Jacoby, G.C., Curtis, A.E., Nachin, B. (2006) Extension of drought records for central Asia using tree rings: west central Mongolia. *Journal of Climate* 19, 288-299.
- De Grandpré, L., Jacques, C.T., Hessel, A., Pederson, N., Conciatori, F., Green, T.R., Byambasuren O., Baatarbileg, N. (2011) Seasonal shift in the climate responses of *Pinus sibirica*, *Pinus sylvestris*, and *Larix sibirica* trees from semi-arid, north-central Mongolia. *Canadian Journal of Forest Research* 41, 1242-1255.
- Dieterich, J.H., Swetnam, T.W. (1984) Dendrochronology of a fire scarred ponderosa pine. *Forest Science* 30, 238-247.
- Dorjsuren, Ch. (2008) Post-fire successions of the larch forests in Mongolia. Paper presented at the First International Central Asian Wildland Fire Joint Conference and Consultation, Ulaanbaatar, Mongolia. Abstract available at: <http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/ICAWFCC-2008-Programme-Abstracts.pdf>
- Dugarjav, Ch., Tsogt, Z. (2008) Forest and fire situation in Mongolia. Paper presented at the First International Central Asian Wildland Fire Joint Conference and Consultation, Ulaanbaatar, Mongolia. Abstract available at: <http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/ICAWFCC-2008-Programme-Abstracts.pdf>
- Engelmark, O. (1987) Fire history correlations to forest type and topography in northern Sweden. *Ann. Bot. Fenn.* 24, 317-324.
- Enkhtur, D., Chuluunbaatar, Ts., Olzvoi, D., Zezenba, D. (2005) Report of the Mongolian Delegation to the Consultation of the Regional Central Asia Wildland Fire Network, Irkutsk, Russian Federation, 5-7 and 8 September 2005. Website of the Regional Central Asia Wildland Fire Network: http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/CentralAsia_2.html
- Farrar, Jr., R.M. (1998) Prescribed burning in selection stands of southern pine: current practice and future promise. In: *Fire in Ecosystem Management: Shifting the Paradigm from Suppression to Prescription* (T.L. Pruden and L.A. Brennan, eds.), 151-160. Tall Timbers Fire Ecology Conference Proceedings 20. Tall Timbers Research Station, Tallahassee, Florida.
- Fowler, P.M., Asleson, D.O. (1984) The location of lightning-caused wildland fires in northern Idaho. *Physical Geography* 5, 240-252.
- Furyaev, V.V., Vaganov, E.A., Tchekbakova, N.M., Valendik, E.N. (2001) Effects of fire and climate on successions and structural changes in the Siberian boreal forests. *Eurasian Journal of Forestry Research* 2, 1-15.
- DeWeese, G.G. (2007) Past fire regimes of Table Mountain pine (*Pinus pungens* Lamb.) Stands in the Central Appalachian Mountains, Virginia, U.S.A. Ph.D. dissertation, The University of Tennessee, Knoxville, 308 p.
- GFMC (Global Fire Monitoring Center) (2008). Proceedings of the First International Central Asian Wildland Fire Joint Conference and Consultation, Ulaanbaatar, Mongolia. 93 p. <http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/ICAWFCC-2008-Programme-Abstracts.pdf>

- Goldammer, J.G., Furyaev, V.V. (1996) Fire in ecosystems of boreal Eurasia. In: *Fire in Ecosystems of boreal Eurasia* (J.G. Goldammer and V.V. Furyaev, eds.), 1-20. Kluwer Academic Publishers. Dordrecht.
- Goldammer, J.G. (2002) Fire situation in Mongolia. *Int. For. Fire News* No. 26, 75-83.
- Goldammer, J.G., Davidenko, E.P., Kondrashov, L.G., Ezhov, N.I. (2004) Recent trends of forest fires in Central Asia and opportunities for regional cooperation in forest fire management. Paper prepared for the Regional Forest Congress "Forest Policy: Problems and Solutions", 25-27 November 2004, Bishkek, Kyrgyzstan. *Int. Forest Fire News* No. 31, 91-101.
- Goldammer, J.G. (2006) *Global Forest Resources Assessment 2005. Thematic report on forest fires in the Central Asian Region and adjacent countries*. FAO Fire Management Working Paper 16, 45 p.
- Grissino-Mayer, H.D. (1995) Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. Ph.D. dissertation, The University of Arizona, Tucson, Arizona.
- Grissino-Mayer, H.D. (2001a) Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research* 57, 205-221.
- Grissino-Mayer, H.D. (2001b) FHX2 – Software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-Ring Research* 57, 115-124.
- Grissino-Mayer, H.D., Romme, W.H., Floyd, M.L., Hanna, D.D. (2004) Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. *Ecology* 85, 1708-1724.
- Heinselman, M.L. (1973) Fire in the virgin forests of the Boundary Waters Canoe Area. Minnesota. *Quaternary Research* 3, 329-382.
- Heinselman, M.L. (1981) Fire and succession in the conifer forests of North America. In: *Forest succession: Concepts and application* (D.C. West, H.H. Shugart, and D.B. Botkin, eds.), 374-406. Springer-Verlag, New York, New York, USA.
- Hessl, A., Ariya, U., Brown, P., Byambasuren, O., Green, T., Gordon, J., Sutherland, E.K., Nachin, B., Maxwell, R.S., Pederson, N., De Grandpré, L., Saladyga, T., Tardif, J.C. (2012) Reconstructing fire history in central Mongolia from tree-rings. *Int. J. Wildland Fire*. 21, 86-92.
- ICC (Information and Computer Center of Mongolia) (2010) *Forest Map of Mongolia*. Ulaanbaatar, Mongolia.
- Jacoby, G.C., D'Arrigo, R.D., Davaajamts, T. (1996) Mongolian tree-rings and 20th-century warming. *Science* 273, 771-773.
- Jacoby, G., Pederson, N., D'Arrigo, R.D. (2003) Temperature and precipitation in Mongolia based on dendroclimatic investigations. *Chinese Science Bulletin* 48 (14), 1474-1479.
- Jambaajamts, B. (1983) *Agricultural Climate Resource of Mongolia*. National Publishing Agency. Ulaanbaatar, 140 pp.
- Jambaajamts, B. (1989) *Climate of Mongolia*. National Publishing Agency. Ulaanbaatar, 268 pp.
- Johnson, E.A., Van Wagner, C.E. (1985) The theory and use of two fire history models. *Canadian Journal of Forest Research* 15, 214-220.

- Johnson, E.A. (1992) Fire and vegetation dynamics. Cambridge University Press, Cambridge, England.
- Johnstone, J.F., Hollingsworth., T.N., Chapin, F.S., Mack, M.C. (2010) Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology* 16, 1281-1295.
- Knight, D.H. (1987) Parasites, lightning, and the vegetation mosaic in wilderness landscapes. *Landscape Heterogeneity and Disturbance* (ed. M.G. Turner), pp. 59-83. Springer-Verlag, New York, NY, USA.
- Lafon, C.W., Hoss, J.A., Grissino-Mayer, H.D. (2005) The contemporary fire regime of the central Appalachian Mountains and its relation to climate. *Physical Geography* 26, 126-146.
- Lewis, D.B. (2003) Fire regimes of Kipuka forests in El Malpais National Monument, New Mexico. M.S. thesis. The University of Tennessee, Knoxville, TN, 145 pp.
- MNE (2006) Mongolian Third National Report on Implementation of Convention on Biological Diversity. Report of Ministry of Nature and Environment, Mongolia, Ulaanbaatar, 206 pp.
- Mühlenberg, M., Slowik, J., Samiya, R., Dulamsuren, Ch., Gantigmaa, Ch., Woyciechowski, M. (2000) The Conservation Value of West-Khentii, North Mongolia: Evaluation of Plant and Butterfly Communities. – *Fragmenta Floristica et Geobotanica*, Ann 45 (1-2), 63-90.
- Natsagdorj, L., Dagvadorj, D., Gomboluudev, P (1998) Climate change in Mongolia and its future trend. – A Scientific Organization of Meteorological Institute, No. 20, Ulaanbaatar, pp.114-133.
- NEMA (2011) Fire statistics database of the National Emergency Agency of Mongolia.
- Ogorodnikov, A.V. (1981) Soil of Mountain Forests of MNR. Novosibirsk., 143 p.
- Oyunsanaa B., Bayartaa, N., Baatarbileg, N. (2006) Impact of fires and climate change on Northern Mongolian Forest. Proceedings of the First International Northeast Asia Forest Fire Conference and the Third International Meeting of the Northeast Asia Wildland Fire Network. Khabarovsk, Russia, pp. 111-117.
- Payette, S., Morneau, C., Sirois, L., Despons, M. (1989) Recent fire history of the northern Québec biomes. *Ecology* 70, 656-673.
- Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., Buckley, B.M., Dugarjav, C., Mijiddorj, R. (2001) Hydrometeorological reconstructions for Northeastern Mongolia derived from Tree Rings: AD 1651-1995. *Journal of Climate* 14, 872-881.
- Romme, W.H., Knight, D.H. (1981) Fire frequency and subalpine forest succession along a topographic gradient in Wyoming. *Ecology* 62, 319-326.
- Seklecki, M.T., Grissino-Mayer, H.D., Swetnam, T.W. (1996) Fire history and the possible role of Apache-set fires in the Chiricahua Mountains of southeastern Arizona. In: Effects of fire on Madrean Province ecosystems (P. F. Folliott, L. F. DeBano, M. B. Maker, Jr., G. J. Gottfried, G. Solis-Garza, C. B. Edminster, D. G. Neary, L. S. Allen, and R. H. Hamre, tech. coord.), 238-246. USDA Forest Service General Technical Report RM-GTR-289, Fort Collins, Colorado, USA.
- Sherbakov, I.P. (1979) Forest fires in Yakutia and their effects on forest ecology. Nauka Publ., Novosibirsk, Russia, 223 p. (in Russian).

- Stephens, S.L., Skinner, C.N., Gill, S.J. (2003) Dendrochronology-based fire history of Jeffrey pine – mixed conifer forests in the Sierra San Pedro Martir, Mexico. *Can. J. For. Res.* 33, 1090-1101. doi:10.1139/x03-031.
- Swetnam, T.W., Baisan, C.H.; Kaib, J.M. (2001) Forest fire histories in the sky islands of La Frontera. In: *Changing plant life of La Frontera: observations on vegetation in the United States/Mexico borderlands* (G.L. Webster and C.J. Bahre, eds.) 95-119. Albuquerque, New Mexico: University of New Mexico Press.
- Takahashi, K. (2006) Future perspective of forest management in a Siberian permafrost area. In: *Symptoms of environmental change in Siberian permafrost region* (R. Hatanoto and G. Guggenberger, eds.), 163-170. Hokkaido University Press, Sapporo, Japan.
- Tchebakova, N.M., Parfenova, E., Soja, A.J. (2009) The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. *Environmental Research Letters* 4, 9 p.
- Tsedendash, G. (1995) Forest vegetation of the Khentii Mountains, Dissertation, Ulaanbaatar [in Mongolian].
- Tsegmid, Sh. (1969) Mongolian Physico-Geography. Institute of Geography and Permafrost Research. MAS. Ulaanbaatar, 240 pp.
- Tsogtbaatar, J. (2002) Forest Policy Development in Mongolia. M.S. Swaminathan Research Foundation, Chennai, India.
- Tsvetkov, P.A. (2004) Pyrophytic properties of the larch *Larix gmelinii* in terms of life strategies. *Russian Journal of Ecology* 35, 224-229.
- Turner, M.G., Romme, W.H. (1994) Landscape dynamics in crown fire ecosystems. *Landscape Ecology* 9, 59-77.
- Tuvshintogtokh, I., Magsar, U. (2007) Fire effects on productivity and community dynamics of Mongolian grassland. *Int. Forest Fire News* No. 36, 67-75.
- Tuvshintogtokh, I., Urgamal, M., Chuluunbaatar, Ts. (2008) Fire effect on eastern Mongolian grassland steppe. Paper presented at the First International Central Asian Wildland Fire Joint Conference and Consultation, Ulaanbaatar, Mongolia. Abstract available at:
<http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/ICAWFCC-2008-Programme-Abstracts.pdf>
- Valendik, E.N., Ivanova, G.A., Chuluunbatar, Ts., Goldammer, J.G. (1998) Fire in forest ecosystems of Mongolia. *International Forest Fire News* No. 19, 58-63.
- Wirth, C., Schulze, E-D., Schulze, W., von Stünzner-Karbe, D., Ziegler, W., Miljukowa, I.M., Sogatchev, A., Varlagin, A.B., Panvyorov, M., Grigorev, S., Kusnetzova, W., Siry, M., Harges, G., Zimmermann, R. Vygodskaya, N.N. (1999) Above-ground biomass and structure of pristine Siberian Scots pine forests as controlled by competition and fire. *Oecologia* 121, 66-80.
- World Bank (2003) Land resources and their management. Mongolia environment monitored. Washington, D.C.
- World Bank (2012) Mongolia - Country partnership strategy for the period FY2013-2017. Washington, D.C.
<http://documents.worldbank.org/curated/en/2012/01/16244913/mongolia-country-partnership-strategy-period-fy2013-2017>

Part IV: White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia

Johann G. Goldammer (ed.)

White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia

Edited and published on behalf of the participants of the Symposium on Fire Management in Cultural and Natural Landscapes, Nature Conservation and Forestry in Temperate-Boreal Eurasia and members of the Eurasian Fire in Nature Conservation Network (EFNCN) ¹

by the Global Fire Monitoring Center / Fire Ecology Research Group, Freiburg, Germany

In the landscapes of temperate-boreal Europe – the western part of the Euro-Siberian region of the Holarctic Floral Kingdom² – the prevailing fire regimes are shaped by human-ignited fires. Direct fire application in land-use systems and human-caused wildfires – ignited accidentally, by negligence or otherwise deliberately set – have influenced cultural and natural landscape since the beginning of land cultivation. Only in Northern Europe and the adjoining Western and Central Asian region natural fires constitute a significant factor, which is influencing the natural composition and dynamics of ecosystems. Thus, the targeted use of fire in ecosystem management in Europe is predominantly in those vegetation types that either have been shaped by human-ignited fires over historic time scales or where the application of prescribed fire reduces the vulnerability to and damages of uncontrolled fires. Fire is also used as a tool to substitute abandoned cultivation practices and for the control of wildfires.

In the following broad classification of fire regimes and burning practices a number of examples of fire use in ecosystem management are provided which reflect a highly diverse range of applications.

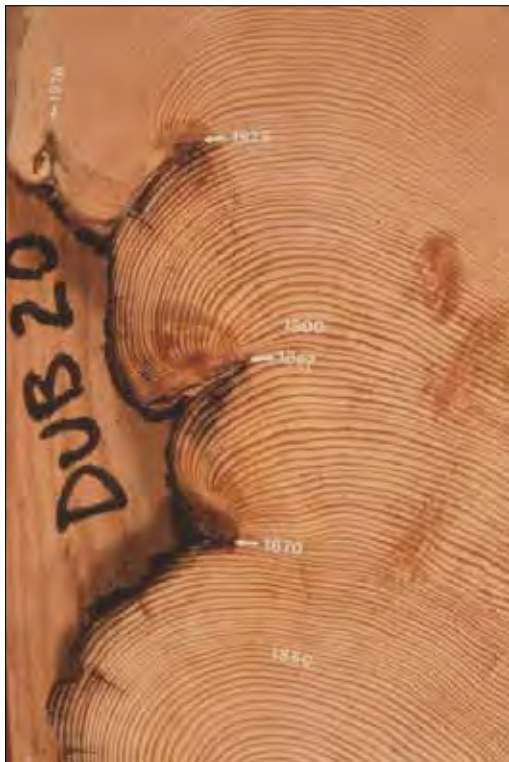
1 Note: A printed version of the White Paper is also available online: <http://www.fire.uni-freiburg.de/programmes/natcon/EFNCN-White-Paper-2010.pdf>

2 This White Paper follows the definition of “landscape” in accordance with the European Landscape Convention (Council of Europe, 2000): “Landscape means an area, as perceived by people, whose character is the result of action and interaction of natural and / or human factors”. The geographic region is the Euro-Siberian region of the Holarctic Floral Kingdom.

1. Natural Fire Regimes

The integration of naturally ignited fires (by lightning) in vegetation management aims at maintaining the natural dynamics of fire-dependent or at least fire-adapted or fire-tolerant ecosystems. In North America, a continent hosting a broad range of fire-adapted ecosystems, the use or “integration” of natural fire under controlled conditions in the overall management of the ecosystems dates back to the 1960s and was referred to as “Let Burn”, “Prescribed Natural Fire”, and more recently “Wildland Fire Use” (van Wagtendonk, 2007). In the greater European / Eurasian space the use or the management of naturally ignited wildland fire to accomplish resource management objectives is not yet developed. In Western Europe (including the Euro-Mediterranean region and the Nordic countries) the functional role of natural fire had limited impact on the evolution of ecosystem properties and thus to their future maintenance – despite the presence of remarkable adaptations to fire, e.g. in some Mediterranean ecosystems (Naveh, 1975). Thus, there is a limited acceptance of allowing a naturally ignited fire to burn – even if the wildfire would burn within the “prescriptions” set by the ecosystem management plan.

However, in the Western and Central Asian region there are large tracts of forest ecosystems that have been shaped by natural fire, e.g. the pine (*Pinus* spp.) and larch (*Larix* spp.) forests that constitute the “light taiga” in Siberia and adjacent regions. In this rather extended biome there is a strong need to introduce the concept of allowing natural fires to burn, mainly in order to maintain open, fire-resilient stand structures and to reduce the risk of stand-replacement fires. Starting with the first East-West international conference “Fire in Ecosystems of Boreal Eurasia” (Goldammer and Furyaev, 1996) and the Fire Research Campaign Asia-North (FIRESCAN) (FIRESCAN Science Team, 1996) a dialogue with the forestry authorities of Russia (and the predecessor administration in the former Soviet Union, the State Forest Committee) has been initiated to replace the fire exclusion policy in the protected zone of Russia by an integrated fire management approach, which would include the use of natural fire and prescribed burning. While this approach has not yet been introduced in practice, there is a progress in the scientific and the policy acceptance of the concept. Given the magnitude and importance of wildfires in Central Eurasia there is need to prioritize the implementation of such a concept in the region, particularly in the Russian Federation.



Dendrochronological analyses provide historic evidence of recurrence of natural surface fires in the “light taiga” of Siberia and thus the influence of fire in shaping the composition and dynamics of pine (*Pinus* spp.) and larch (*Larix* spp.) forest ecosystems. Photos: GFMC.

2. Cultural Fire Regimes

Pollen and charcoal records in Western Europe reveal the advent of slash-and-burn agriculture in the late Neolithic between 4300 and 2300 BC (Rösch et al., 2004). Since then the historic use of fire has been manifested in the development and shaping of a variety of land-use systems in the region (Goldammer et al., 1997a,b; Pyne, 1997). Mechanical treatment, intensive utilization of biomass for domestic purposes, the impact of domestic livestock grazing and the application of fire modified formerly forested lands to open lands and shaped distinct landscape mosaics. These open land ecosystems provided habitat requirements for a flora and fauna that otherwise is not occurring in forest ecosystems. Modern agricultural practices and the reduction of fire use due to legal restrictions or prohibitions in most European countries on the one side, and the rural exodus associated with the abandonment of traditional land management practices, including fire use, on the other side are dramatically altering these ecosystems. The rural depopulation and the rapid increase of fallow is resulting in a loss of open land ecosystems and habitats and is even resulting in an alteration of whole landscape patterns. At the same time the increasing availability of phytomass – a consequence of the decrease of its use – has resulted in an increase of fuel loads at landscape level and thus in increasing wildfire hazard.

There are a number of reasons and approaches in Europe to maintain or to restore the traditional use of fire in some ecosystems or land-use systems.

2.1 Restoration of traditional practices of swidden agriculture

There are a few cases in Europe where a reconstruction or restoration of abandoned slash-and-burn agriculture practices is demonstrated. These attempts have primarily a “museum” character and are serving educational purposes with a touch of landscape pattern restoration. Until the middle of the 20th Century slash-and-burn agriculture with a spatio-temporal land-use pattern similar to the “shifting cultivation” system was widely practiced in Europe and has left landscape features that are still visible today, e.g. the still visible small-sized burning plots with their distinct successional patterns (Goldammer et al., 1997). There are two regions where this kind of fire treatment is practiced for demonstration purpose:



Swidden agriculture in the Black Forest, Germany, around the late 19th Century. Source: Historic copperplate print, archive of GFMC.

Demonstration traditional slash-and-burn practice in Koli National Park, Finland. Photo: Koli National Park.





Prescribed burning of a *Cystisus purgans* heath in the Pyrénées-Orientales (Sournia, February 2008).
Photo: J. Faerber.



Demonstration of traditional fire cultivation practices in the Black Forest, Germany
(Vorderlehengericht, June 2007). Photo: GFMC.

- Koli National Park in Finland is the only national park in the world that has a fire symbol in its logo. In Koli the traditional slash-and-burn practice is demonstrated regularly and reveals the importance of this traditional land use on the composition of Finland's boreal coniferous forest that has been shaped by this cultivation over centuries (Lovén and Äänismaa, 2004).
- Historic slash-and-burn practice in the Black Forest of Germany: There are two sites near Freiburg (Yach, Vorderlehengericht) where the procedure of rotational cutting and use of coppice trees, the burning of residuals, followed by seeding and harvest of wheat, with subsequent fallow and forest regrowth period, are demonstrated (Lutz, 2008).

There is also a scientific interest to reconstruct earlier slash-and-burn practices, e.g. those that evolved in the late Neolithic. The most recent experiment to reconstruct Neolithic fire cultivation was conducted in 1999 in Forchtenberg, Germany (Rösch et al., 2002).

2.2 Maintenance of grazing lands

The use of fire in maintaining openness and species composition on grazing lands is the most common practice that has survived its early application throughout Eurasia. Pastures that are threatened by succession are traditionally burned in a region stretching from the Western Mediterranean via the Balkans to East Europe. Although banned by law in most countries, the burnings are still practiced in many places. Together with burning of agricultural residuals (c.f. section 2.4) pasture burnings are a major cause of wildfires that are also affecting forests and even the wildland-residential interface. The illegality of burning is often resulting in "hit-and-run" practices, i.e. pastoralists setting fires and disappear from the site in order not to be sued. This is often resulting in uncontrolled fires with a high likelihood of developing and spread of devastating wildfires to adjoining terrain. While many countries did not yet attempt to introduce a solution to this problem, Spain has made significant progress by developing a government-supported permit and support system for the use of prescribed fire for grazing improvement and fire social prevention (Velez, 2007). Similarly, prescribed burning for rangeland improvement is practiced by several French prescribed burning teams, including the Department Pyrénées-Orientales (Faerber, 2009). For a European survey on prescribed burning practices, including grazing land management, see Lázaro (2009).

2.3 Nature conservation and biodiversity management

The major focus and activities in the use of prescribed fire in Western Europe is for the conservation and restoration of the biodiversity heritage of former cultivated lands or lands otherwise affected by human-ignited fires (habitat and biodiversity management). The range of application is rather wide, as reflected by the activities conducted in the frame of the Eurasian Network for Fire in Nature Conservation (ENFNC).³ The following examples represent the main target systems for the application of prescribed fire:

- **Heathlands:** The composition and extent of Atlantic and continental heathlands (mainly dominated by *Calluna vulgaris*) has been shaped by grazing, cutting of heath, sod and turf layers and by burning throughout centuries. Burning is conducted in the United Kingdom (Davies et al., 2008; Scotland Government, 2008), to a lesser extent in Southern European countries such as Portugal and Italy (Ascoli et al., 2009), and predominantly in Central and Northern Europe, e.g. in Denmark (Jensen, 2004), the Netherlands (Vogels, 2009; Bobbink et al., 2009), Norway (Kvamme and Kaland, 2009) and Germany (e.g., Brunn, 2009; Mause, 2009; Gollammer et al., 2009). Endangered target species for habitat conservation burning include e.g. the Black Grouse (*Tetrao tetrix*) or game species such as Red Grouse (*Lagopus scoticus*).
- **Wetlands:** Maintenance of peat bogs, open fen mires, e.g. in Poland and Belarus, is practiced to maintain the habitat requirements of endangered plant and animal species, e.g. birds such as the Aquatic Warbler (*Acrocephalus paludicola*) or the Spotted Eagle (*Aquila clanga*) (Tanneberger et al., 2009). Moorlands in Germany that are threatened by succession are treated with prescribed fire in addition to other means such as waterlogging, tree cutting, mowing and mulching (Niemeyer, 2004).
- **Grasslands:** Similarly to the wetlands, xerothermic grasslands or *Molinia* meadows are hosting birdlife or plant species threatened by extinction, e.g. orchids, steppe grasslands plants or calcareous grasslands plants. Prescribed burning the Münsingen range in Southern Germany, a former military exercise and shooting range in which fires caused by the military had created and maintained openness for a century, is used for preserving the open habitats for endangered birds such as the Northern Wheatear (*Oenanthe oenanthe*) and the Woodlark (*Lullula arborea*).
- **Forests:** The use of prescribed fire in the restoration and maintenance of habitats of species dwelling in forests is pioneered by management in Finland and Sweden. Traditionally fire has been used in the boreal forests of the Nordic countries in order to improve growth and productivity of tree stands by removing the temperature-

3 <http://www.fire.uni-freiburg.de/programmes/natcon/natcon.htm>. See also the special issue of UNECE/FAO International Forest Fire News at http://www.fire.uni-freiburg.de/iffn/iffn_30/content30.htm

isolating raw humus layers or to facilitate natural forest regeneration (Viro, 1974; Mälikönen and Levula, 1996). Since the 1990s there are first experiments and currently extended application underway to use fire for creating forest stands under the pre-industrial conditions, i.e. more open stand structures, and to create habitats of endangered insect species (e.g. *Stephanopachys linearis* and *S. substriatus*; *Aradus* spp.) and wood-decaying fungi as well as habitats for vascular plants (Rydqvist, 2009).



Danish postcard showing a fire set in Randbøl Hede – today Randbøl Hede Nature Reserve – in the early 20th Century. Source: GFMC archive.



Modern farmers learning the ancient farming technique of heathland burning in Norway in 2005. Source: Kvamme and Kaland (2009), photo by Aslaug Aalen.



Structurally rich heath-juniper ecosystems with individual pine and birch trees in Lunenburg Heath Nature Park shaped by fire, grazing and mechanical treatment. Photos: R. Köpsell and J. Prüter.





Control of birch and pine succession (left) in Zschor-noer Heide Nature Reserve (Brandenburg State, Germany) is controlled by prescribed fire (middle and right: prescribed burning in 2002). Photos: GFMC.





Post-fire views of prescribed burns in Zschornoer Heide Nature Reserve immediately after the burn (left) and two years after the fire. Photos: GFMC / E. Brunn.



3. Substitutional Fire Use

The use of fire as a tool to substitute or replace another form of vegetation treatment is referred to as substitutional fire use. In Central Europe there are abundant open vegetation types that were shaped by agriculture, grazing or other land use (e.g., extraction of biomass for harvesting domestic fuels, stable litter, thatching material, etc.). Some of these open land habitats have a high biodiversity or landscape conservation value. In the late 20th Century many sites threatened by succession have been maintained by mechanical (mowing, mulching, etc.) or prescribed grazing measures that were financed by public subsidies. However, increasing costs and financial constraints of public budgets on the one side, and a rapid increase of fallow on the other side during the last three decades, have prompted scientists and conservationists to replace costly mechanical and grazing measures by prescribed fire.

3.1 Fallow management on small-scale and extreme habitats

The problem of increasing fallow is not only restricted to former grazing lands. The abandonment of traditional land use is also affecting sites that have been utilized for hay production by mowing. In regions where the open grasslands have a high value for landscape aesthetics and tourism, major public subsidies have been used in the past to keep these lands open by mechanical means. However, besides the limitations due to increasing costs there are also limitations to use machinery on small-sized private property plots, on open lands on steep slopes or on sites intermixed with trees, e.g., high-conservation value xerothermic grasslands with interspersed trees. Long-term investigations in using fire to maintain openness on small-scale fallow plots in Southwest Germany were initiated and monitored since the mid-1970s (Schreiber, 2004).

Another example of using fire as a substitutional tool is practiced in the viticulture region of Southwest Germany. Traditionally the xerothermic slopes between vineyard terraces in Southwest Germany (Kaiserstuhl) were mowed by the landowners and the hay used to feed cattle. The mowing of the grass strata on the slopes was very labor intensive and could not be mechanized. Thus, with the socio-economic changes in the viticulture sector beginning in the 1950s the winegrowers abandoned the treatment of slope vegetation, which very rap-

idly responded by bush encroachment and succession towards tree stands – a development detrimental to the microclimate for wine growing and also not well perceived for landscape-aesthetic reasons by the local populations. Excessive use of fire to maintain openness during the 1960s did not observe the rules necessary to protect vulnerable flora and fauna, especially when burning was conducted large scale and at progressed development stages in springtime. A complete fire ban imposed by law in the 1970s resulted in progressing succession as a consequence of neglected maintenance of the xerothermic sites. Since the late 1990s a scientific research project elaborated a framework of a prescribed fire regime (Page and Goldammer, 2004) which is now replacing mechanical treatment and is practiced by ecologically sound small-sized burnings during the winter period in two counties of Southwest Germany (Rietze, 2008; Goldammer et al., 2009).



Prescribed fire is used to maintain openness of fallow slopes in the Kaiserstuhl viticulture region. Fire is now replacing traditional mowing (Southwest Germany). Photo: GFMC.

The targeted application of small-sized fires for creating mosaic- or edge-rich habitat structures is common in the management endangered bird species, e.g. Black Grouse (*Tetrao tetrix*) (cf. 2.2.3), capercaillie (*Tetrao urogallus*) and Hazel Grouse (*Tetrastes bonasia*). While

capercaillie habitat management by fire has been proven successful in Scottish pine-heath forests (Bruce and Servant, 2004), similar approaches elsewhere in Europe were less successful. For instance, capercaillie populations increased in some sites of the Black Forest (Germany) that were disturbed by hurricane “Lothar” in 1999. Wind throws and wind falls, partially salvage-logged but with snags remaining, resulted in the formation of edge-rich habitat structures preferred by capercaillie. The populations began to disappear with the onset of regeneration of spruce (*Picea abies*) and the development of succession towards dense forest. Small-scale, mosaic-rich prescribed burning application was intended to

- control abundant regeneration of spruce (*Picea abies*) to maintain general openness
- create vegetation-free areas (mineral soil exposed) for food search / scratching
- maintain refuge areas (small groups of young stands and thickets)
- foster berry/shrub cover, particularly black berry (*Vaccinium myrtillus*), as a key source of nutrition
- foster softwoods
- foster structural diversity through a detention of the development of closed high forests in parts of the stands
- maintain tree stumps and snags as sitting places
- maintain appropriate trees as sleeping and singing places

However, in the long run these burnings could not be implemented on a regular basis because of the prevailing moist conditions on altitudes of around 1000 m a.s.l. of the Black Forest.

3.2 Landscape management

The Middle Rhine Valley (Germany) represents a typical example of the widespread conflict between a high nature conservation value of the cultural landscape on the one hand and the abandonment of traditional land use on the other hand. The Valley constitutes one of the largest coherent xerothermic areas of Germany with habitats and vegetation types that are classified as endangered at European level. The necessity for the development of management concepts to protect this landscape was emphasized by the inscription of the Upper Middle Rhine Valley in the UNESCO World Heritage List as a protected cultural landscape in 2002 (Bonn, 2004). In order to prevent further loss of the characteristic open habitats as a consequence of dramatic reduction of vine cultivation and other land use, a research and development project investigated the more or less uncontrolled (“semi-wild”), extensive grazing by horses and goats on the steep slopes, clearing the shrub-dominated shallow slopes with tank-tracks, and prescribed burning (Bonn et al., 2009). Prescribed burning was applied successfully during the experimental phase of the project, especially in the grass stage and earlier succession dominated by *Rubus* spp., but turned out to be limited as a tool for

restoring overgrown xerothermic habitats on sites in progressed development stages dominated by *Prunus mahaleb* and *Cornus sanguinea* (Driessen et al., 2006).



The Middle Rhine cultural landscape with small-scale viticulture terraces is rapidly changing under fallow and succession. Combined grazing, mechanical and fire treatments are possible solutions for maintaining the aesthetic impressions of this unique cultural asset. Photos: S. Bonn and S. Bonn / GFMC Archive.



There are areas where the objectives of both nature conservation and landscape management are matching and prescribed fire is used for biodiversity management and maintenance of landscape aesthetics, mainly for recreational purpose. Nature conservation sites and nature parks (national parks) hosting *Calluna* heathlands are the most prominent examples of this dual use of fire, especially in Central Europe where these protected areas are important spots for national and regional tourism. The aesthetic impression of the old cultural landscape dominated by the colorful flowering of heath is a high attraction for visitors. A prominent example of such an area is the Lunenburg heath (Germany) with the Lunenburg Heath

Nature Park (area: 1,130 square kilometres) and at its center the Lunenburg Heath Nature Reserve. As mentioned above, the composition and extent of Atlantic and continental heathlands (mainly dominated by *Calluna vulgaris*) historically has been shaped by grazing, cutting of heath, sod and turf layers and by burning throughout centuries. The use of fire for regeneration of over-aged heath, however, played a role as one of many disturbance agents and has now been restored successfully in Lunenburg heath (Keienburg and Prüter, 2006).

4. Waste Disposal

The use of fire in biomass waste disposal merits to be regarded at separately. While all burning objectives mentioned previously are targeting for a removal or suppression of unwanted, competitive dead or live vegetation elements – either by combustion or by the impact of heat – the removal of unused dead biomass by burning in agriculture (e.g., stubble burning after harvest) and forestry (slash / harvest residual burning after timber harvest, notably on clearcuts) aims at facilitating the growing of the next crops or the regeneration or reforestation of forest stands.

Burning of stubble fields and other agricultural crop residuals in Europe has a long tradition, similar to other regions and continents, but is now largely banned by law since these burnings are a major source of wildfires and air pollution. In Eastern Europe and Central Asia, however, agricultural burning – despite its legal ban – is very widespread and constitutes one of the major areas worldwide that are burned annually (Korontzi et al., 2006).

Burning of forest slash – the unused materials left on site after timber harvest – is still practiced in Europe, although to a decreasing extent. In the Nordic countries the main aim is site preparation for regeneration, i.e. to improve accessibility of the site for planting, including the use of machinery. Two techniques are practiced: burning on piles and broadcast burning over a larger area, usually on clearcuts with or without seed trees (particularly in the Nordic countries). At the same time slash burning is also serving to improve site conditions by reducing the raw humus layers and, as a silvicultural tool, to facilitate the germination of natural regeneration. In Russia the use of broadcast slash burning is now practiced to decrease fire hazard on logged sites and promote natural regeneration (Valendik et al., 2000, 2001). Also prescribed burning was used to restore forests killed at large scale by insects (Valendik et al., 2006). In the Mediterranean countries, burning on piles is used for eliminating tree branches and other residues after tree clearing and thinning on fuel breaks.

The recent move towards more intensive use of renewable energy is calling for the use of forest slash for bioenergy production. At medium- to long-term perspective this may result in a reduction of open forest residual burning.

5. Wildfire Hazard Reduction Burning

In Europe the concept of using prescribed fire as a management tool to reduce the combustible materials on the surface inside of forest stands, and thus the energy potential and the risk of high-intensity and -severity wildfires, has a relatively short history. It was only after the pioneering work of U.S. scientists in the 1970s and the official recognition of the use of “fire by prescription” by the U.S. Forest Service in 1976 when Europeans formulated the first ideas to consider prescribed burning as a tool for wildfire hazard reduction and presented the first research. The Fire Ecology Symposia held at Freiburg University in 1977 and 1983 (Forstzoologisches Institut, 1978; Goldammer 1978, 1983) and a dedicated workshop in Avignon in 1988 (INRA, 1988) brought together a community that intended to investigate prescribed fire as a forest and fire management tool. First practical applications and increasingly sophisticated approaches in fundamental prescribed fire research were conducted in Southern and Central Europe starting in the late 1970s (e.g., Goldammer, 1979; Delabrazé and Valette, 1983; Rego et al., 1983; Trabaud, 1983; Vega et al., 1983). The use of fire to reduce wildfire hazard in open lands, including brush lands, namely for the creation and maintenance of fuelbreaks, then entered practice in the Southern European countries Spain, France and Portugal (Valette et al., 1993). In the Mediterranean part of France, prescribed burning for hazard reduction has continuously been developed and consolidated along years (Rigolot, 2000; Lambert, 2008). Prescribed burning for fuel reduction inside forests was practiced first in Portugal in the 1980s (Rego et al., 1983; Fernandes and Botelho, 2004). Subsequently, in this country, its application became dormant until its recent revival in the frame of the EU Fire Paradox project.

None of the forest ecosystems in Southern and Central Europe, including the natural pine forests, are natural fire ecosystems. Thus, the introduction of prescribed fire for wildfire hazard reduction can be considered as an innovative tool, applicable only in forests with target species resilient or tolerant to low-severity surface fires, such as *Pinus* spp. or *Quercus* spp.. In some cases prescribed fire can be regarded as a substitution tool for replacing historic fuel reduction methods, e.g. the intensive use of biomass for domestic use, or silvopastoral forest use.

In the overall context of landscape ecology the use of prescribed fire on open (non-forest) lands may serve several objectives. On the one hand well-maintained open landscape fragments – either a heritage of the cultural history or strategically planned to reduce “fuel bridges” between fire-vulnerable forests or other ecosystem – allow better access, ease the control of wildfires and enhance safety for firefighting operations. On the other hand the open lands may serve as pasture or for conservation purposes.



Use of prescribed broadcast burning in a coniferous forest clearcut in Siberia (“dark taiga” – with main species *Abies sibirica*, *Picea obovata*, *Pinus sibirica*, *Betula pendula*, *Populus tremula*) east of Yenisei river (Yenisei Ridge), Bolshaya Murta leskhoz, in June 1997, for slash removal and stimulation of forest regeneration. Photo: Y. Kisilyakhov.



The main objective of prescribed fire application in the Stormyrän-Lommyrån nature reserve (Sweden) is to restore open stand structures and provide habitats for fire-dependent and fire-adapted species, e.g. the insect species *Stephanopachys linearis* and *S. substriatus*, *Aradus* spp.. Photo: T. Rydkvist.



Prescribed burning inside of standing coniferous forests for wildfire hazard reduction is not yet practiced systematically in the region, although demonstrated occasionally such as here in a pine stand (*Pinus sylvestris*) in Southwest Germany in 2008. Its future application in the Western part of the Euro-Siberian region is probably less likely, whereas its application is strongly recommended in natural coniferous forests of the Central Asian region. Photos: GFMC.



Joint training of professionals and local villagers in the use of prescribed fire for wildfire hazard reduction in native mountain pine forests (*Pinus sylvestris*) in northern Mongolia. The hand-over of prescribed fire by scientists to the practitioners is a high priority issue aimed at reducing destructive wildfires. Photos: GFMC.

6. Limitations for Prescribed Burning: Contaminated Terrains

In some Eurasian countries high-value nature conservation sites are located on former military training areas or shooting ranges. In Germany many of these areas have been used by the military since more than 100 years, others were newly created and especially used during the Cold War. The total extent of sites in Germany contaminated by Unexploded Ordnance (UXO) is close to ca. 700,000 ha on active and former military training and combat theater sites, i.e. 2% of Germany's land cover. Many of these military exercise areas were located on the territory of the former German Democratic Republic, used by the Soviet Army and the Warsaw Pact allies. The disturbances caused by military activities (e.g., mechanical impacts of direct shooting, fires started by shooting, mechanical impacts by tanks and other vehicles) have resulted in the creation and maintenance of valuable open ecosystems. With the closing of the exercise areas many vegetation types, notably the *Calluna vulgaris* heathlands, are becoming subjected to succession and development towards forests – a trend that is rather undesirable from the point of view of landscape and biodiversity conservation.

On these former military sites there are some obstacles for using prescribed fire as they are densely contaminated with UXO, which may explode during prescribed burning operations and also during wildfires. A new approach in the use of prescribed fire to maintain openness of UXO-contaminated terrain has been launched in 2009 in Brandenburg State in the nature conservation site „Heidehof-Golmberg“ in Teltow-Flaeming County, South of Berlin. This site is classified according to the “Fauna-Flora-Habitat Directive” (FFH) of the European Commission and belong to an overall area of ca. 70,000 ha of FFH lands in Brandenburg State that are endangered by succession and loss of open habitats. The new approach is going to use armored vehicles (former combat tanks converted to fire extinguishing vehicles) to secure personnel during ignition, control of the prescribed fire and mop-up). In future it is envisaged to use aerial incendiary ignition systems to start the prescribed fires from safe distance and over large areas simultaneously, and use Unmanned Aerial Vehicles (UAV) to monitor progress and safety (Goldammer, 2009; Goldammer et al., 2009). This first project of its kind reveals that prescribed burning operations under such circumstances are rather complex and costly.

Similarly there are problems on lands contaminated with UXO and land mines inherited from recent conflicts, e.g. the extended areas covered by land mines on the Balkans, notably in Croatia, Bosnia and Herzegovina and Serbia, totaling ca. 300,000 ha. Not all of these

territories may be candidates for prescribed burning. In the context of wildfire prevention and control, however, the connected ness between contamination by explosives, must be kept in mind.



The use of prescribed fire in the maintenance of open habitats on former military exercise areas or shooting ranges requires special safety precautions as unexploded ordnance may detonate during the burning. Photo: GFMC.

This refers also particularly to the terrains contaminated by radioactivity, notably in the impact zone of the fallout from the Chernobyl nuclear power plant failure in 1986. Territories most affected and contaminated by long-resident radionuclides of ^{238}Pu , $^{239+240}\text{Pu}$, ^{137}Cs and ^{90}Sr are posing a potential threat to human health and security if lifted, redistributed and newly deposited after lifted by an extremely intense wildfire and dispersed by smoke. In the most affected territories of Ukraine, Belarus and Russia the application of low-intensity prescribed fire for wildfire reduction and biodiversity conservation may be feasible but is not yet acceptable under the current psycho-social settings (Goldammer and Zibtsev, 2009).

7. Conclusions and Recommendations

In evaluating the presentations discussed during the symposium⁴ the participants concluded that recent research and the revival of prescribed burning practices in some regions of Europe have revealed the role and importance of fire in the maintenance and restoration of biodiversity in the cultural and natural landscapes of Europe.

The current trend of rural exodus and abandonment of land cultivation in some regions of Europe and the loss of traditional land use is leading to an alarmingly increasing rate of loss of open land habitats with its inherent biodiversity.

The maintenance and in many cases also the restoration of open land habitats by grazing, mechanical treatment and fire use is imperative if threatened biodiversity and landscape features are to be preserved.

Prescribed fire may be used in those ecosystems which historically were shaped by cultural fire, or in which prescribed fire may substitute other historic land-use techniques.

A sound understanding of the “pros and cons” of prescribed fire application is necessary as well as the consideration of side effects of fire use. Large areas threatened by land abandonment are embedded in industrialized regions in which society is becoming increasingly unreceptive to smoke emissions. Legal restrictions for open burning must be understood in the context of clean-air rules and overall goal of reducing gaseous and particle emissions that are threatening human health. This perception is reinforced by hysteria of some who consider prescribed fire emissions to increase the anthropogenic “greenhouse effect” and thus global warming.

On the other side it is noted that nature conservation agencies, non-government actors and the general public meanwhile turn out to have a rather sound understanding of the natural role of fire in various ecosystems. Thus the general perception of the “nature of fire” nowadays is better as compared to the situation two to three decades ago.

Based on the facts and recent trends presented in the Symposium on “Fire Management in Cultural and Natural Landscapes, Nature Conservation and Forestry in Temperate-Boreal Eurasia” the following recommendations are given:

Prescribed Fire Research

The symposium revealed that there is a need in:

⁴ See symposium report available at: <http://www.fire.uni-freiburg.de/programmes/natcon/EFNCN-meetings-1-2008.html>

- Continued support for prescribed burning research
- Clear analysis of the pro's and con's of prescribed burning in a European context, e.g., via meta analysis and expert knowledge regarding, environmental, economic and societal issues
- Studies of additional, not yet identified areas / ecosystems that require prescribed fire treatment
- Identification of possible vulnerabilities of systems subjected to prescribed fire
- Setting up a European group of scientists, managers and policy makers who are involved in management of temperate grazing systems and have adopted (or not yet) fire as an additional management tool. Besides the Eurasian Fire in Nature Conservation Network supporting groups/ organizations could include the European Heathland Network, the Husbandry Animal Group, the European Grassland Group, Aquatic Warbler Conservation Team, the UK Heather Trust and Moorland Forum
- Special emphasis on the use of fire in open fen mire habitats, e.g. in Eastern Germany, Belarus, and Poland

Prescribed Fire Management and Capacity Building

Since prescribed fire in ecosystem management is not yet largely applied, despite its recent revival, tools and systems must be developed to develop and support fire management capability. Action is needed to:

- Adjust the Canadian Fire Behavior Prediction System to European conditions with fuel types from every country
- Develop expert systems to assist burners to understand whether they should burn and to guide them to burn safely
- Enhance closer cooperation on the issue of prescribed burning for nature conservancy and landscape management between Temperate-Boreal Eurasia and the Mediterranean Region
- Develop prescribed specific regional fire guidelines which consider the biophysical and social settings, for the use of agencies, land owners and other stakeholders involved
- Limit bureaucracy and develop easier rules for permitting the application of traditional burning as well as advanced prescribed burning practices
- Develop specific prescribed burning training systems
- Develop a scheme for the certification of Burn Boss and Ignition Specialist on a European level and with national modifications
- Assist in capacity building of fire specialists in countries in transition
- Establishment of regional Training / Education Centers for Fire Management for the Balkans and for East European and adjoining Central Asian / Far East countries

Modified Fire Policies

The legislative framework in most European and neighboring Eurasian countries does not provide regulations for the use of prescribed fire. In contrary, in general the use of fire is banned by law – although law enforcement in some countries is nil. Besides national legal instruments a regional European framework directive would be needed to create an enabling environment for the sound use of prescribed fire in nature conservation, landscape management and forestry. Thus it is needed to:

- Emphasize at national level on the importance of prescribed burning and the consequences of not burning
- Using model projects (examples of “good practices”) to demonstrate to local to national authorities in the need of the application of prescribed fire in combination with other complementing means of vegetations treatment
- Create an appendix with list of reference books / publications explaining core methods and showing the examples of “good practices” (aimed at informing influencing decision / policy makers)
- Cooperate with the EU *Fire Paradox* project⁵ and its follow-up arrangement to support the development of a European Fire Framework Directive, which would create an enabling policy supporting the use of fire⁶

Public Relations and Education

Most important is to inform society on the dual role of fire on ecosystems, to allow the general public to understand the use of prescribed fire in some land-use system vs. the need to prevent and combat fires in others. Collectively we need to:

- Show the policy makers that there is a strong alliance and cooperation in promoting the use of fire at European level
- Show the public and policy makers that the severity and impacts of wildfires are increasing as a consequence of land-use change (increase of wildfire hazard resulting from rural exodus, land abandonment and fallow)
- Prove that prescribed burning is cost-efficient to restore and regenerate important and threatened habitats
- Prove that prescribed burning will contribute to stabilizing some forest ecosystems by making them less vulnerable to destructive wildfires, thus reduce the threat of land degradation and a decrease of net carbon emission to the atmosphere

5 <http://www.fireparadox.org/>

6 see Agudo and Montiel (2009)

General Remarks on Fire and livelihood of some Rural Populations

There are also some very pragmatic aspects for fire use that are crucial for livelihoods of people all over Eurasia. For instance, in the coastal heathlands of Norway it is important to maintain the traditional vegetation mosaic between heath-dominated and grass-dominated vegetation. The grassland represents the main fodder for the animals during the summer season, while evergreen heath species provide the main fodder during the winter. Heath burning is an important tool to maintain the mosaic, which does not only shape the highest possible biological diversity within the heath ecosystem but also the highest fodder value over the year. Similarly, many shepherds and their families throughout Southern and South-eastern Europe and the Balkans are dependent for their livelihood on the productivity of grazing lands regularly maintained by fire.

The International Context

In 2007 the 4th International Wildland Fire Conference was held in Sevilla, Spain. Participants from 88 countries, representing government organizations and civil society from all regions of the world, the United Nations and other international organizations, recommended in particular⁷:

- Regional strategies for fire management be developed and designed to the specific needs of regions;
- An international framework for fire management standards be developed and regional wildland fire training be supported, especially to meet the needs for capacity building in developing countries;

This White Paper – a call of the Eurasian Fire in Nature Conservation Network (EFNCN) through the conclusions of the Freiburg Symposium on “Fire Management in Cultural and Natural Landscapes, Nature Conservation and Forestry in Temperate-Boreal Eurasia” – is in line with these recommendations and also the outcomes of the “Fire Paradox” project (Sande Silva et al., 2010).

7 <http://www.fire.uni-freiburg.de/sevilla-2007/Conference-Statement-en.pdf>

8. References

- Agudo, J., and C. Montiel. 2009. Basis to start the process for a proposal of a new legislation at EU level. Deliverable D7.1-1-3 of the Integrated Project "Fire Paradox", Project No. FP6-08505. European Commission, 66 p.
- Ascoli, D., R. Beghin, R. Ceccato, A. Gorlier, G. Lombardi, M. Lonati, R. Marzano, G. Bovio, and A. Cavallero. 2009. Developing an Adaptive Management approach to prescribed burning: a long-term heathland conservation experiment in north-west Italy. *International Journal of Wildland Fire* 18, 727-735.
- Bobbink, R., M. Weijters, M. Nijssen, J. Vogels, R. Haveman, and L. Kuiters. 2009. Branden als EGM-maatregel. Ede: Directie Kennis, Ministerie LNV (Rapport / DK 2009/dk117-O).
- Bonn, S. 2004. Research and development project "Sustainable development of xerothermic slopes of the Middle Rhine Valley, Germany". *Int. Forest Fire News* No. 30, 59-62.
- Bonn, S., J. Albrech, K. Bylebyl, N. Driessen, P. Poschlod, U. Sander, and M. Veith. 2009. Offenlandmanagement mit Panzerketten. *Naturschutz und Biologische Vielfalt* 73, 189-205.
- Bruce, M., and G. Servant. 2004. Prescribed Fire in a Scottish Pinewood: A Summary of Recent Research at Glen Tanar Estate, Aberdeenshire. *Int. Forest Fire News* No. 30, 84-93.
- Brunn, E. 2009. Feuermanagement auf Truppenübungsplätzen in Brandenburg. *Naturschutz und Biologische Vielfalt* 73, 165-178.
- Davies, M.G., A. Gray, A. Hamilton, and C.J. Legg. 2008. The future of fire management in the British uplands. *International Journal of Biodiversity Science and Management* 4 (3), 127-147.
- Delabraze, P., and J.Ch. Valette. 1983. The fire, a tool for clearing the French Mediterranean forest associations. In: DFG-Symposium Feuerökologie. Symposionsbeiträge (J.G. Goldammer, ed.), 27-38. *Freiburger Waldschutz-Abh.* 4, Institute of Forest Zoology, Freiburg University, 301 p.
- Driessen, N., J. Albrech, S. Bonn, K. Bylebyl, P. Poschlod, U. Sander, P. Sound, and M. Veith. 2006. Nachhaltige Entwicklung xerothermer Hanglagen am Beispiel des Mittelrheintals (Sustainable development of xerothermic hillsides in the Middle Rhine valley). *Natur und Landschaft* 81, 130-137.
- Faerber, J. 2009. Prescribed range burning in the Pyrenees: From a traditional practice to a modern management tool. *Int. Forest Fire News* No. 38, 12-22.

- FAO-GFMC. 1999. Wildland Fire Management Terminology. Update of the FAO Wildland Fire Management Terminology of 1986 (Food and Agriculture Organization of the United Nations, FAO Forestry Paper 70, 257 p.), published online at GFMC: <http://www.fire.uni-freiburg.de/literature/glossary.htm>
- Fernandes, P., and H. Botelho. 2004. Analysis of the prescribed burning practice in the pine forest of northwestern Portugal. *Journal of Environmental Management* 70, 15-26.
- FIRESCAN Science Team. 1996. Fire in ecosystems of boreal Eurasia: The Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESCAN). In: Biomass burning and global change. Vol.II (J.S.Levine, ed.), 848-873. The MIT Press, Cambridge, MA.
- Forstzoologisches Institut. 1978. VW-Symposium Feuerökologie. Symposionsbeiträge. Freiburger Waldschutz-Abh. 1 (1), 1-159. Institute for Forest Zoology, Freiburg University, Freiburg, Germany.
- GFMC Team. 2009. The LIFE Rohrhardsberg project: The use of Prescribed Fire in Maintaining Endangered Habitats and Landscape Feature in the Foothills of the Black Forest. *Int. Forest Fire News* No. 38, 84-87.
- Goldammer, J.G. 1978. Feuerökologie und Feuer-Management. Freiburger Waldschutz Abh. 1 (2), 1-50. Institute for Forest Zoology, Freiburg University, Freiburg, Germany.
- Goldammer, J.G. 1979. Der Einsatz von kontrolliertem Feuer im Forstschutz. *Allg. Forst- u. J. Ztg.* 150, 41-44.
- Goldammer, J.G. (ed.). 1983. DFG-Symposium Feuerökologie. Symposionsbeiträge. Freiburger Waldschutz-Abh. 4, 301 p.
- Goldammer, J.G. 2009. The use of Prescribed Fire on Nature Conservation Areas in Germany contaminated by Unexploded Ordnance (UXO). In: Advanced Seminar "Wildfires and Human Security: Fire Management on Terrain Contaminated by Radioactivity, Unexploded Ordnance (UXO) and Land Mines", Kyiv / Chornobyl, Ukraine, 6-8 October 2009, Abstract Volume (J.G. Goldammer, ed.), 21-22. – <http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/GFMC-CoE-OSCE-Seminar-Ukraine-Brochure-Final-06-Oct-2009.pdf>
- Goldammer, J.G., and V.V. Furyaev (eds.). 1996. Fire in ecosystems of boreal Eurasia. Kluwer Academic Publ., Dordrecht, 528 pp.
- Goldammer, J.G., S. Montag, and H. Page. 1997a. Nutzung des Feuers in mittel- und nordeuropäischen Landschaften. Geschichte, Methoden, Probleme, Perspektiven. Alfred Toepfer Akademie für Naturschutz, Schneverdingen, NNA-Berichte 10, Heft 5, 18-38.
- Goldammer, J.G., J. Prüter, and H. Page. 1997b. Feueinsatz im Naturschutz in Mitteleuropa. Ein Positionspapier. Alfred Toepfer Akademie für Naturschutz, Schneverdingen, NNA-Berichte 10, Heft 5, 2-17.
- Goldammer, J.G., E. Brunn, G. Hoffmann, T. Keienburg, R. Mause, H. Page, J. Prüter, E. Remke, and M. Spielmann. 2009. Einsatz des Kontrollierten Feuers in Naturschutz, Landschaftspflege und Forstwirtschaft – Erfahrungen und Perspektiven für Deutschland. *Naturschutz und Biologische Vielfalt* 73, 137-164.

- Goldammer, J.G., and S. Zibtsev (eds.) 2009. Advanced Seminar "Wildfires and Human Security: Fire Management on Terrain Contaminated by Radioactivity, Unexploded Ordnance (UXO) and Land Mines", Kyiv / Chornobyl, Ukraine, 6-8 October 2009, Abstract Volume, 41p. <http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/GFMC-CoE-OSCE-Seminar-Ukraine-Brochure-Final-06-Oct-2009.pdf>
- INRA. 1988. Proceedings, International Prescribed Burning Workshop, Avignon, 14-18 March 1988. Institut National de la Recherche Agronomique (INRA), Station de Sylviculture Méditerranéenne.
- Jensen, H.S. 2004. Restoration of dune habitats along the Danish west coast. Int. Forest Fire News No. 30, 14-15.
- Keienburg, T., and J. Prüter. 2006. Naturschutzgebiet Lüneburger Heide – Erhaltung und Entwicklung einer alten Kulturlandschaft. Mitteilungen aus der NNA 17 (1), 68 p.
- Korontzi, S., J. McCarty, T. Loboda, S. Kumar, and C. Justice. 2006. Global distribution of agricultural fires in croplands from 3 years of Moderate Resolution Imaging Spectroradiometer (MODIS) data. Global Biogeochem. Cycles 20, GB2021, doi: 10.1029/2005GB002529.
- Kvamme, M., and P.E. Kaland. 2009. Prescribed burning of coastal heathlands in Western Norway: History and present day experiences. Int. Forest Fire News No. 38, 35-50.
- Lambert, B. 2008. Bilan et perspectives du réseau brûlage dirigé. Réseau des équipes de brûlage dirigé, SUAMME, Conservatoire de la Forêt Méditerranéenne. 32p.+CDRom.
- Lázaro, A. 2009. Collection and mapping of prescribed burning practices in Europe: A first approach. Int. Forest Fire News No. 38, 110-119.
- Lovén, L., and P. Äänismaa. 2004. Planning of the Sustainable Slash-and-Burn Cultivation Programme in Koli National Park, Finland. Int. Forest Fire News No. 30, 16-21.
- Lutz, P. 2008. Traditional slash-and-burn agriculture in the Black Forest: Reconstruction of burning and agricultural techniques. Paper presented at the Symposium on Fire Management in Cultural and Natural Landscapes, Nature Conservation and Forestry in Temperate-Boreal Eurasia, Freiburg, Germany, 25-27 January 2008. <http://www.fire.uni-freiburg.de/programmes/natcon/ppt/23-EFNCN-2008-1-Germany-Swidden-Lutz.pdf>
- Mälikönen, E., and T. Levula. 1996. Impacts of Prescribed Burning on Soil Fertility and Regeneration of Scots Pine (*Pinus sylvestris* L.). In: Fire in ecosystems of boreal Eurasia (J.G. Goldammer and V.V. Furyaev, eds.), 453-464. Kluwer Academic Publ., Dordrecht, 528 pp.
- Mause, R. 2009. The Use of Prescribed Fire for Maintaining open Calluna Heathlands in North Rhine-Westphalia, Germany. Int. Forest Fire News No. 38, 75-80.
- Montiel, C., P. Costa, and M. Galán. 2010. Overview of suppression fire policies and practices in Europe. In: Towards Integrated Fire Management – Outcomes of the European Project Fire Paradox (J. Sande Silva, F. Rego, P. Fernandes, and E. Rigolot, eds. European Forest Institute Research Report 23.
- Naveh, Z. 1975. The Evolutionary significance of fire in the Mediterranean Region. Vegetatio 29, 199-208.
- Niemeyer, F. 2004. Prescribed Burning of Moorlands in the Diepholzer Moorniederung, Lower Saxony State, Germany. Int. Forest Fire News No. 30, 43-44.

- Page, H., and J.G. Goldammer. 2004. Prescribed Burning in Landscape Management and Nature Conservation: The First Long-Term Pilot Project in Germany in the Kaiserstuhl Viticulture Area, Baden-Württemberg, Germany. *Int. Forest Fire News* No. 30, 49-58.
- Pyne, S.J. 1997. *Vestal Fire. An environmental history, told through fire, of Europe and Europe's encounter with the World.* University of Washington Press, 680 p.
- Rego, F.G., J.M. da Silva, and M.T. Cabral. 1983. The use of prescribed burning in the Northwest of Portugal. In: DFG-Symposium Feuerökologie. Symposionsbeiträge (J.G. Goldammer, ed.), 88-104. *Freiburger Waldschutz-Abh.* 4, Institute of Forest Zoology, Freiburg University, 301 p.
- Rietze, J. 2008. Ecological monitoring of the management of slope-vegetation by prescribed burning in the Kaiserstuhl-Region, Germany. *Int. Forest Fire News* No. 38, 63-66.
- Rigolot, E., 2000. Le brûlage dirigé en France: outil de gestion et recherches associées. In: Vega, J.A., Vélez, R. (Eds.), *Actas de la Reunión sobre Quemas Prescritas, Cuadernos de la Sociedad Española de Ciencias Forestales* 9, 165-178.
- Rösch, M., O. Ehrmann, L. Herrmann, E. Schulz, A. Bogenrieder, J.G. Goldammer, M. Hall, H. Page, and W. Schier. 2002. An experimental approach to Neolithic shifting cultivation. *Vegetation History and Archaeobotany* 11, 143-154.
- Rösch, M., O. Ehrmann, L. Herrmann, E. Schulz, A. Bogenrieder, J.G. Goldammer, H. Page, M. Hall, and W. Schier. 2004. Slash-and-burn experiments to reconstruct late Neolithic shifting cultivation. *Int. Forest Fire News* No. 30, 70-74.
- Rydkvist, T. 2009. Prescribed fire as a restoration tool and its past, present and future use in the County of Västernorrland, Sweden. *Int. Forest Fire News* No. 38, 63-66.
- Sande Silva, J., F. Rego, P. Fernandes, and E. Rigolot (eds.). 2010. *Towards Integrated Fire Management – Outcomes of the European Project Fire Paradox.* European Forest Institute Research Report 23.
- Schreiber, K.-F. 2004. Germany: Use of Prescribed Fire in Maintaining Open Cultural Landscapes in Baden-Württemberg State. *Int. Forest Fire News* No. 30, 45-48.
- Scotland Government. 2008. *The Muirburn Code. Guidance on safe burning of heather (principal legislation constraints that apply for the wise use of fire in moorland management of Scotland).* ISBN 978-0-7559-1004-5.
<http://www.scotland.gov.uk/Publications/2008/04/08154231/0>
- Tanneberger, F., J. Krogulec, and A. Kozulin. 2009. *Feuermanagement im Niedermoor - Beispiele aus Polen und Weißrussland.* *Naturschutz und Biologische Vielfalt* 73, 179-188.
- Valendik, E.N., V.N. Vekshin, S.V. Verkhovets, A.I. Zabelin, G.A. Ivanova, and Ye.K. Kisilyakhov. 2000. Prescribed burning of logged sites in dark coniferous forests. *Siberian Branch Russ. Acad. Sci. Publishing, Novosibirsk.* 209 pp <in Russian>.
- Valendik, E.N., V.N. Vekshin, G.A. Ivanova, Ye. K. Kisilyakhov, V.D. Perevoznikova, A.V. Bryukhanov, V.A. Bychkov, and S.V. Verkhovets. 2001. Prescribed burning of logged mountain forest sites. *Siberian Branch Russ. Acad. Sci. Publishing, Novosibirsk,* 172 pp. <in Russian>.

- Valendik, E.N., J.C. Brissette, Ye.K. Kisilyakhov, R.J. Lasko, S.V. Verkhovets, S.T. Eubanks, I.V. Kosov, and A.Yu. Lantukh. 2006. An experimental burn to restore a moth killed boreal conifer forest, Krasnoyarsk Region, Russia. *Mitigation and Adaptation Strategies for Global Change* 11 (4), 883-896.
- Valette, J.Ch., E. Rigolot, and M. Etienne. 1993. Intégration des techniques de débroussaillage dans l'aménagement de défense de la forêt contre les incendies. *Forêt Méditerranéenne* XIV(2), 141-154.
- van Wagtendonk, J.W. 2007. History and evolution of wildland fire use. *Fire Ecology* Special Issue Vol. 3 (2), 3-17.
- Vega, J.A., S. Bará, and C. Gil. 1983. Prescribed burning in pine stands for fire prevention in the Northwest of Spain: Some results and effects. In: *DFG-Symposium Feuerökologie. Symposionsbeiträge* (J.G. Goldammer, ed.), 49-74. *Freiburger Waldschutz-Abh.* 4, Institute of Forest Zoology, Freiburg University, 301 p.
- Vélez Muñoz, R. 2007. Experiences in Spain of Community Based Fire Management. Paper presented at the 4th International Wildland Fire Conference, Sevilla, Spain 13-17 May 2007.
- http://www.fire.uni-freiburg.de/sevilla-2007/contributions/doc/cd/SESIONES_TEMATICAS/ST2/Velez_SPAIN_DGB_ExpeEnglish.pdf
- Viro, P.J. 1974. Effects of forest fire on soil. In: *Fire and ecosystems* (T.T. Kozlowski and C.E. Ahlgren, eds.), 7-45. Academic Press, New York.
- Vogels, J. 2009. Fire as a restoration tool in the Netherlands – first results from Dutch dune areas indicate potential pitfalls and possibilities. *Int. Forest Fire News* No. 38, 23-35.

Part V: The Krasnoyarsk 10-Point Programme on the Future of Fire Management in Russia

PART V

Recommendations of the “International Fire Management Week”

Krasnoyarsk Krai, 2-8 September 2012

The Krasnoyarsk 10-Point Programme on the Future of Fire Management in Russia

Rationale

Sustainable management and protection of forest resources are key elements of the forest policy of the Russian Federation. For more than a century the prevention and control of all forest fires has been primary task of agencies responsible for forest management and fire protection. However, scientific evidence reveals that some forest types in the different ecoregions of Russia's territory have co-evolved with natural fires (lightning fires) and even human-set fires. The effects of fire disturbances include removal of dead and live accumulated biomass, recycling of nutrients, stand thinning and regeneration of forest stands. Fire disturbances are creating valuable wildlife habitats. Recurrent surface fires of low intensity remove combustible materials and result in an overall reduction of the risk of severe and large destructive fires, which are considered threat to sustainable forest management and utilization, and may lead to large, uncontrollable outbreaks of pests and diseases.

With the presence of natural fires over millennia some forest types can be classified as fire-tolerant, fire-adapted or even fire dependent. Thus, a complete exclusion of fire from some forest ecosystems is neither ecologically desirable, nor economically feasible. Considering the increasing importance of managing long-term stable forest cover, forest productivity and carbon sequestration, a future forest and fire management policy of Russia shall include the integration of planned and prescribed natural and accidental wildfires, as well as prescribed management fires.

Wildfire prescriptions need to be determined for each forest type, allowing wildfires to burn if their effects are expected to be beneficial to the forest ecosystem short- to long-term.

The application of prescribed management fires (prescribed burning) shall reduce hazardous combustible materials within forest stands (under canopy burning); burning residuals (slash) of forests destroyed by pests, diseases and wind; or induce forest regeneration and secure ecological dynamics of natural protected forests. Currently there are no regulations on prescribed natural and prescribed fire management operations under canopy of forests in Russia.

The International Fire Management Week

Between 2 and 8 September 2012 the „International Fire Management Week“ was organized under the joint umbrella of the Federal Forestry Agency ROSLEZKHOZ of Russia and the Global Fire Monitoring Center (GFMC), both cooperating partners under the bilateral Russian-German Agreement on Cooperation in Sustainable Forest Management, and under the framework of the UN International Strategy for Disaster Reduction (UNISDR) and the UN Economic Commission for Europe (UNECE).

During this event the latest and up-to-date state of the art of fire ecology and advanced fire management methods on the use of prescribed fire for wildfire hazard reduction in temperate-boreal Eurasia were presented and discussed between scientists, practitioners and policy makers at national level of the Russian Federation, and with representatives of the administrations of Krasnoyarsk Krai.

Participating and consulted institutions included:

- Federal Forestry Agency (Roslezkhoz)
- Global Fire Monitoring Center (GFMC)
- Aerial Forest Fire Center (Avialesookhrana)
- Forest Inventory and Planning Enterprise “RoslesinforG”
- All Russian Institute of Continuous Education in Forestry (VIPKLH)
- Vice Governor of Krasnoyarsk Krai
- Minister of Natural Resources and Forest Complex of Krasnoyarsk Krai
- Sukachev Institute of Forest SB RAS
- Krasnoyarsk Krai Forestry Agency
- Krasnoyarsk Forest Fire Center
- National University of Life and Environmental Sciences of Ukraine
- National University of Mongolia
- National Emergency Agency of Mongolia
- Sankt Peterburg Forestry Research Institute (SPbNIILH)
- Krasnoyarsk Forest Health Center (Regional office of Roslesozaschita)
- Krasnoyarsk Center of EMERCOM of Russia

In a seminar basic statements and papers were presented on the role of fire in ecosystems and the implications on fire management.

At a field demonstration on prescribed burning under canopy of a pine stand nearby Krasnoyarsk media representatives were briefed about the objectives of prescribed sub-canopy burning in pine forests. Attendees of this demonstration witnessed for the first time that a prescribed low-intensity surface fire can be set in a forest to safely reduce surface fuels without damaging the stand.

An expedition to the site of Bor Forest Island Fire Experiment of 1993, located between the settlements Yartsevo and Bor, demonstrated the concept of a long-term research project of the consequences of a severe, high-intensity fire. The experiment, scheduled for the

200-years research period 1992-2192, investigates the consequences of a high-intensity forest fire, followed by secondary pests, on the regeneration of a natural forest.

A Round Table on the 4th day of the International Fire Management Week evaluated the seminar, the prescribed burning experiment and the visit of the Bor Forest Island Fire Experiment.

The Krasnoyarsk 10-Point Programme on the Future of Fire Management in Russia

The Round Table concluded that there is an urgent need to revise the policy and practice of fire management in the Russian Federation, and agreed upon the following recommendations:

1. Legal and other normative documents that are regulating forest management and forest fire protection need to be complemented concerning the use of prescribed fires and prophylactic burning under forest canopy.
2. Methodological guidelines for prescribed burning under forest canopy need to be developed at federal level.
3. Educational programs for the training of forest firefighters and fire management specialists at different educational levels need to be developed and approved at Federal level.
4. Programs of advanced continuous professional education for foresters on prescribed burning need to be developed and approved.
5. Create the occupation categories "Forest Fire Fighter" and Fire Crew Leader in the tariff-classification reference book.
6. Further scientific research concerning prescribed fires needs to be supported at Federal level.
7. The Order of the Federal Forestry Agency № 174 of 27 April 2012 "Approval of the normative for forest fire management plans" need to be changed in the section on planning the prophylactic burnings at forest district unit level and to determine the normatives for fire prevention operation plans in the 1-km zone around settlements.
8. Concepts for the use of fire on agricultural and other non-forested lands of the Russian Federation need to be developed.
9. A new system of statistical accounting and classification of types of forest and other vegetation fires and their consequences needs to be developed, and appropriate changes to be made in the GOST № 17.6.1.01-83 (approved by Decree of the State Committee on Standards, 19 December 1983).
10. International expertise in the field of fire management needs to be used, including the system of statistical accounting and classification of vegetation fires proposed by GFMC.

Международная неделя пожароуправления Красноярский край, 2-8 сентября 2012 г.

Рекомендации

Красноярская Программа из 10-ти пунктов по вопросу о будущем пожароуправления в России

Обоснование

Устойчивое управление и охрана лесных ресурсов являются ключевыми элементами лесной политики Российской Федерации. В течении более чем столетнего периода профилактика и борьба с лесными пожарами были основными задачами государственных органов управления, ответственных за ведение лесного хозяйства, в том числе за охрану лесов. В то же время, результаты научных исследований показывают, что природные пожары (возникшие от молний), а в некоторых случаях и пожары антропогенного происхождения, были неотъемлемой частью динамики отдельных типов леса различных экорегионов на территории России. Воздействие огня на лесную экосистему заключается в удалении отмершей и живой накопленной биомассы, стимулировании круговорота питательных элементов, прореживании древостоя и содействии природному восстановлению лесов. Нарушения, произведенные огнем, содействуют формированию ценных местообитаний диких животных. Периодические низовые лесные пожары низкой интенсивности удаляют лесные горючие материалы и, таким образом, способствуют снижению риска развития катастрофических разрушительных пожаров, которые являются угрозой для устойчивого управления лесами, лесопользования, и могут привести к большим, неконтролируемым вспышкам вредителей и болезней леса.

Природные пожары были одним из факторов, который наравне с другими экологическими факторами, на протяжении тысячелетий влиял на формирование некоторых типов леса. В этой связи данные леса могут классифицироваться как устойчивые к пожарам, адаптированные к пожарам или даже зависимые от пожаров. Таким образом, полное исключение пожаров из некоторых типов лесных экосистем является нежелательным с экологической точки зрения и нецелесообразным экономически. Учитывая возрастающее значение управления долгосрочным и стабильным лесным покровом, продуктивностью лесов и депонированием углерода, будущая лесная политика и политика в области охраны лесов от пожаров России должна включать интеграцию предписанных запланированных

природных пожаров и пожаров антропогенного происхождения, а также профилактических выжиганий.

Предписания, касающиеся природных пожаров (возникших от гроз или по антропогенным факторам), должны быть определены для каждого типа леса, что будет предусматривать возможность развития пожара, если ожидается, что его влияние будет позитивным для лесных экосистем, как в кратко- так и в долгосрочной перспективе.

Применение профилактических выжиганий должно включать снижение накопления пожароопасных горючих материалов в лесных насаждениях (выжигание под пологом леса); сжигание растительных остатков (валежа) в лесах, поврежденных вредителями и болезнями леса, ветровалами; или стимулировать природное возобновление леса и обеспечивать природную динамику коренных лесов на охраняемых территориях. В настоящее время в России не существует утвержденных инструкций о проведении предписанных природных пожаров и профилактических выжиганий под пологом леса.

Международная неделя пожароуправления

«Международная неделя пожароуправления» была организована с 2 по 8 сентября 2012 г. совместно Федеральным агентством лесного хозяйства и Центром по глобальному мониторингу пожаров (GFMC) в рамках двустороннего Российско-Германского Соглашения о сотрудничестве в области устойчивого лесопользования и под эгидой Международной стратегии ООН по уменьшению опасности стихийных бедствий (UNISDR) и Европейской Экономической Комиссии ООН (UNECE).

Во время этого события, было представлено и обсуждено современное состояние знаний в области экологии пожаров и передовых методов пожароуправления, в частности, использование предписанных пожаров для снижения природной пожарной опасности в лесах умеренно-бореальной Евразии учеными, практиками и политиками на национальном уровне России, а также представителями администрации Красноярского края.

В обсуждении и консультациях принимали участие следующие организации и их представители:

- Федеральное агентство лесного хозяйства (Рослесхоз)

- Центр по глобальному мониторингу пожаров (GFMC, Германия)
- Федеральное Бюджетное Учреждение «Авиалесоохрана»
- Восточно-Сибирский филиал Рослесинфорг «Востсиблеспроект»
- Всероссийский институт повышения квалификации руководящих работников и специалистов лесного хозяйства (ВИПКЛХ)
- Заместитель губернатора Красноярского края
- Министр природных ресурсов и лесного комплекса Красноярского края
- Институт леса им. В.Н.Сукачева СО РАН
- Агентство лесной отрасли Красноярского края
- Краевое государственное автономное учреждение «Красноярская база авиационной и наземной охраны лесов» (КГАУ «Лесопожарный центр»)
- Национальный университет биоресурсов и природопользования Украины
- Национальный университет Монголии
- Национальное агентство по чрезвычайным ситуациям Монголии
- Федеральное Бюджетное Учреждение «СПБНИИЛХ»
- Филиал ФБУ Рослесозащита «Центр защиты леса Красноярского края»
- Главное управление МЧС по Красноярскому краю

В рамках «Международной недели пожароуправления» был проведен семинар, на котором были представлены сообщения и научные доклады, посвященные роли огня в экосистемах и перспективам использования огня в системе охраны лесов от пожаров.

Во время демонстрации контролируемого пала под пологом соснового насаждения, расположенного в окрестностях г. Красноярска, представители СМИ были проинформированы о целях предписанных выжиганий под пологом сосновых лесов. Участники данной демонстрации в первый раз в регионе были свидетелями того, что предписанный низовой пал низкой интенсивности может проводиться в лесу с целью безопасного уменьшения количества напочвенных лесных горючих материалов без ущерба для древостоя.

Экспедиция к месту лесопирологического полевого эксперимента «Лесной остров Бор» 1993 года, расположенного между поселками Ярцево и Бор, продемонстрировала концепцию долговременного исследовательского проекта, посвященного изучению экологических аспектов лесного пожара высокой интенсивности. Эксперимент, который

запланирован на 200-летний период исследований (1992-2192), позволит установить закономерности динамики растительности после лесного пожара высокой интенсивности, динамики популяций вторичных вредителей и восстановления естественного насаждения.

Круглый Стол, который был организован на 4-й день «Международной недели пожароуправления», был посвящен оценке семинара, демонстрационного эксперимента по проведению предписанного пала и результатам экспедиции на «Лесной остров Бор» спустя 19 лет после начала долговременного лесопирологического эксперимента.

Красноярская Программа из 10-ти пунктов по вопросу о будущем пожароуправления в России

Участники дискуссии на заседании Круглого Стола пришли к выводу, что существует настоятельная необходимость в пересмотре политики и практики пожароуправления в Российской Федерации и пришли к согласию относительно следующих рекомендаций:

1. Ввести в нормативные правовые документы изменения и дополнения в области использования предписанных пожаров и профилактических выжиганий под пологом леса.
2. Разработать методические указания по проведению профилактических выжиганий под пологом леса на федеральном уровне.
3. Разработать и утвердить единые программы подготовки специалистов по пожароуправлению и лесных пожарных различного уровня.
4. Разработать и утвердить программы повышения квалификации работников лесного хозяйства по проведению предписанных (контролируемых, профилактических) выжиганий.
5. Создать категории профессий «Лесной пожарный» и «Бригадир пожарной группы» в отраслевом тарифно-квалификационном справочнике.
6. Инициировать дальнейшие научные исследования по предписанным выжиганиям и их поддержку на федеральном уровне.
7. Внести изменения в приказ Рослесхоза № 174 от 27 апреля 2012 г «Об утверждении нормативов противопожарного обустройства лесов» в части планирования работ по предписанным (профилактическим) выжиганиям в разрезе лесничеств и определить нормативы

- противопожарного обустройства в 1-километровых припоселковых зонах.
8. Учитывая большое количество лесных пожаров от сельхозпалов, разработать единую концепцию использования огня на землях различного назначения Российской Федерации.
 9. Разработать новую систему статистического учета и классификации видов пожаров и их последствий, внести соответствующие изменения в ГОСТ № 17.6.1.01-83 (Постановление Госкомитета СССР по стандартам от 19.12.1983).
 10. Использовать международный опыт пожароуправления, включая систему учета растительных пожаров, используемый Центром глобального мониторинга пожаров (ЦГМП).

In the landscapes of temperate-boreal Europe – the western part of the Euro-Siberian region of the Holarctic Floral Kingdom – the prevailing fire regimes are shaped by human-ignited fires. Direct fire application in land-use systems – agricultural burning and burning of pastures – and human-caused wildfires, ignited accidentally, by negligence or otherwise deliberately set, have influenced cultural and natural landscapes since the beginning of land cultivation. However, in the Central Euro-Siberian region there are large tracts of forest ecosystems that have been shaped by natural fire, e.g. the forests dominated by pine (*Pinus* spp.) and larch (*Larix* spp.) that constitute the “light taiga” in Siberia and adjacent regions.

Starting with the first East-West international conference “Fire in Ecosystems of Boreal Eurasia” and the Fire Research Campaign Asia-North (FIRESCAN) and its “Bor Forest Island Fire Experiment”, organized in 1993 in Krasnoyarsk, Russian Federation, the scientific dialogue revealed the rich knowledge of the fire ecology of temperate-boreal Eurasia. The results of the following two decades of joint scientific research encouraged the participation of forest authorities in devising new concepts in fire management and to consider replacing fire exclusion policies by integrated fire management approaches, which would include the use of natural fire and prescribed burning (prescribed management fires).

Fire scientists of the Sukachev Institute for Forest, Russian Academy of Sciences, Siberian Branch, Krasnoyarsk, and the Fire Ecology Research Group at the Global Fire Monitoring Center (GFMC), Freiburg University / United Nations University, Germany, have now summarized experience and provide targeted advice to the development of advanced fire management policies.

www.forestrybooks.com
www.forstbuch.de
ISBN: 978-3-941300-71-2

