

**FIRE AND STAND DYNAMICS IN DIFFERENT FOREST TYPES OF THE WEST KHENTEY
MOUNTAINS, MONGOLIA**

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ACRONYMS AND ABBREVIATIONS

Abbreviation	Description
App.	Appendix
BePl	<i>Betula platyphylla</i>
CI	Confidence interval
Coef. Var	Coefficient of variation
Fig.	Figure
FMC	Forest Management Center
JICA	Japanese International Cooperation Agency
LaSi	<i>Larix sibirica</i>
MNE	Ministry of Nature and Environment
NEMA	National Emergency Management Agency
PiSi	<i>Pinus sibirica</i>
PiSy	<i>Pinus sylvestris</i>
PcOb	<i>Picea obovata</i>
Std. Dev	Standard deviation
Std. Error	Standard Error
Tab.	Table
UNDP	United Nations Development Programme
WB	World Bank

CHAPTER 1: INTRODUCTION

1.1. Introduction

An understanding of forest stand dynamics (i.e., natural disturbance regimes, natural regeneration, and natural stand development) has long been considered essential underpinnings of scientific silviculture and management (Goldammer, 1996).

Nowadays, human activities influence natural fire regimes by increasing fires in forest that would seldom burn under natural conditions, and by suppressing natural fires, which causes ecological impacts that lead to infrequent, catastrophic fires due to a build up of flammable material (IUCN and WWF, 2003).

One of the major causes of forest degradation in Mongolia is forest fire. The long-term fire history of the Mongolian forests is poorly known, although the disturbance dynamics is one of the key questions in attempts to develop sustainable forestry practices. There is a need to fully understand the fire ecology of natural forest systems so that silvicultural systems can be adapted to this natural and important disturbance regime. Such an understanding would contribute significantly to better fire management programs and improved, ecologically-based silvicultural prescription (Haynes *et al.*, 2002).

The past decade has seen an increasing interest in forest ecosystem management and, in particular, forest management strategies based on an understanding of natural disturbances. Currently, there is considerable agreement that a management approach aimed at maintenance of stand composition and structures similar to those characterizing natural environments could provide a means of maintaining biodiversity and the essential functions of forest ecosystems. In this context, background information on natural fire cycles and their impact on composition and structure of the forest ecosystems are pivotal to the sustainable management of forests (Heinselman, 1973).

The structural patterns of old growth forest include a wide range of tree sizes and ages, a higher proportion of small trees than large trees, more young trees than old trees, many standing dead trees and snags, abundant large logs on the ground (e.g., Whitney, 1987; Oliver and Larson, 1996; Goodburn and Lorimer, 1998; McGee *et al.*, 1999; Ziegler, 2000).

Standing dead trees and downed logs are an important structural component of many forest ecosystems (Harmon *et al.*, 1986). They are significant for biodiversity, as a large number of dead wood dependent organisms are confined to standing dead trees during their life cycle

(Nilsson *et al.*, 2001). In ecosystems, where trees die and remain standing or lying on the ground, they form an important part of the overall cycle of coarse woody debris, influencing the cycling and storage of nutrients and carbon (Harmon *et al.*, 1986), and seedbed availability (Hofgaard, 1993).

Sustainable forest management has to consider both the natural fire dynamics and the anthropogenic driven fire frequency. Fire characteristics (type-ground, surface and crown, and seasonal timing of burning) and frequency in correlation to distance to human settlements, roads, other human activities and natural site conditions must be investigated. Tree-ring analysis will enable the analysis of the fire history within the different forest stands (Heinselman, 1973). Also, tree-ring analysis can determine the effect of growth rate (diameter increment) and age structure in relation to the fire history of the site (Baisan, 1990).

Dendrochronology, or tree-ring analysis, is defined as the study of the patterns in sequence of annual growth rings in trees through time. Once founded as a science by the astronomer Andrew E. Douglass (1867-1962), dendrochronology underwent a pioneer phase, being used in studies of the relationships between solar activity and the earth's climate. Later, it passed through a major developmental phase encouraging and enriching forest dynamics and fire ecological research. Dendroecology is an alternative tool permitting the reconstruction of stand history and dynamics. It has been successfully applied in many different forest types for this purpose. A better understanding of the role of frequent, to moderately severe to low severe fire intensity or effect on stand development patterns is needed by managers to evaluate risks associated with different management options, especially those that limit use of fire as a process in these ecosystems (e.g. Attiwill, 1994; Mutch and Cook, 1996; Arno *et al.*, 1997). Furthermore, there is a need for region-specific understanding of fire regime effects on forest dynamics because disturbance regimes and stand development patterns vary geographically (e.g. Spies and Franklin, 1989; Veblen, 1989; Veblen *et al.*, 1992; Agee, 1993).

There is little sense in the fact that the forests of Mongolia can be said to have ever been subject to science-based sustainable forest management (SFM), by any common understanding of the term. This study is focused on the forest structure, stand dynamics, long-term fire history and disturbance dynamic of northern Mongolian forests.

1.2. Geographic context of Mongolia

Mongolia is situated in northern central Asia, bordering the Peoples Republic of China in the South and the Russian Federation in the North, and its territory comprises 1.56 million square kilometers (Fig. 1.1). Average elevation is 1,580 m, and eighty percent of the country lies above 1000 m. The highest point, the Khuiten peak is 4,374 m above sea level, the lowest Khukh Nuur depression, 532 m, is in the east. Roughly 75% of the territory is steppe and pasture, about 11 percent is forested and less than 0.5 percent is currently cultivated (Tab. 1.1). Overall, Mongolia has six basic natural ecoregions: high mountain, taiga forest, mountain steppe, steppe, desert steppe and desert - differing in their climate, landscape, soil, flora and fauna (UNEP and MNE, 1998, 2000, 2002; UNDP, 2001; WB, 2004).

Table 1.1: Land area and land use in Mongolia

Land use	Land area	
	Ha	%
Land used for agriculture:	119.398.000	76.2
Pasture	116.783.000	74.6 ⁵⁾
Hayfield	1.915.000	1.2 ⁵⁾
Cultivated land	700.000 ²⁾	0.45
Forest land (including certain non-forest areas)	17.852.000	11.4
Closed forest	12.808.000 ³⁾	8.2
Open forest	3.604.000 ³⁾	2.3
Non-forest	1.440.000 ³⁾	0.9
Other land	(19.400.000)	(12.4)
Land occupied by cities and settlements	469.000	0.3 ³⁾
Land use for state special needs	16.267.000 ¹⁾	10.4 ⁵⁾
Unused land or land unsuitable for utilization	2.659.000	1.7 ⁵⁾
Grand total land area	156.650.000 ⁴⁾	100

¹⁾ Including land allocated for state security and defense purposes, special protected areas, roads and communication network of national importance.

²⁾ Currently cultivated area. Source: Specialist at Ministry of Agriculture and Industry.

³⁾ Source: Forest Management Center.

⁴⁾ Source: FAO.

⁵⁾ Source: Enhkbat *et al.* 1997

1.3. Overview of Mongolian forest

The area classified as forest (including certain non-forest areas) is estimated at 17.8 million ha (11.4 percent of the land area), the area of closed forest at 12.8 million ha (Tab. 1.2). Most forests are larch forests - Siberian larch (*Larix sibirica*); important are also Scots pine (*Pinus sylvestris*) and Siberian stone pine (*Pinus sibirica*). The saxaul shrub forests (*Haloxylon ammodendron*) in the south are important for protection and as a firewood resource

(Enkhbat and Tsogtbaatar, 1997). The growth rate of Mongolian forests is slow because of the harsh continental climate, which is much harsher than in other countries within a similar latitudinal zone- and characterized by extremes in both temperature and its fluctuations. Precipitation, concentrated during the summer period, is low with an annual average of about 230 mm, higher in mountainous areas in the north but less than 100 mm in desert regions in the south. The average in the northern forest zone is about 300 mm. As a result of the harsh climate, these northern forests are easily influenced by fire, pests, disease and human activities. The total standing volume is estimated at about 1335.9 million m³ with an average standing volume per hectares of 109 m³/ha and the annual increment is 5.5 million m³ (Erdenechuluun, 2006).



Figure 1.1: Map of Mongolia. *Source:* Nations Online Project

Since closed forest cover accounts for only 8.2%, Mongolia is included into the group of countries, which has low forest resources as determined by the FAO (Adyasuren, 1998). Industrial logging of forest resources in Mongolia has increased since the 1960s. According to government reports, Mongolia produced 1.7 million cubic meter of timber annually. Reforestation activities in Mongolia started in the 1970s. Since 1975, reforestation was carried out on 68,748 ha within the country where most of the areas were replanted by

seedlings. Although positive results of restoration were observed, fires, disease infection and grazing by the livestock, have damaged some of these planted forests (MNE of Mongolia, 1998, 2000, 2001; Crisp *et al.*, 2004).

Table 1.2: Forest land categories of Mongolia

Forest land category	Area		Wood volume	
	ha	%	ha	%
Forest land (in, certain non-forest areas)	17.852.241			
Closed forest ¹⁾	12.807.923	72.6	1.362.774.300 ⁹⁾	
Open forest ²⁾	3.604.389	19.4		
Non-forest ³⁾	1.439.929	8.0		
Natural closed forest land (except saxaul)	10.402.599		1.361.474.300 ¹⁰⁾	
Strict zone forest ^{4) 5)}	172.866 ⁸⁾	1.7	25.578.900 ⁸⁾	1.9
Protected zone forest ^{4) 6)}	3.260.310 ⁸⁾	31.3	403.424.400 ⁸⁾	29.6
Utilization zone forest ^{4) 7)}	6.969.423 ⁸⁾	67.0	932.471.000 ⁸⁾	68.5
Grand total	17.852.241	100		

¹⁾ Closed forest

²⁾ Open forest: density less than 0.30.

³⁾ Non-forest in this connection: Inside forest generally small area of grassland, farmland, lake, river, swamp, nursery, windbreak belt (though outside forest), sandy area, mining, rocky area, landslide site, power-line etc.

⁴⁾ Natural closed forest classified according to Forest Law into strict zone forest, protected zone forest and utilization forest

⁵⁾ Include (forest Law, Article 8): "subalpine forests, pristine and conservation zone forests within strictly protected areas and special zone forests within national conservation parks"

⁶⁾ Include (Forest Law, Article 10) "forests within special protected areas, green zones, prohibited strips, saxaul forests, oases, forest areas covering up to 100 hectares, small tree groupings, shrubs, sun-exposed forest areas and forests at slopes greater than 30 degrees..."

⁷⁾ Commercial or industrial forests

⁸⁾ Approximate estimate, based on a mix of old and new information from the aimags

⁹⁾ Including saxaul

¹⁰⁾ Excluding saxaul

Source: Forest Management Center (1998)

1.4. Fire situation in Mongolia

Forest resources in Mongolia have increasingly degraded over the past few years, due to illegal timber cutting, forest fires, pests and diseases, which cause severe ecological stress in some regions. Although fire plays a natural role in Mongolia's ecology, anthropogenic fires generally result in ecological imbalance and economical damage. Forest losses in Mongolia due to fire and insects are dramatic (Enkhbat *et al.*, 1997). According to fire statistics, the number of both forest and steppe fires in the country from 1963 to 2009 were 6,442 (Fig. 1.2). A total of 14.3 million ha forested areas were affected by fire, i.e. an average of about 2,200 ha per fire and about 298,400 ha per year. A total of 85.3 million ha area was burnt in the steppes, i.e. 13,242 ha per fire and 1,814,800 ha per year (JICA, FMC, MNE, 1998 and NEMA, 2009). Mongolia is threatened by increasing wildfires. The northern forest areas of

Khovsgol, Bulgan, Selenge, Khentey, and Dornod and the pasture areas of Dornod and Sukhbaatar were largely burnt in these fire episodes.

From 1963 to 1990s, forest and steppe fires burned on an average of 1.21 million ha annually. In 1996 and 1997, due to low rainfall and extremely dry conditions during

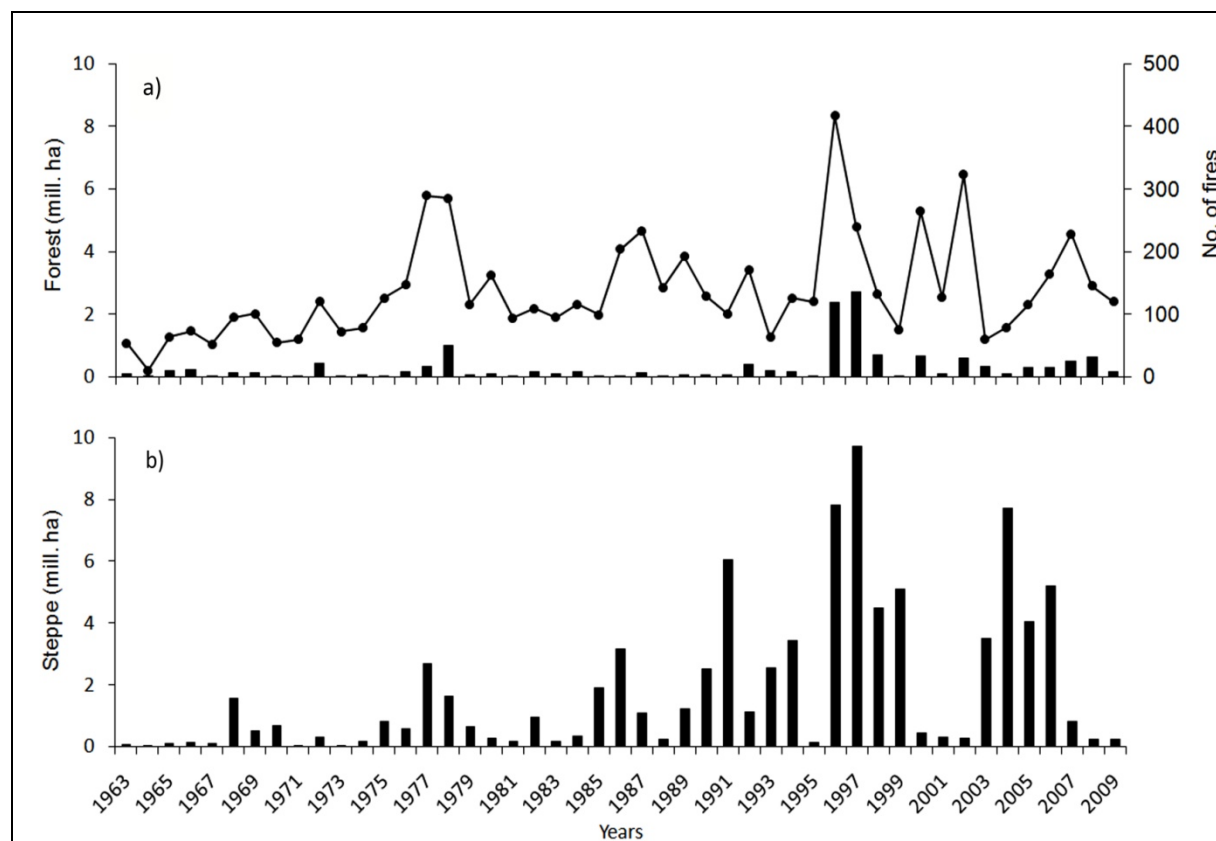


Figure 1.2: Number of fire occurrences, burnt area of forest (a) and steppe (b). A dotted line indicates total number of steppe and forest fires per year, and bars show size of burnt areas (NEMA, 2009).

spring, fires of unprecedented proportions, classified as a national disaster, occurred in the northern forests and pastures causing environmental and economic havoc. The areas affected by fire were 10.7 and 12.4 million ha respectively – an increase of more than six-fold. During these fire episodes, 29 people died, 82 people were injured and 11700 livestock were killed. Also, 218 family houses, 1066 communication facilities, 750 fences and 26.3 million ha of pasture and forest were burned. The total costs of property losses amounted to 820.2 million MNT (Mongolian Tugruk). Ecological and economical damage was estimated as 1 850.5 million MNT (ca. \$US 1.8 million).

CHAPTER 2: DESCRIPTION OF STUDY AREA

2.1. Khentey Mountains and Research Sites

2.1.1. Topography

The Khentey Mountains stretch about 200 km from the Mongolian capital in a north-east direction to the Russian border. In Russia, they further continue for over 150 km to the northeast, changing their names to Chikoyskiy Khrebet and Khrebet Stanovik. The Khentey Mountains are surrounded by the Mongolian-Daurian steppe in the west and south and by the Eastern Mongolian steppe in the east. Elevation of the study area ranges from 900 m in river valleys up to 1600 m on the mountain tops. The central parts of the Khentey Mountains generally exceed an elevation of 1500 m with the highest peak, 2799 m, Mt. Asralt Khayrkhan (Dulamsuren *et al.*, 2005a). Geologically, the Khentey Mountains mainly consist of Proterozoic and Paleozoic rocks, especially of granite (Dulamsuren *et al.*, 2005a). The location of the study area is presented in Figure 2.1.

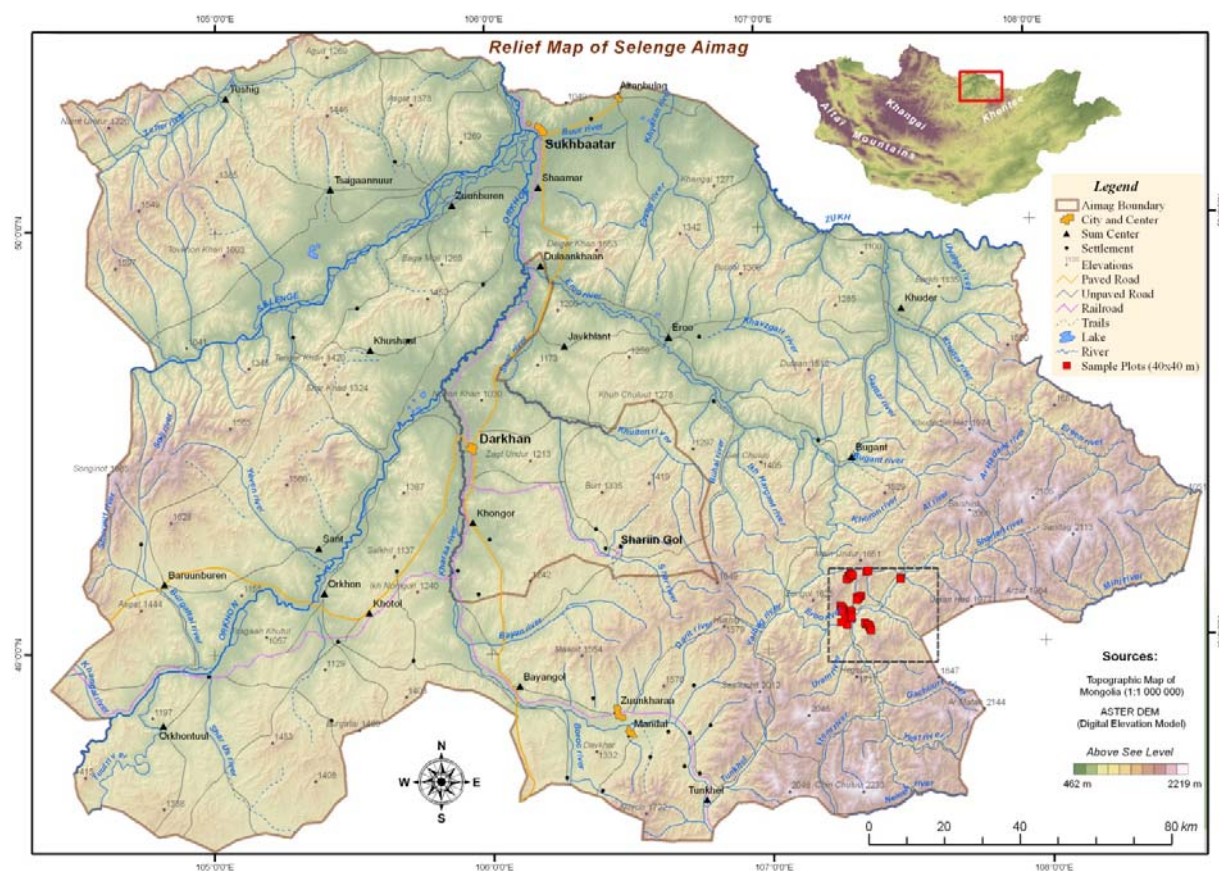


Figure 2.1: Map of Selenge province, Mongolia, and location of research sites marked by red quadrates. Map: B. Oyunsanaa.

2.1.2. Vegetation and forest types

The Khentey Mountains in Northern Mongolia represent a huge natural landscape consisting of unique ecosystems with very little fragmentation and a high biodiversity because they are not yet altered by civilization. Around half of the entire fauna and flora of this area consists of Palearctic species of which many populations in Europe are threatened (Mühlenberg *et al.*, 2000; Woyciechowski *et al.*, 2001).

The forests in the West Khentey are mixed forest with variable successional stages, so that boreal coniferous forests are of high structural diversity and spatial heterogeneity, due to the natural disturbances (Gunin *et al.*, 1999; Goldammer and Furyaer, 1996). The Khentey Mountain region represents a natural landscape mosaic of western Siberian dark taiga forests, eastern Siberian light taiga forests and of Mongolian-Daurian forest steppe vegetation which is particularly rich in plant species. Dulamsuren (2004) described four main vegetation communities according to ecological criteria in the west Khentey mountains; (1) dark mountain taiga forests of the upper and lower montane belt, (2) light taiga forests of northern slopes in the lower montane belt, (3) forest and steppe vegetation of southern slopes in the lower montane belt, and (4) floodplain vegetation.

The present research study was conducted within the dark taiga and light taiga vegetation types. The dark taiga forests occur on slopes of every aspect in the upper montane belt and directly borders the open fields or clearings that may have resulted from natural or anthropogenic disturbances. They occur at the most humid sites and the main tree species is *Pinus sibirica*, which is associated with other conifer species, i.e., primarily with *Abies sibirica* and to a lower degree, *Picea obovata*. Also, dark taiga vegetation in the lower montane belt is stocked with *Picea obovata* and *Picea obovata-Abies sibirica* forests (Dulamsuren, 2004).

The light subtaiga forests dominated by *Larix sibirica* and *Betula platyphylla* grow on relatively dry northern slopes of the lower montane belt and they are rich in undergrowth vegetation: *Calamagrostis obtusata*, *Vaccinium vitis-idaea*, *Maianthemum bifolium*, *Fragaria orientalis*, *Viola uniflora*, *Artemisia sericea*, *Atragene sibirica*, *Bromus pumpellianus*, *Geranium pseudosibiricum*, *Aconitum septentrionale*, *Equisetum sylvaticum*, *Iris ruthenica*, *Cacalia hastata*, *Lathyrus humilis* and *Vicia unijuga*. Typical in the shrub stratum are *Rosa acicularis*, *Spiraea flexuosa* and *Rhododendron dahuricum*. *Chamaeneron angustifolium* is

frequent, occurring in particular in secondary forest after fire or clearcutting. Also, light subtaiga forests dominated by *Pinus sylvestris* and mixed with *Larix* and *Betula ssp.* are distributed on the dry eastern slopes of mountains with relatively shallow soils (<30 cm). In addition to the common plants of the conifer forest, heliophilous species of shrubland and steppe such as *Chrysanthemum zawadskii*, *Silene repens*, *Melica turczaninovina*, *Atragalus frigidus*, *Carex pediformis*, *Erigeron acer*, *Dracocephalum nutans*, *Polygonatum officinalis* and *Galium boreale* occur (Dulamsuren, 2004).

2.1.3. Climate

Generally, the climate of the Khentey Mountains is characterized by the Asiatic anticyclone in winter, which typically has its center southwest of Lake Baikal and causes dry and cold winters (Tsegmid, 1969; Tsedendash, 1995). Monthly instrumental precipitation and temperature records from Bugant (1988-2009) and Eröö (1961-2009) permanent stations at the forest margin of the West Khentey Mountains are shown in Figure 2.2. The average air temperature from these two stations ranges from 19.4 °C in July to -24.3 °C in January, with an absolute maximum of 41.7 °C and absolute minimum of -45.7 °C for the period from 1961 to 2009. Precipitation occurs mainly in the summer months and especially in July - August precipitation reaches about 145 mm. The mean annual precipitation is 286.6 mm, increasing to 505 mm in the higher elevations, specifically in Bugant station.

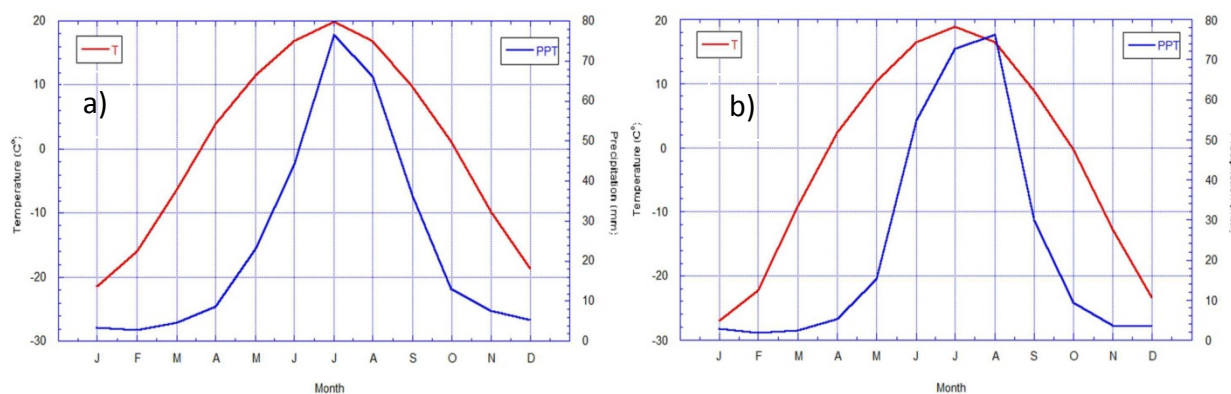


Figure 2.2: Climate diagrams of meteorological stations close to the study area: a) Bugant (ca. 40 km) and b) Eröö (87 km). Red line indicates average temperature and blue line shows monthly precipitation. *Source:* The Meteorology, Hydrology and Environment Monitoring Center of Selenge Province, Mongolia.

2.1.4. Research sites

Four types of forests which were sampled for this research are located in the Khonin Nuga region of the western Khentey Mountains. It is situated in the territory of Mandal, Eröo sums of Selenge province and Erdene sum of Töv province. Khongi and Sharlan Rivers unite here to form the Eröo River, which flows into the Orkhon and Selenge rivers that finally drain into the Lake Baikal (Fig. 2.1; Fig. 2.3).

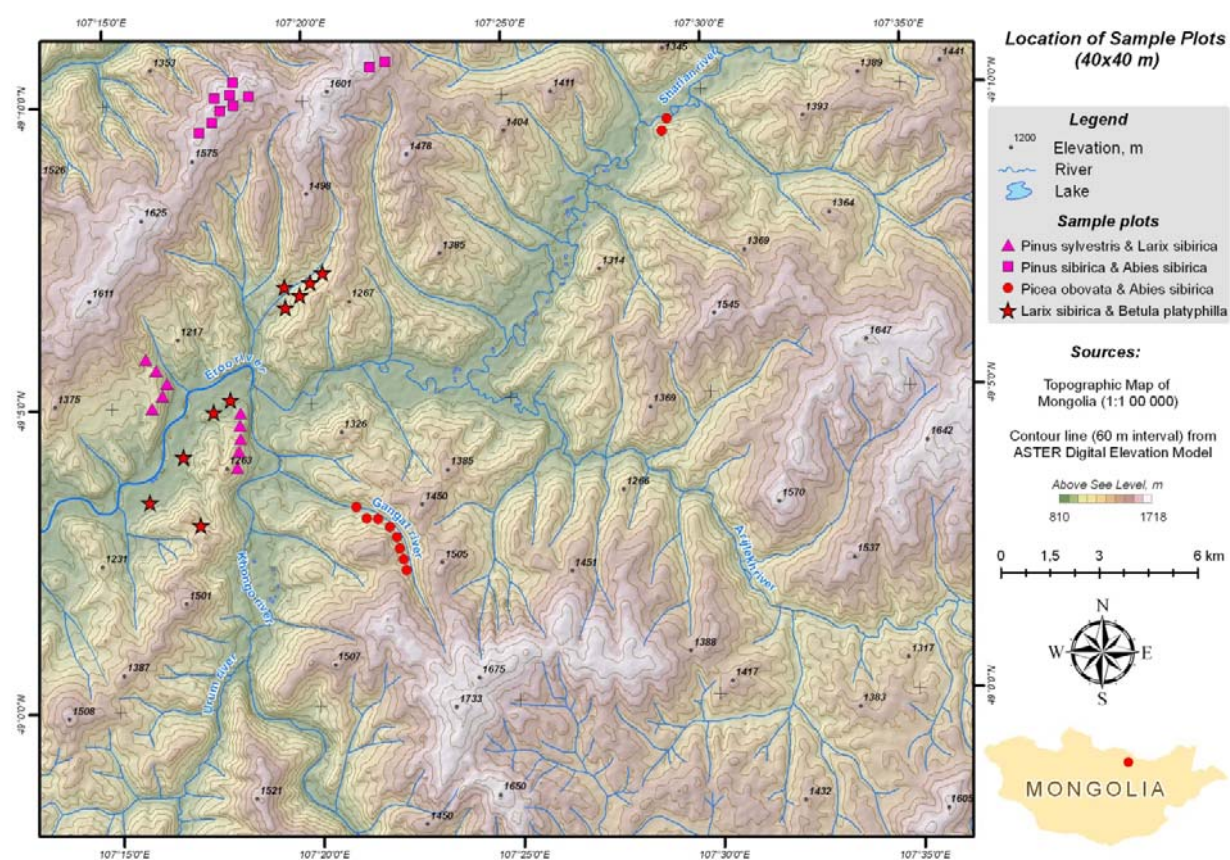


Figure 2.3: Location of sample plots, West Khentey Mountains, Mongolia. Map: B. Oyunsanaa

The uniqueness of Khonin nuga in Mongolia is indicated by the tree *Abies sibirica* which occurs only in that region and the type of the taiga which resembles the southern Siberian taiga, including old-growth *Pinus sibirica* forests, not found elsewhere in Mongolia. The forest structure and composition in the west Khentey Mountains are more complex and unique compared to other regions of the country.

2.1.4.1. *Pinus sibirica*-*Abies sibirica* dark taiga forest

Abies sibirica is the prevalent tree species associated with *Pinus sibirica* in this type of forest. The most humid sites within *Pinus sibirica*-*Abies sibirica* forest are inhabited by its *Cinna latifolia*-*Agrostis clavata* variant. *Picea obovata* can also be a part of the tree layer in these type of forests (Dulamsuren *et al.*, 2005a). The *Pinus sibirica*-*Abies sibirica* forest sites lie on the Sangastai and Gatsuurt ridges (Fig. 2.3; Fig. 2.4). Eight plots were established on Sangastai ridge, 15 km north of the Khonin nuga research station, and two plots at the Gatsuurt ridge, 20 km to the northeast of the Khonin nuga research station. The Sangastai sites are located at 49°09.965'N and 107°17.847'E, and Gatsuurt sites are located at 49°10.536'N and 107°21.713'E. All plots ranged from 1518 m elevation to 1584 m and from 90° to 360° aspect. Slopes were ranging from 6° to 11°. Hereafter, these sites referred to as a *Pinus sibirica*-*Abies sibirica* forest (in some cases it will be shortened as a *PiSi*-*AbSi* forest).



Figure 2.4: *Pinus sibirica*-*Abies sibirica* forest. Photo: B. Oyunsanaa

2.1.4.2. *Picea obovata*-*Abies sibirica* dark taiga forest

Picea obovata-*Abies sibirica* dark taiga forests without significant presence of *Pinus sibirica* cover northern slopes of the lower montane belt in the Khonin Nuga area (Fig. 2.5). This

type of forest occurs on upper-narrow valleys with humid conditions. Here, ground vegetation strongly differs from that of dark taiga forests in the upper montane belt with, e.g., *Ledum incarnata* and *Schisachne callosa* (Dulamsuren *et al.*, 2005a).



Figure 2.5: *Picea obovata*-*Abies sibirica* forest. Photo: B. Oyunsanaa

Sample plots in the *Picea obovata*-*Abies sibirica* forest were located at the Ataa (two plots) and Gangat valleys (eight plots), elevation ranged from 983 m to 1132 m a.s.l, 25-360° aspect, and 1-33° slope (Fig. 2.3; Fig. 2.6). These plots were markedly different from the *Pinus sibirica* dominated sites in both topographic characteristics and site series. These sites will be named *Picea obovata*-*Abies sibirica* forest (in some cases it will be shortened as a *PcOb*-*AbSi* forest) throughout the dissertation.

2.1.4.3. *Larix sibirica*-*Betula platyphylla* light taiga forest

Larix sibirica-*Betula platyphylla* forests are found at its most southern borderline in Mongolia and are distributed at northern slopes of the lower montane belt of the Khentey Mountains (Korotkov and Dorjsuren, 1988; Savin *et al.*, 1988; and Tsedendash, 1995). Five plots were selected on Mt. Dologyin Am, 3 km to the south-west of the Khonin nuga

research station, and another set of five plots were selected at Sangastai lower valley, 6 km to the northeast of the Khonin nuga research station (Fig. 2.3; Fig. 2.6).



Figure 2.6: *Larix sibirica*-*Betula platyphylla* forest. Photo: B. Oyunsanaa

The sites at the Mt. Dologyin Am are located at 49°04.906'N and 107°17.652'E, elevation ranged from 958 m to 1135 m. The Sangastai lower valley sites are located at 49°05.056'N and 107°16.060'E. The plots ranged from 1058 m elevation to 1180 m and from 110° to 340° aspect. Slopes were ranging from 18° to 28°. This forest type will be named *Larix sibirica*-*Betula platyphylla* forest (in some cases it will be shortened as a *LaSi-BePl* forest) throughout the dissertation.

2.1.4.4. *Pinus sylvestris*-*Larix sibirica* light taiga forest

These types of forests occur on moderately to deeply inclined southern and eastern dry slopes. Ground vegetation is characterized by the occurrence of e.g., *Iris ruthenica*, *Anemone crinita* and *Pyrola incarnata* (Dulamsuren *et al.* 2005). Sample plots in the *Pinus sylvestris*-*Larix sibirica* forest were located at the top of the hills of Khongi river valley (five plots);

elevation ranged from 1102 m to 1345 m a.s.l, 88-130° aspect, 25-34° slope while at the Shar tsaram ridge, five plots were selected (Fig. 2.3; Fig. 2.7), with an elevation ranging from 1151 m to 1200 m a.s.l, 90-315° aspect, 18-23° slope.



Figure 2.7: *Pinus sylvestris-Larix sibirica* forest. Photo: B. Oyunsanaa

These sites will be named *Pinus sylvestris-Larix sibirica* forest (in some cases it will be shortened as a *PiSy-LaSi* forest) throughout the dissertation.

CHAPTER 3: STRUCTURE AND DYNAMICS OF SOUTHERN TAIGA FORESTS OF WEST KHENTEY MOUNTAINS, MONGOLIA

3.1. Objectives

The objective was to study the structure, dynamic pattern of different type of forests and specifically, to examine present tree species composition, regeneration pattern, size distribution, radial growth pattern of trees, composition and structure of downed logs within different type of forests. The results of this study will improve our understanding of the structure, dynamics and succession of old-growth mixed forests in north-west Khentey Mountains, Mongolia.

3.2. Materials and methods

3.2.1. Field Methods

A forest stand is defined as an aggregation of trees occupying a specific area and sufficiently uniform in species composition, age, arrangement and condition, so that it is distinguishable from the adjacent forest areas. Stand structure in forestry is generally concerned with the different horizontal and vertical physical elements of the forest, such as basal area and volume, the diameter distribution, and the age of the stand. This quantitative information regarding a stand is related directly to silvicultural and management decisions (Aguirre *et al.*, 2003; Gadow *et al.*, 2003), as well as conservation activities.

In this study we tried to focus on the documentation of the current structure, and dynamic patterns of four different forest types. A total of 40 sample plots were established in the study area, 10 plots in each forest type. In each forest type, 40x40 m (0.16 ha) square plots were established and the number of living trees, tree species, diameter at breast height (DBH; measured at 1.3m) was recorded. A total of 5333 trees were measured. Within each plot, coordinates of the square corners, slope gradient and aspects were also recorded.

Tree species present in the study area included Siberian stone pine (*Pinus sibirica* Du Tour), Siberian fir (*Abies sibirica* L.), Siberian spruce (*Picea obovata* L.), Siberian larch (*Larix sibirica* L.), Scots pine (*Pinus sylvestris* L.), Asian white birch (*Betula platyphylla* Suk.), and European aspen (*Populus tremula* L.). The number of snags (standing dead trees) and its species (if distinguishable) within plots were recorded. In order to characterize under-story, circular

sub-plots were established within the square plots (10 m radius from the plot center=31.4 m²) and saplings species, number, height class (I = 50-150 cm, II = 151-250 cm, III = 251-350 cm, IV = >351 cm, and DBH < 5.0 cm) and condition (live, dying, and dead) were recorded.

Also, species of downed logs, diameter class (10 cm), and length and decay stage within these circular sub-plots were recorded, to document structural features, disturbance history, and decay dynamics.

For the radial growth and age structure analysis, the core samples were taken from trees (>10 cm, at the DBH 1.3 m) within different canopy layers, as well as from different tree species. Also, the disk samples were taken for both fire history (see Field methods in Chapter 5) and age structure analysis, the sampling height of disks ranged from 0.5 m to 1.3 m above ground. Site characteristic, amount of core and disk samples are shown in Table 5.1.

3.2.2. Data analysis

Diameter Distribution

Diameters and variation in diameters are often used for the first characterization of a stand. For a detailed stand analysis, it is necessary to have information on diameter structure. For many purposes in practice, however, the use of mean values is sufficient.

Arithmetic Mean Diameter (\bar{d})

Arithmetic mean diameter of a stand is calculated as

$$\bar{d} = \sum_{i=1}^N \frac{d_i}{N} \quad (2.1)$$

here, d_i is the diameter of the individual tree and N the total number of trees in the stand.

Besides the mean diameter itself, the standard deviation is a very meaningful value. It equals to the square root of the variance. Standard deviation is a measure of the homogeneity of the diameter distribution. The variance (δ_x^2) and standard deviation (δ_x) of a population are calculated using the following equations

$$\delta_x^2 = \sum_{i=1}^N \frac{(x_i - \mu)^2}{N} \quad (2.2)$$

$$\delta_x = \pm \sqrt{\delta_x^2} \quad (2.3)$$

To compare variance for values of different orders of magnitude, the coefficient of variation ($\delta_x \%$) is useful.

$$\delta_x \% = \frac{\delta_x}{\mu_x} * 100 \quad (2.4)$$

The absolute distribution of the number of stems per diameter class gives a good perception of the stand structure (Gadow *et al.*, 2003). These values, which can be calculated from the compiled basic data, are usually depicted in a graphical form.

Stand Density

The stand density expresses to which extent a given area is covered with trees. It is an indicator for the productivity of a stand and can be used to estimate the potential yield (Gadow *et al.*, 2003). Basal area and number of stems are the commonly used parameters for describing stand density.

Stand basal area

Basal area and number of stems are two parameters, which are commonly used to describe stand density. Stand basal area (G) is defined as the sum of the cross section of all trees of a stand, measured at 1.3 m height. It is usually expressed per hectare (Gadow, 2003):

$$G = \sum_{i=1}^N g_i \quad (2.6)$$

where

$$g_i = \frac{\pi}{4} * d_i^2 \quad (2.7)$$

and g_i is the basal area of a single tree.

Importance value

The importance value index (IV), which is the sum of the percentages of relative density, relative frequency and relative dominance, was calculated for each component species of the stands. The relative density (number of individuals of a species versus total number of individuals) and the relative frequency (frequency of the presence of a species in the quadrats compared to the sum of frequencies of all species) were determined from all 40x40 m quadrats. The relative dominance was computed from the total basal area at breast height relative to the sum of basal area of all species. Each fraction is expressed in a

percentage with a sum of 100 (Mueller-Dombois D and Ellenberg, 1974; Cottam and Curtus, 1956). Microsoft EXCEL and STATISTICA version 9.0 software (StatSoft, Inc., Tulsa, OK, USA, 1984-2009) were used for various statistical analyses.

Downed logs

Data from sample plots were pooled by each forest type for coarse wood debris (CWD) analysis. Species composition, size distribution (diameter), decay classes of logs were compared and presented by graphics. Decay of logs was recorded and classified on a 5-grade scale (adapted and modified from McCullough, 1948; Söderström, 1988a). The decay classes were defined as:

1. Log fall down recently, bark intact;
2. Some bark loss, more than 50% bark remaining, wood hard;
3. Less than 50% bark remaining, wood hard;
4. Wood slightly soft;
5. Wood soft, small pieces lost

3.2.3. Sample preparation, Crossdating and Chronology Construction

Increment cores were stored in plastic straws, dried and mounted on wooden core mounts (Stokes and Smiley, 1996). Cross-sections were stored and transported in paper boxes and dried in the laboratory. All cores and cross-sections were progressively sanded with a belt sander machine beginning with 40-grit and ending with 800-grit sanding belts, until individual cells were visible under magnification (Orvis and Grissino-Mayer, 2002).

Every tenth ring on all series was first dotted from the outermost complete ring to the innermost ring and marker rings were identified (Stokes and Smiley, 1996). The tree rings on all species increment cores were measured to the nearest 0.001 mm using a LINTAB measuring system (Rinntech, Heidelberg, Germany). All increment cores were then crossdated using skeleton plots and verified using COFECHA software (Holmes 1983; Grissino-Mayer, 2001a). COFECHA is a computer program used as a tool by dendrochronologists to gauge the quality of crossdating and measurement accuracy of and among tree-ring series (Grissino-Mayer, 2001a). Individual series were analyzed in COFECHA using 50-yr segments lagged successively by 32 yrs. Since we were focused on examining the

radial growth pattern of trees, only raw-measurements without any standartization were used for the chronology construction.

For the age structure analysis, increment cores missing the pith and the number of rings required to reach the pith was estimated geometrically (Duncan, 1989; Szeicz and Macdonald, 1995) and compared with pith dated samples.

The small diameter trees from 5 cm to 10 cm in diameter at breast height were not cored for age analysis. Instead we calculated the radial growth rate based on the cored trees by species. First, we averaged the growth of all trees by species and then calculated the time span to reach 10 cm of DBH. The number of trees which were counted within 5 cm to 10 cm range was grouped in five year age classes.

3.3. Results

3.3.1. Tree composition

The importance value (IV) can be used to demonstrate changes in vegetation dynamics through succession. The *Pinus sibirica-Abies sibirica* forest comprised of six tree species and was dominated by *Abies sibirica*, which had the highest percentages for density and relative frequency, thus resulting in the highest importance value (IV) of 41.1 (Tab. 3.1). The second most abundant tree species was *Pinus sibirica* which had an IV of 33.4, confirming that the stands largely consisted of *Pinus sibirica* and *Abies sibirica* trees. *Pinus sibirica* showed less importance value than *Abies sibirica*; however, *Pinus sibirica* had the highest basal area and relative dominance. Of lesser importance were *Picea obovata*, *Larix sibirica*, *Betula platyphylla* and *Salix spp.* The total density and basal area in this forest are 924 stems/ha and 47.22 m²/ha, respectively.

The *Picea obovata-Abies sibirica* forest consisted of six tree species within the canopy diversity (Tab. 3.2). Because of the high relative density, *Abies sibirica* dominated the canopy resulting in the slightly higher importance value (28.30) than *Picea obovata*. *Picea obovata* was the second most dominant tree species with an IV of 26.49. *Picea obovata-Abies sibirica* forest had two other tree species that could be considered as codominants: *Betula platyphylla* (IV = 19.46) and *Pinus sibirica* (IV = 15.00). Other tree species were *Larix sibirica* and *Salix spp.* which showed lesser IV. The total density and basal area were 1078 stems/ha and 26.55 m²/ha, respectively.

Table 3.1: Stand composition of trees > 5 cm dbh at *Pinus sibirica*-*Abies sibirica* forest

Tree species	Species frequency	Species density (stems/ha)	Basal area (m ² /ha)	Relative frequency (%)	Relative density (%)	Relative dominance (%)	Importance value (%)
<i>Abies sibirica</i>	1.0	591	15.88	25.64	63.90	33.63	41.1
<i>Pinus sibirica</i>	1.0	215	24.16	25.64	23.26	51.16	33.4
<i>Picea obovata</i>	0.9	96	3.93	23.08	10.41	8.32	13.9
<i>Larix sibirica</i>	0.7	18	3.2	17.95	1.89	6.78	8.9
<i>Betula platyphylla</i>	0.2	4	0.04	5.13	0.47	0.08	1.9
<i>Salix spp.</i>	0.1	1	0.01	2.56	0.07	0.02	0.9
Totals	3.9	924	47.22	100	100	100	100

The *Larix sibirica* dominated forests had five tree species in the composition. *Larix sibirica* dominated the canopy with the highest frequency, density, and basal area, resulting in an IV of 53.27. *Betula platyphylla* was the second most important tree species with an IV of 33.70. Other tree species found in the canopy included *Pinus sylvestris*, *Pinus sibirica*, *Abies sibirica*, and *Populus tremula*. The total density and basal area were 517 stems/ha and 28.50 m²/ha, respectively (Tab. 3.3).

Table 3.2: Stand composition of trees > 5 cm dbh at *Picea obovata*-*Abies sibirica* forest

Tree species	Species Frequency	Species Density (stems/ha)	Basal area (m ² /ha)	Relative Frequency (%)	Relative Density (%)	Relative (%)	Importance Value (%)
<i>Abies sibirica</i>	1.0	428	6.47	20.83	39.71	24.37	28.30
<i>Picea obovata</i>	0.9	333	7.93	18.75	30.84	29.87	26.49
<i>Betula platyphylla</i>	0.9	233	4.8	18.75	21.57	18.08	19.46
<i>Pinus sibirica</i>	1.0	64	4.85	20.83	5.91	18.27	15.00
<i>Larix sibirica</i>	0.9	18	2.43	18.75	1.68	9.15	9.86
<i>Salix spp.</i>	0.1	3	0.07	2.08	0.29	0.26	0.88
Totals	4.8	1078	26.55	100	100	100	100

Table 3.3: Stand composition of trees > 5 cm dbh at *Larix sibirica*-*Betula platyphylla* forest

Tree species	Species frequency	Species density (stems/ha)	Basal area (m ² /ha)	Relative frequency (%)	Relative density (%)	Relative dominance (%)	Importance value (%)
<i>Larix sibirica</i>	1.0	281	20.56	33.33	54.33	72.14	53.27
<i>Betula platyphylla</i>	1.0	218	7.33	33.33	42.05	25.72	33.70
<i>Pinus sylvestris</i>	0.3	4	0.42	10.00	0.72	1.47	4.07
<i>Pinus sibirica</i>	0.5	14	0.15	16.67	2.66	0.53	6.62
<i>Abies sibirica</i>	0.1	1	0.009	3.33	0.12	0.03	1.16
<i>Populus tremula</i>	0.1	1	0.03	3.33	0.12	0.11	1.19
Totals	3.0	517	28.50	100	100	100	100

The current stand composition of tree species in *Pinus sylvestris* forest was the same as that found in the *Larix sibirica* dominated sites. Five species formed the canopy; dominant species was *Pinus sylvestris*, which had the highest percentages for density, relative dominance, and basal area thus resulting in the highest importance value (IV) of 53.72 (Tab. 3.4). *Betula platyphylla* and *Larix sibirica* had the same relative frequency (31.25%) as the dominant species *Pinus sylvestris*.

Table 3.4: Stand composition of trees > 5 cm dbh at *Pinus sylvestris*-*Larix sibirica* forest

Tree species	Species frequency	Species density (stems/ha)	Basal area (m ² /ha)	Relative frequency (%)	Relative density (%)	Relative dominance (%)	Importance value (%)
<i>Pinus sylvestris</i>	1.0	422	23.15	31.25	51.96	77.96	53.72
<i>Betula platyphylla</i>	1.0	259	2.99	31.25	31.95	10.07	24.42
<i>Larix sibirica</i>	1.0	126	3.47	31.25	15.55	11.69	19.50
<i>Pinus sibirica</i>	0.1	4	0.005	3.13	0.46	0.02	1.20
<i>Populus tremula</i>	0.1	1	0.08	3.13	0.08	0.27	1.16
Totals	3.2	812	29.70	100	100	100	100

Betula platyphylla had IV of 24.42 and was followed by *Larix sibirica*, which showed IV of 19.50. Other tree species included *Pinus sibirica* and *Populus tremula*. The total density and basal area were 812 stems/ha and 29.70 m²/ha, respectively (Tab. 3.4).

3.3.2. Sapling composition

Total densities of different sapling species in *Pinus sibirica*-*Abies sibirica* forest ranged from 63.7 to 4933.8 stems/ha, with a mean of 2482.8 stems/ha (Fig. 3.1a). *A. sibirica* and *P. sibirica* saplings made up the highest percentages at 49.7% and 43.9%, respectively. Other sapling species that were represented included *P. obovata* (5.8%) and *B. platyphylla* (0.6%).

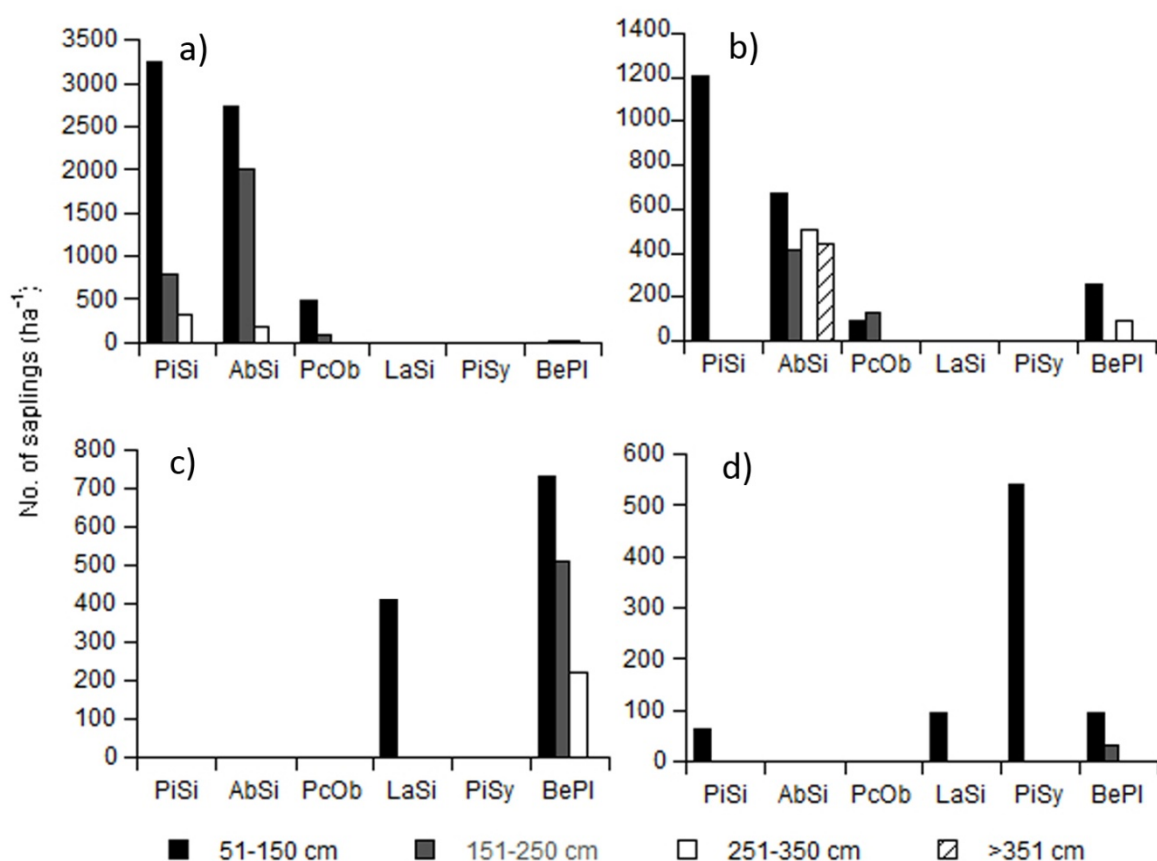


Figure 3.1: Species composition and height class distribution of saplings from 40 sub-plots (each 10 m radius, 31.4 m²) in the four types of forest; a) *PiSi*-*AbSi* forest, b) *PcOb*-*AbSi* forest, c) *LaSi*-*BePI* forest, d) *PiSy*-*LaSi* forest. Sapling species are indicated in the x-axis; siberian stone pine (*PiSi*), siberian fir (*AbSi*), siberian spruce (*PcOb*), siberian larch (*LaSi*), scots pine (*PiSy*), and asian white birch (*BePI*). The height classes of saplings are indicated below the graphs. Note that values on the y-axis are not same on each graph.

The sapling number in the height classes showed that from small height class to higher class,

the saplings abundance was rapidly decreasing. All sapling species in the height class of 51-150 cm comprised of a total of 65.1%, whereas the height class of 151-250 cm was represented by 29.5% and height class of 251-350 cm were represented by 5.4% (Fig. 3.1a, App. 21a, b).

The densities of different sapling species in *Picea obovata-Abies sibirica* forest ranged from 222.8 to 2037.2 stems/ha, with a mean of 954.9 stems/ha (Fig. 3.1b). *A. sibirica* saplings made up the highest percentage (53.3%) of total saplings and were followed by *P. sibirica* saplings (31.7%). Other sapling species included *B. platyphylla* (9.2%) and *P. obovata* (5.8%). The sapling abundance within the height classes was varied. *P. sibirica* saplings were abundant only in the height class of 50-150 cm. *A. sibirica* saplings were present in all height classes (Fig. 3.1b, App. 22a, b).

The sapling composition in *Larix sibirica-Betula platyphylla* forest included only *L. sibirica* and *B. platyphylla* (Fig. 3.1c). While the *L. sibirica* trees made up 54.3% of canopy stems (Tab. 3.3), they occurred in the sapling stratum to a lesser extent (423 saplings/ha or 22.4% of all saplings) than *B. platyphylla*. Total density of *B. platyphylla* saplings was 1464.2 stems/ha (77.6% of all saplings). The sapling distributions of *B. platyphylla* in the height classes of 51-150 cm, 151-250 cm and 251-350 cm were 38.8%, 27.0% and 11.8%, respectively, while the saplings of *L. sibirica* occurred in height class of 51-150 cm (App. 23a, b).

Total densities of different sapling species in *Pinus sylvestris-Larix sibirica* forest ranged from 63.7 to 127.3 stems/ha, with a mean of 206.9 stems/ha (Fig. 3.1d, App. 24a, b). Amongst these saplings, over 65 % of individuals were represented by *P. sylvestris*. The saplings of *B. platyphylla* and *L. sibirica* comprised 15.4% and 11.5%, respectively. Interestingly, we found some saplings of *P. sibirica* (7.7%).

Overall, sapling abundances in the *PiSi-AbSi* and *PcOb-AbSi* forests were much higher in contrast to sapling numbers in *LaSi-BePl* and *PiSy-LaSi* forest.

3.3.3. Diameter structure

The diameter-class structure of *Pinus sibirica-Abies sibirica* forest showed a reverse-J shape distribution (Fig. 3.2). Species were grouped and standardized at the hectare level to reveal patterns of diameter distribution. *Pinus sibirica* occurred in all diameter classes and dominated the middle and larger diameter classes from 35 to 95 cm.

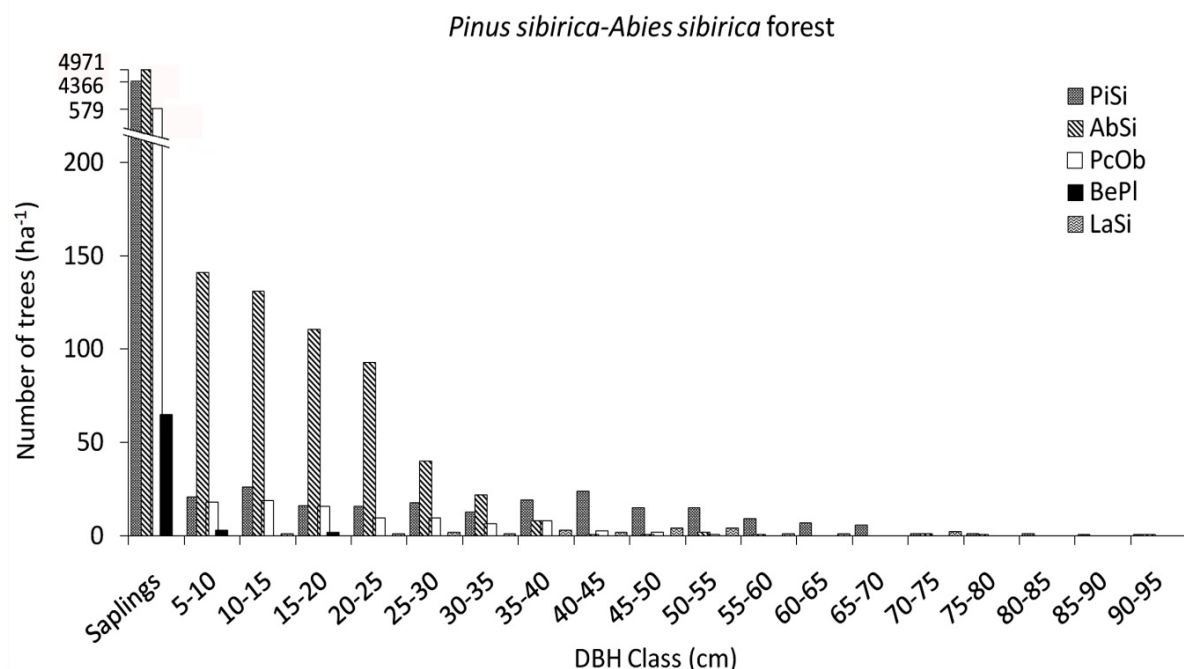


Figure 3.2: Diameter (at 1.3 m above ground) distribution of saplings (dbh <5cm) and tree species of the *Pinus sibirica*-*Abies sibirica* forest. Data has been compiled from 10 plots. Note that the y-axis is interrupted.

Abies sibirica was dominant in the relatively small to middle diameter classes from 5 to 35 cm and only some individuals of *A. sibirica* trees were sparsely represented in the larger diameter classes. *Picea obovata* was represented in the small to middle diameter classes and its maximum diameter was 50 cm; however the number of *P. obovata* was less compared to *Pinus sibirica* and *Abies sibirica* trees. In contrast, few *Betula platyphylla* were present in the smaller diameter classes less than 10 cm, and few *Larix sibirica* occurred in the diameter classes of 10 to 75 cm. Overall mean, maximum and minimum diameter values of different tree species in this forest are shown in Appendix 17.

The diameter distributions of trees in the *Picea obovata*-*Abies sibirica* forest displayed a reverse-J shape, characteristic to the multi-aged forests (Fig. 3.3). *Picea obovata* trees mostly occurred in small to middle diameter classes and the maximum diameter of *P. obovata* was 70.5 cm. *Abies sibirica* was dominant in the relatively small to middle diameter classes from 5 to 35 cm and few *A. sibirica* occurred in the diameter class of 55 cm. *Betula platyphylla* was present mostly in the small to middle diameter classes and its maximum diameter was 45 cm. In contrast, *Pinus sibirica* occurred in all diameter classes; it especially, showed a very high number of occurrence in the diameter class of 5 cm. The maximum diameter of *P. sibirica* was 65 cm in this forest. *Larix sibirica* was represented in all diameter classes with

the maximum diameter class of 80 cm. Overall mean, maximum, and minimum diameter values of different tree species in this forest are shown in Appendix 18.

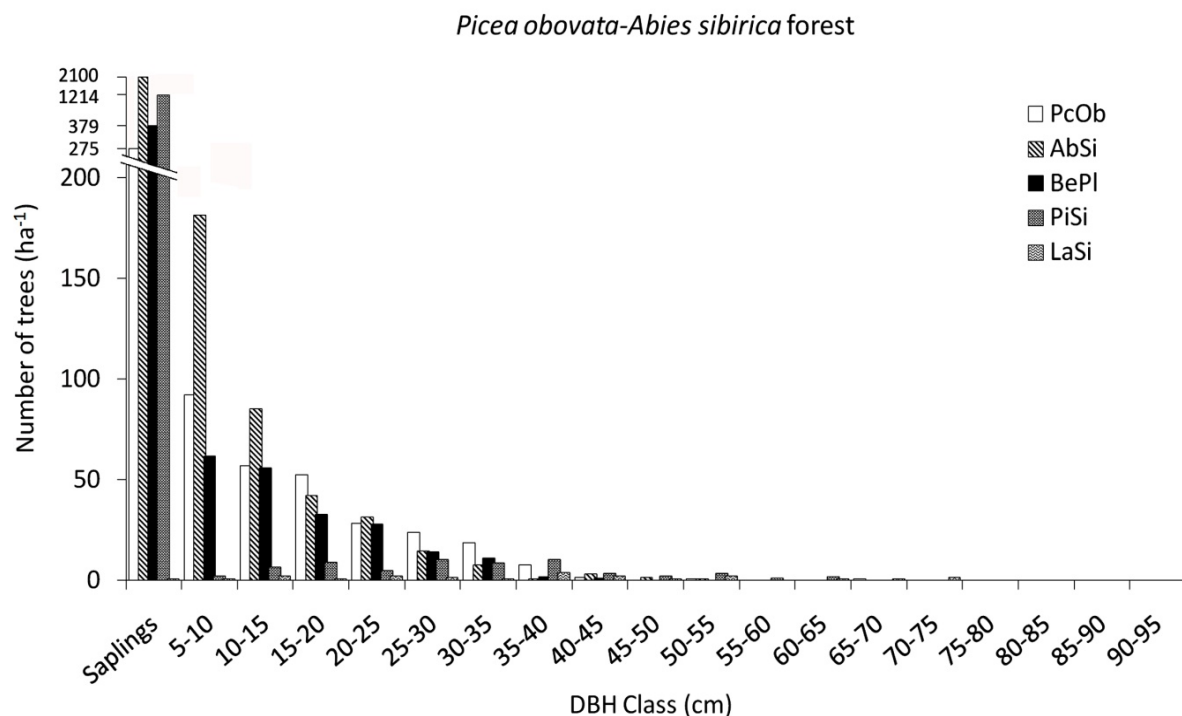


Figure 3.3: Diameter (at 1.3 m above ground) distribution of saplings (dbh <5cm) and tree species of the *Picea obovata*-*Abies sibirica* forest. Data has been compiled from 10 plots. Note that the y-axis is interrupted.

The diameter-class structure of *Larix sibirica*-*Betula platyphylla* forest showed an irregular distribution (Fig. 3.4). *Larix sibirica* occurred in all diameter classes and dominated the middle and larger diameter classes from 30 to 65 cm. The maximum diameter class in which *Larix sibirica* occurred was 80 cm. *Betula platyphylla* mostly occurred in the smaller and middle diameter classes from 5 to 35 cm. A few individuals of *B. platyphylla* were present in the diameter classes of 40 and 60 cm. In contrast, *Pinus sylvestris* was represented sparsely; however, it was present in the diameter classes from 15 to 65 cm whereas *Pinus sibirica* was represented only in the smaller diameter classes less than 20 cm. Overall mean, maximum, and minimum diameter values of different tree species in this forest are shown in Appendix 19.

The diameter-class structure of *Pinus sylvestris*-*Larix sibirica* forest showed a bimodal distribution (Fig. 3.5). *Pinus sylvestris* was dominant in most diameter classes, except 5 to 10 cm class. The maximum diameter class in which *Pinus sylvestris* occurred was 95 cm class.

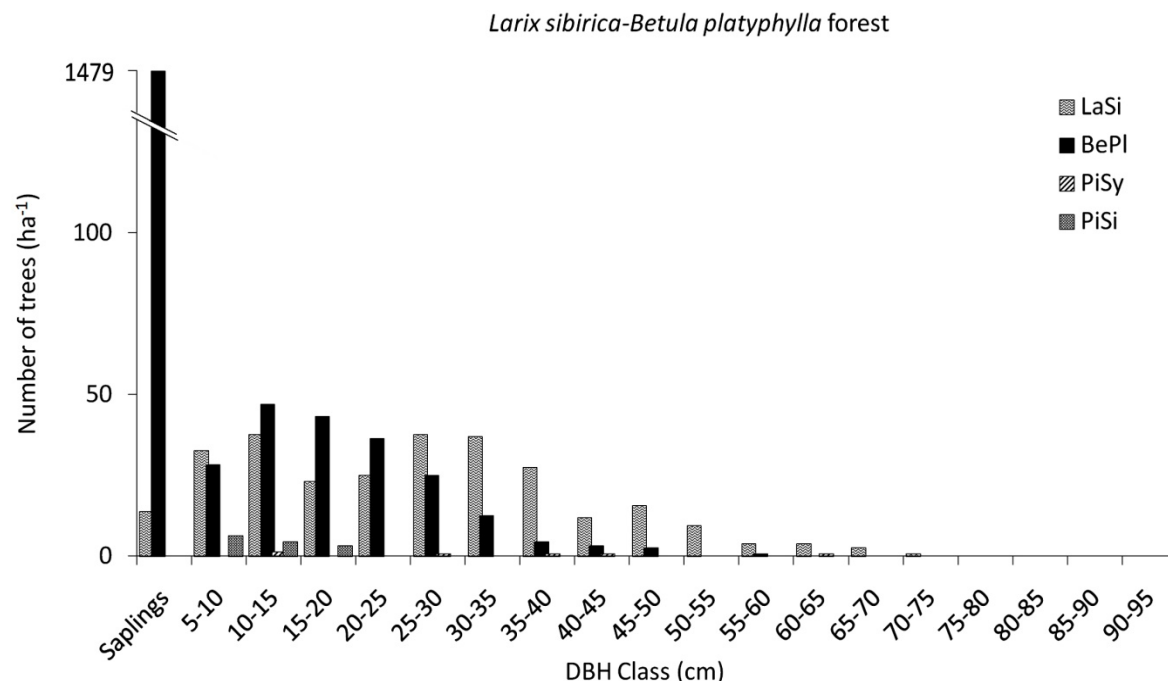


Figure 3.4: Diameter (at 1.3 m above ground) distribution of saplings (dbh <5cm) and tree species of the *Larix sibirica*-*Betula platyphylla* forest. Data has been compiled from 10 plots. Note that the y-axis is interrupted.

Larix sibirica occurred in the smaller and middle diameter classes from 5 to 35 cm. A few individuals of *Larix sibirica* were present in the 60 cm diameter class. *Betula platyphylla* was

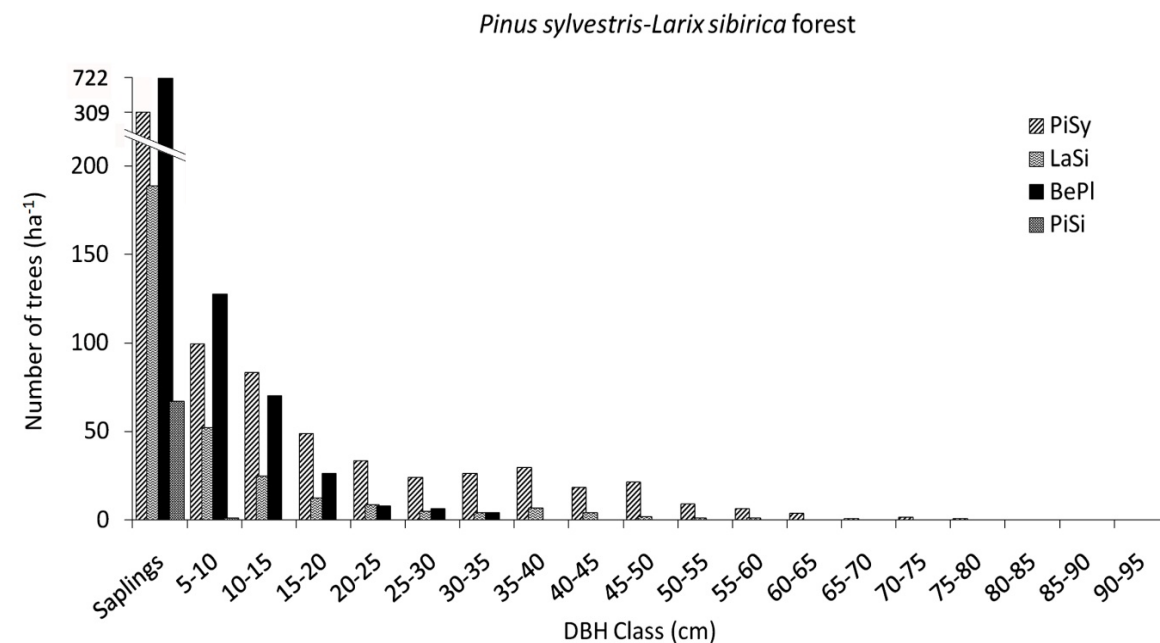


Figure 3.5: Diameter (at 1.3 m above ground) distribution of saplings (dbh <5cm) and tree species of the *Pinus sylvestris*-*Larix sibirica* forest. Data has been compiled from 10 plots. Note that the y-axis is interrupted.

dominant in the small diameter class from 5 to 10 cm and the maximum diameter class of *B. platyphylla* was 35 cm. *Pinus sibirica* was represented only in the small diameter classes less than 10 cm. Overall mean, maximum, and minimum diameter values of different tree species in this forest are shown in Appendix 20.

3.3.4. Tree recruitment and age structure

3.3.4.1. Tree recruitment in *Pinus sibirica* - *Abies sibirica* forest

The age structure or recruitment patterns of *Pinus sibirica*-*Abies sibirica* forest tree populations ordered from canopy to sub-canopy are shown in Figure 3.6. The *Pinus sibirica* trees revealed a broader and older age distribution (Fig. 3.6). *P. sibirica* forest had few older individuals, with the oldest being 370 years old. Since 1640s few trees were sparsely recruited and a majority of *Pinus sibirica* trees were recruited from the 1820s to 1890s with peak number in the mid of 1850s. Since this period, the sparse and small amount of recruitment continued until the 1990s. However since 1990s significant regeneration has occurred. In order to show the regeneration pattern, the saplings numbers were indicated in the height classes. It can be seen that the cohort of newly established *P. sibirica* saplings had a high mortality rate; sapling number in the I height class was 4934 saplings/ha and the amount of saplings from this smallest height class to higher height classes rapidly decreased (namely, from class-I to the class-II - 78%, from class-II to III - 86.9%, and from class-III to IV - 13%).

The *Abies sibirica* tree is a sub-canopy tree species in this forest. The oldest *A. sibirica* was 306 years old. Between 1710s and 1800s, there was no recruitment of *A. sibirica*, while some individuals were established from 1805 to 1830s. A major group of *A. sibirica* trees were established from the 1860s to 1935s. However the number of *A. sibirica* within this period was much lower than canopy species of *P. sibirica* trees.

Maximum age of *Picea obovata* in this forest was 158 years. Overall, recruitment of *P. obovata* trees was sparse (Fig. 3.6).

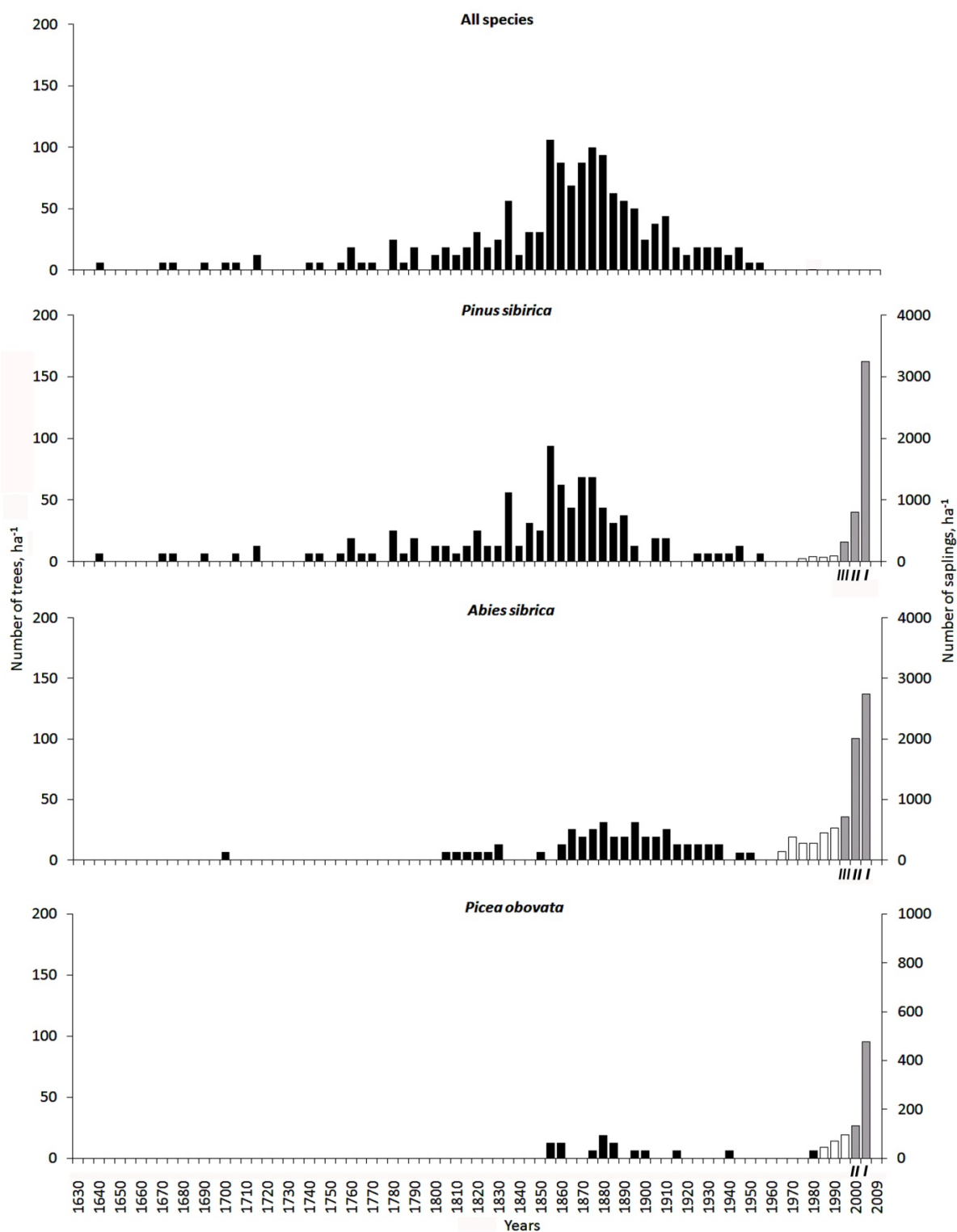


Figure 3.6: Tree recruitment (5-year age class) of *Pinus sibirica* dominated forest: the most above graph shows all species pooled together. The black bars indicate number of mature trees in the class. Open bars show the ages of young trees between 5-10 cm dbh class (detail. see method), while sapling numbers corresponding height classes (Roman numbers) are indicated in grey bars. *Note:* Saplings are only in height classes and the age of saplings was not determined.

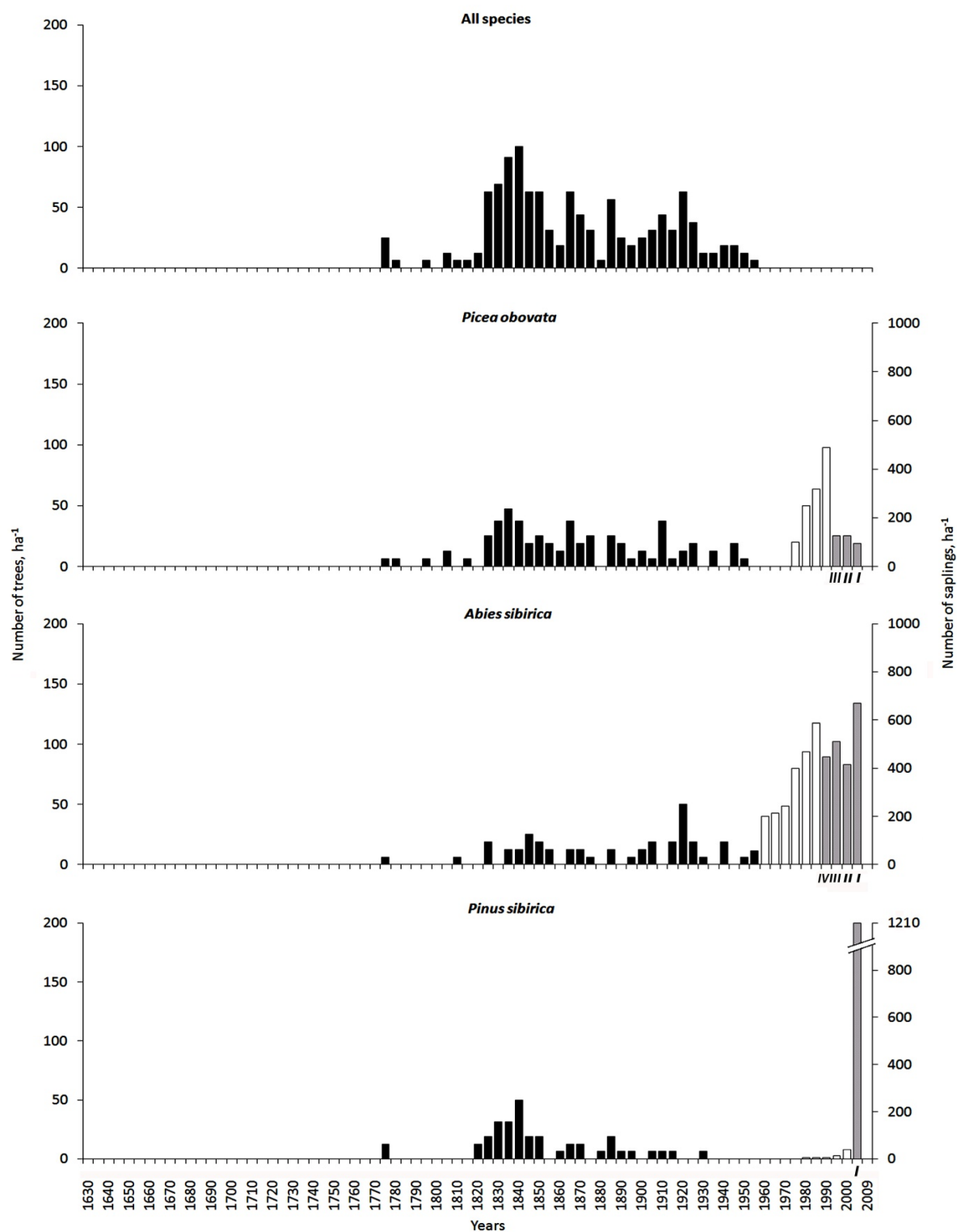


Figure 3.7: Tree recruitment (5-year age class) of *Picea obovata* dominated forest: the most above graph shows all species pooled together. The black bars indicate number of mature trees in the class. Open bars show the ages of young trees between 5-10 cm dbh class (detail. see method), while sapling numbers corresponding height classes (Roman numbers) are indicated in grey bars. *Note:* Saplings are only in height classes and the age of saplings was not determined.

3.3.4.2. Tree recruitment in *Picea obovata* - *Abies sibirica* forest

A few *Picea obovata* trees were established from 1730s to 1820s and the majority of trees were recruited between 1820s and 1860s, continued with some sparse recruitment until the 1950s (Fig. 3.7). The oldest *P. obovata* found in this forest was 277 years old. Between mid 1950s and 1970s, there was no tree establishment, however, two pulses of regeneration occurred during 1975 and 2009.

The *Abies sibirica* trees form the sub-canopy in this forest and the oldest *A. sibirica* was 234 years. The establishment patterns of *Abies sibirica* in this forest was different compared to *P. obovata*, especially in respect of the pulse peaks from 1950s to 1980s. Between 1770s and 1800s, there was no recruitment of *A. sibirica*, while low number of trees was established in the 1805 to 1850s and with the peak in 1915. In general, the number of *A. sibirica* within this period was much lower than of *P. obovata*. *A. sibirica* had a continuous establishment during 1955 and 1970s, while both *P. obovata* and *P. sibirica* trees were absent. *A. sibirica* saplings were the most abundant compared to other sapling species.

Maximum age of *Pinus sibirica* in this forest was 181 years. A majority of *P. sibirica* trees were established from 1820s to 1850s, which is a similar pattern when compared to *P. obovata*. The first few individuals of *P. sibirica* trees were established in the period of 1770s, and no establishment occurred until the 1820s. The biggest cohort of *P. sibirica* originates from the period between 1820s and 1850s, only sparse recruitment occurred between 1850s and 1930s. After 1930s and until the 1970s, no trees were established. Few *P. sibirica* trees were recruited between 1980 and 1995. Number of *P. sibirica* saplings was only in the height class-I (Fig. 3.7).

3.3.4.3. Tree recruitment in *Larix sibirica* - *Betula platyphylla* forest

Larix sibirica was the dominant tree species in this forest. The age structure of the *L. sibirica* populations seemed to indicate a wave-like regeneration pattern (Fig. 3.8). The oldest *L. sibirica* tree had attained 249 years of age. Few *L. sibirica* trees were established in the 1760s, 1785 and 1810s. Continuous and wave-like recruitment pattern occurred from 1820s to 1950s with the peak number in 1895. After a decade without regeneration, there were a small number of trees recruited in the period between 1965 and 1980. Next peak of *L. sibirica* tree recruitment occurred after the 1990s. Saplings only occurred in the height

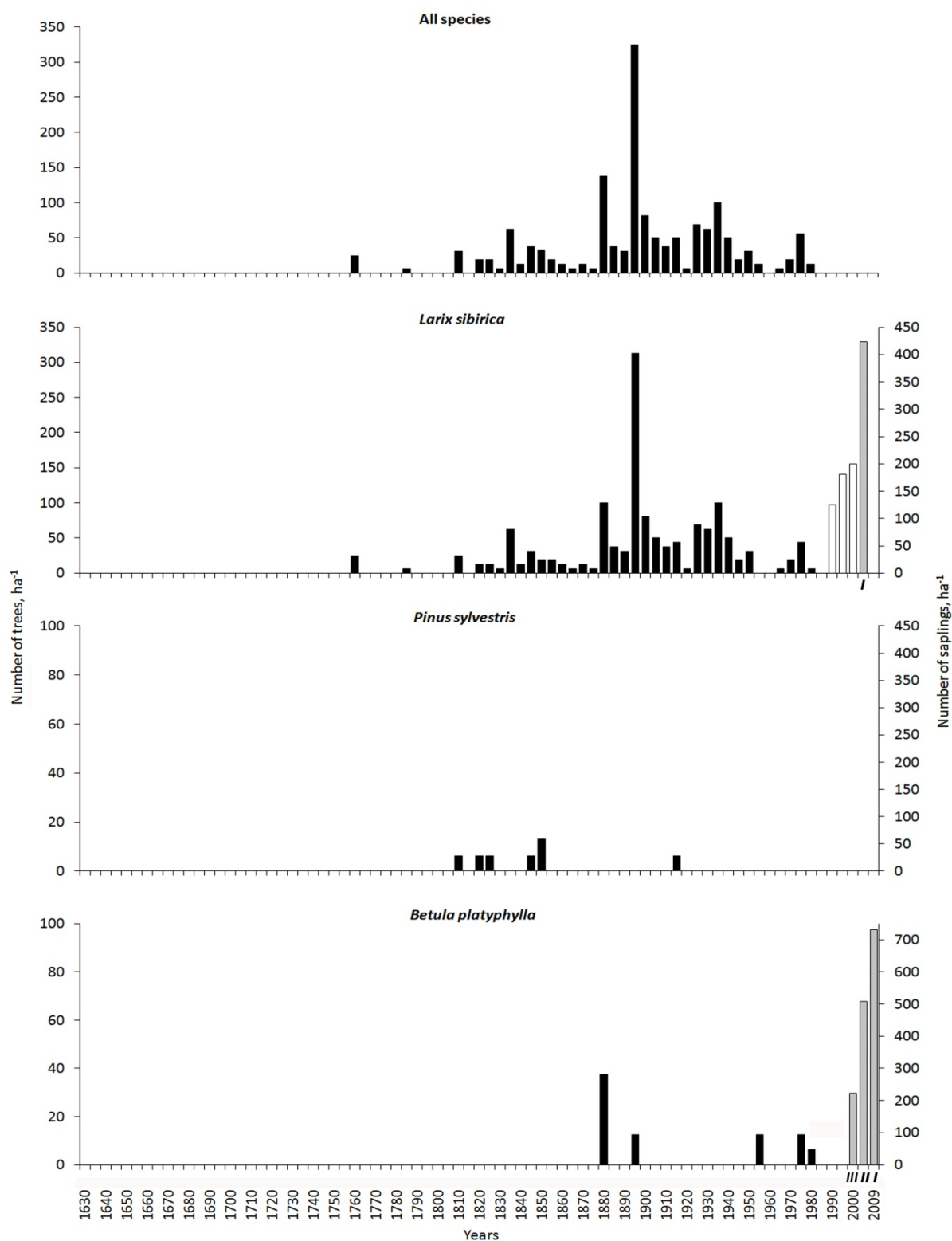


Figure 3.8: Tree recruitment (5-year age class) of *Larix sibirica* dominated forest: the most above graph shows all species pooled together. The black bars indicate number of mature trees in the class. Open bars show the ages of young trees between 5-10 cm dbh class (detail. see method), while sapling numbers corresponding height classes (Roman numbers) are indicated in grey bars. *Note:* Saplings are only in height classes and the age of saplings was not determined.

class-I (50-150 cm). *Pinus sylvestris* trees occur very seldom in this type of forest. A sparse recruitment of *P. sylvestris* trees occurred from the 1810s to 1850s and a very small fraction after the 1850s.

The oldest age of *Betula platyphylla* trees was 124 years. A majority of *B. platyphylla* trees were established in the 1880s, and only few trees were recruited in 1895, 1955, 1975, and 1980s. *B. platyphylla* saplings were abundant in the height classes I to III (Fig. 3.8).

3.3.4.4. Tree recruitment in *Pinus sylvestris* - *Larix sibirica* forest

Tree recruitment pattern of *Pinus sylvestris* - *Larix sibirica* forest is shown in Figure 3.9. Few *P. sylvestris* trees were established between 1740s and 1760s. There was no recruitment of *P. sylvestris* trees between 1760s and 1790s, while less number of trees was established from the 1790s to 1840s. Two major pulses of *P. sylvestris* tree recruitment occurred from 1840s to 1850s and from 1870s to 1890s, with the highest peak in 1880s. After 1890s, trees were sparsely recruited until the 1960s. The oldest *P. sylvestris* found in this forest was 270 years old. Between the mid of 1960s and the late 1980s, there was no tree establishment, however another high peak of tree recruitment occurred in the late 1990s, followed by high number of saplings establishments.

The *Larix sibirica* trees formed the sub-canopy in this forest and the oldest *L. sibirica* was 198 years. The establishment pattern of *Larix sibirica* in this forest was different compared to the *P. sylvestris*, except similar peaks of recruitment in the 1880s. However, overall abundance of *L. sibirica* trees in this forest was lower than *P. sylvestris*. A sparse recruitment of *L. sibirica* trees occurred in the period of 1810s and the late 1850s. There was a long period without a recruitment of *L. sibirica* trees between the 1920s and 1980s. After this period, the *L. sibirica* trees were recruited from 1980s to 2000s, followed by relatively small number of saplings (Fig. 3.9).

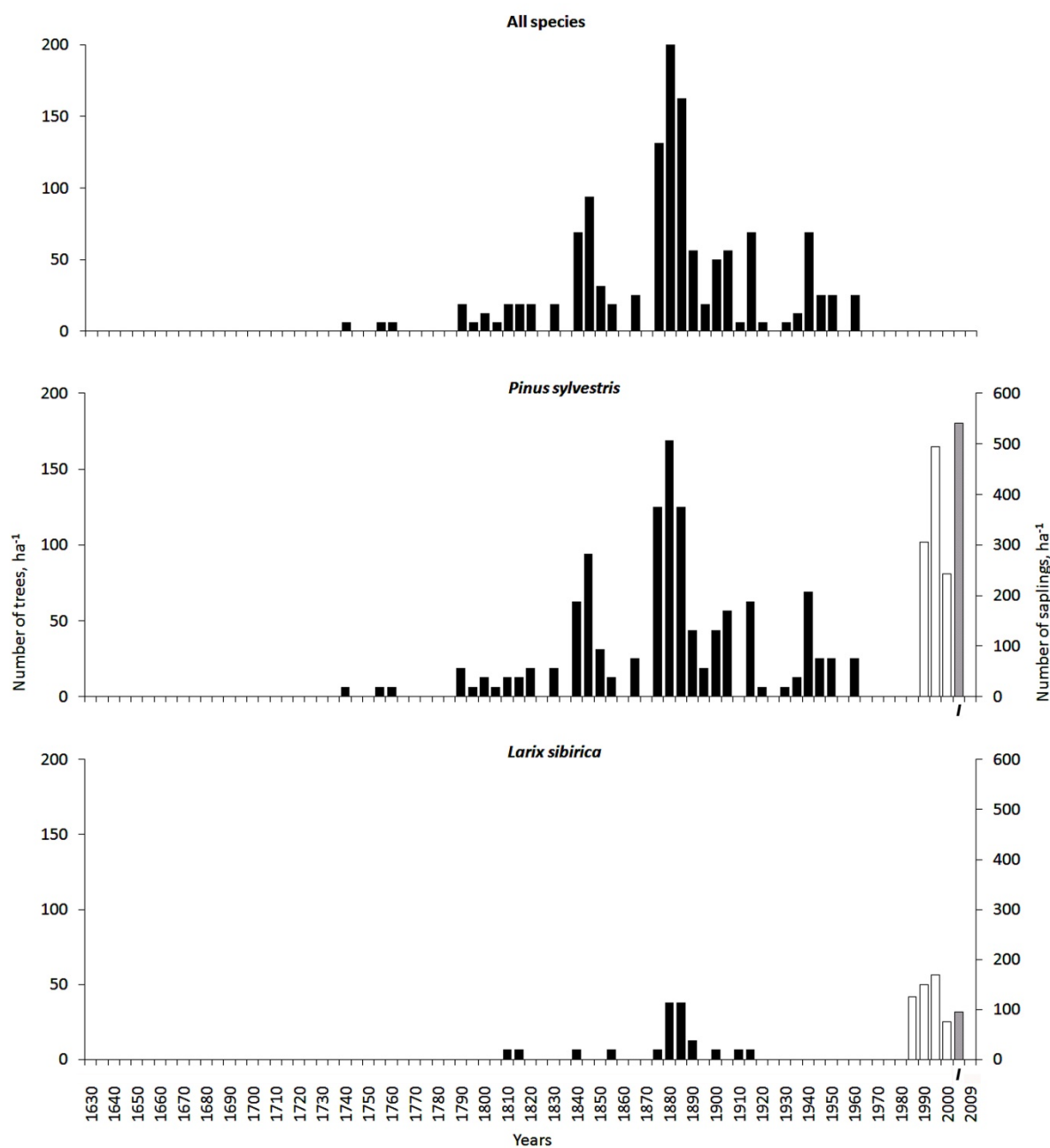


Figure 3.9: Tree recruitment (5-year age class) of *Pinus sylvestris* dominated forest: the most above graph shows all species pooled together. The black bars indicate number of mature trees in the class. Open bars show the ages of young trees between 5-10 cm dbh class (detail. see method), while sapling numbers corresponding height classes (Roman numerals) are indicated in grey bars. *Note:* Saplings are only in height classes and the age of saplings was not determined.

3.3.5. Radial growth patterns of tree species in different forest types

3.3.5.1. Tree-growth of *Pinus sibirica*-*Abies sibirica* forest

To examine the radial growth patterns of differently aged trees, the raw tree-ring

chronologies were classified as (1) the oldest: >200 years, (2) middle aged: >100<200, and (3) younger: <100 years (Fig. 3.10a, b and c). The classification was carried out based on the age distribution of trees. Mean growths for oldest *Pinus sibirica*, middle aged and younger trees were 0.99 mm, 1.46 mm and 1.73 mm, respectively (Tab. 3.5). In 1722, the oldest *P. sibirica* trees experienced the lowest growth. As the majority of middle aged *P. sibirica* (>100<200 years) were established in the beginning of the 18th century, mean growth of the oldest group was gradually decreasing, whereas the growth of middle aged trees was increasing until the 1850s (Fig. 3.10a, b). In the last 60 years, the mean radial-growth of both groups decreased. The younger tree group consisted of few individuals, which were possibly established in the gap. The mean growth of this group increased until the 1980s and has decreased in the last 30 years (Fig. 3.10c).

Tree-ring chronologies of *Abies sibirica*, which are growing at the sub-canopy in *Pinus sibirica* forests, are shown in Figure 3.10 (d) and (e). A single *Abies sibirica* reached 306 years of age, which is not included for the growth analysis. A majority of the *A. sibirica* was in the age group of >100<200 years, which were established since the 1820s. This group of trees showed similar patterns in radial-growth within the same age group of *P. sibirica*, while growth of younger *A. sibirica* increased (Fig. 3.10e) in the first 40 years and decreased since the 1950s. Mean radial growth of middle aged *A. sibirica* was 0.88 mm and younger trees had 1.37 mm (Tab. 3.5).

Overall, mean growths of both *P. sibirica* and *A. sibirica* species decreased in the last 60 years; even younger trees exhibited similar growth decrease within this period.

3.3.5.2. Tree-growth of *Picea obovata*-*Abies sibirica* forest

Mean growth of *Picea obovata* for the oldest, middle aged and younger trees were 0.54 mm (range 0.11 - 1.95 mm), 0.75 mm and 1.53 mm, respectively (Tab. 3.5). The oldest group (>200 yrs) of *Picea obovata* trees had relatively low mean-growth between the 1800 and 1890s. The mean radial growth of trees gradually increased from 1890 to 1940s and rapidly decreased until the beginning of the 1970s. Over the last 30 years, the mean growth of *P. obovata* trees slightly increased (Fig. 3.11a). The majority of the *Picea obovata* trees fall into the middle aged group (>100<200 yrs). In general, mean growth of trees in this group

decreased over time, except for a considerable increase in the 1870s (Fig. 3.11b). The

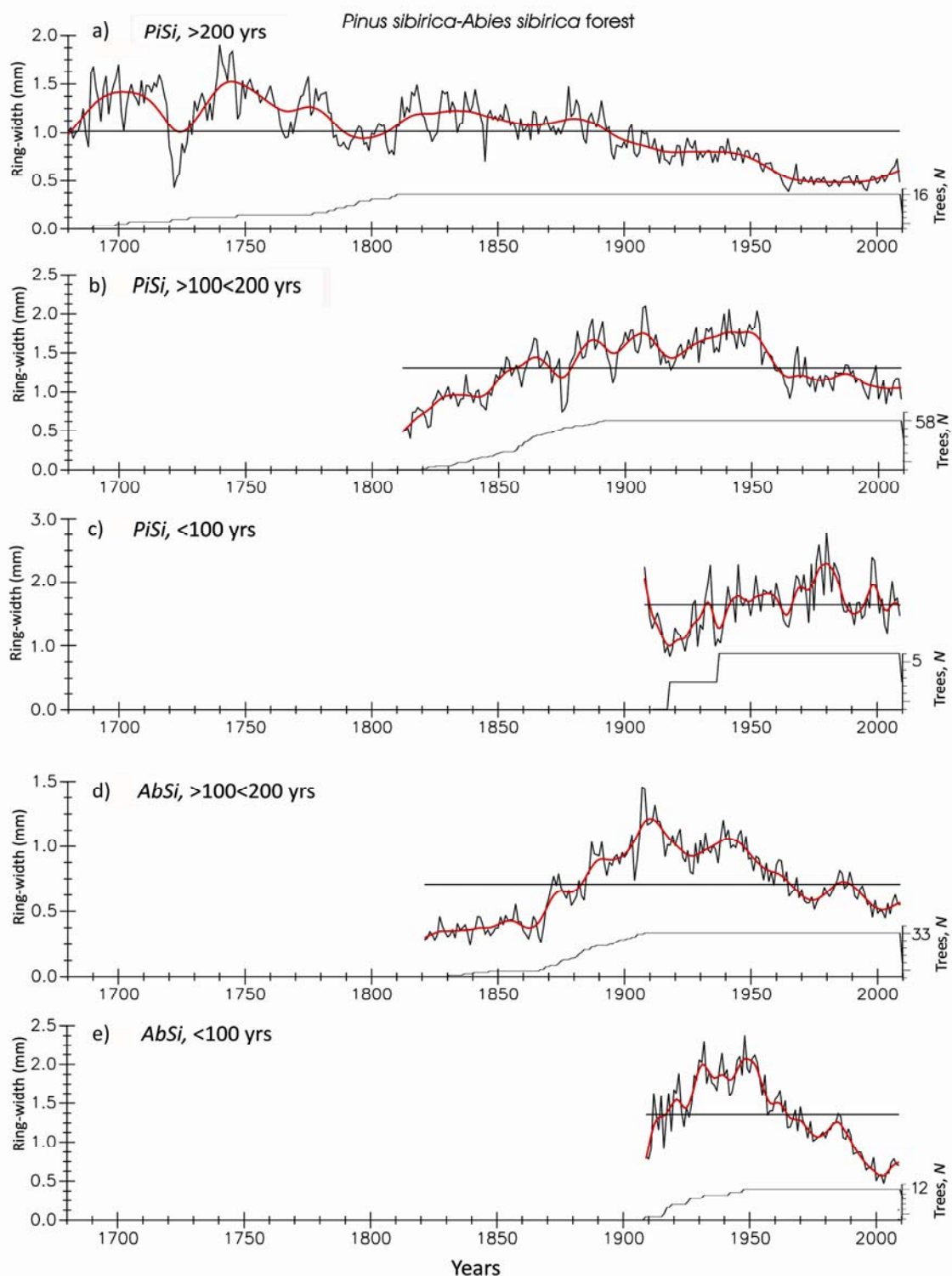


Figure 3.10: Tree-ring chronologies of *Pinus sibirica* and *Abies sibirica*: a) *Pinus sibirica*- more than 200 years old; b) *P. sibirica*-100 to 200 years old; c) *P. sibirica*-less than 100 years old; d) *Abies sibirica*-100 to 200 years old; e) *A.sibirica*-less than 100 years old. Y-axis indicates tree ring-width with moving average in red. Y2-axis shows number of samples and the reference line indicates the mean tree-ring width over the dataset.

younger age group of *P. obovata* trees showed different growth patterns than the other two groups. Mean growth of trees increased until the mid 1940s and showed sharp decrease in 1950. In the mid 1950s the mean growth was the highest and decreased until the beginning of the 1970s. After ten years of growth release since the 1970s, mean growth of trees in this group rapidly decreased until present (Fig. 3.11c).

Table 3.5: Tree-ring chronology statistics of four forest types

Forest type	Tree species and Age group	No. of samples	First	Last	Length (years)	Radial growth (mm)			SD
						mean	max	min	
<i>PiSi-AbSi</i>	<i>Pinus sibirica</i> ; >200 yrs	16	1680	2009	320	0.99	1.35	0.73	0.58
	>100<200 yrs	58	1812	2009	198	1.46	2.21	0.84	0.60
	<100 yrs	5	1910	2009	100	1.73	1.81	1.68	0.57
	<i>Abies sibirica</i> ; >100<200 yrs	33	1821	2009	189	0.88	1.39	0.36	0.38
	<100 yrs	12	1911	2009	99	1.37	1.78	0.95	0.57
<i>PcOb-AbSi</i>	<i>Picea obovata</i> ; >200 yrs	5	1733	2009	277	0.54	1.95	0.11	0.28
	>100<200 yrs	29	1815	2009	195	0.75	1.13	0.40	0.33
	<100 yrs	10	1910	2009	100	1.53	2.89	0.91	0.59
	<i>Abies sibirica</i> ; >100<200 yrs	15	1818	2009	191	0.62	0.86	0.36	0.28
	<100 yrs	10	1911	2009	99	0.96	1.34	0.43	0.35
<i>LaSi-BePl</i>	* <i>Larix sibirica</i> ;	118	1768	2009	242	1.50	2.84	0.69	0.45
	* <i>Betula platyphylla</i> ;	10	1885	2008	124	1.7	2.75	0.63	0.76
<i>PiSy-LaSi</i>	* <i>Pinus sylvestris</i> ;	111	1773	2009	237	1.46	2.54	0.63	0.41
	* <i>Larix sibirica</i> ;	13	1844	2009	166	1.21	1.52	0.87	0.65

* Chronologies are not categorized by age groups.

In the *Picea obovata* dominated forest, *Abies sibirica* trees were present in the sub-canopy. The mean growth of *A. sibirica* trees (>100<200 years) was fairly constant over the last 150 years, except the early growth of first 30 years (Fig. 3.11d).

The mean growth of *A. sibirica* trees in the younger age group showed notable decrease in the mid of the 1940s, 1970s and 1990s (Fig. 3.11e). Also, these trees showed an increase of mean growths in the 1920s, 1950s, 1980s and the beginning of 2000 (Tab. 3.5). Mean growths for middle aged *Abies sibirica* and younger *A. sibirica* trees were 0.62 mm, and 0.96 mm, respectively.

3.3.5.3. Tree-growth of *Larix sibirica*-*Betula platyphylla* forest

The mean tree-ring width chronologies for the *Larix sibirica* and *Betula platyphylla* trees are shown in Figure 3.12a, which illustrates the different growth behaviour of the trees within the stand. *Larix sibirica* trees showed age-related growth trends, which means that the radial increment is decreasing with increasing age. The tree ring series (total 118) included in the chronology was with lengths between 111 and 242 years. The mean, minimal and maximal ring widths for *L. sibirica* chronology were 1.50 mm, 0.69 mm, and 2.84 mm (Tab. 3.5). The mean growth of *Larix sibirica* exhibited similar patterns compared to the *Pinus sylvestris* growth. The mean growth of *L. sibirica* showed rapid decrease from 1940 to 2009.

Betula platyphylla is a sub-canopy species in *L. sibirica* forest and its radial growth chronology length was 124 years (Fig. 3.12b). In general, the mean growth of *B. platyphylla* decreased until the mid of the 1950s and increased during the mid of 1990s; conversely, growth of *L. sibirica* decreased during this period. In the last decade, mean growth of *B. platyphylla* decreased. The mean, maximum, and minimum growth of *B. platyphylla* trees were 1.7 mm, 2.75 mm and 0.63mm, respectively.

3.3.5.4. Tree-growth of *Pinus sylvestris* and *Larix sibirica* forest

The radial growth patterns of *Pinus sylvestris* (111 series) and *Larix sibirica* (13 series) chronologies are shown in Figure 3.13a. The length of the chronology derived from raw measurements of *P. sylvestris* is 237 years and *L. sibirica* is 166 years. The mean, minimal and maximal ring widths for *L. sibirica* chronology were 1.46 mm, 0.63 mm, and 2.54 mm (Table 3.5). *P. sylvestris* showed an age-related growth trend similar to *L. sibirica* trees. *P. sylvestris* had the lowest growth value in 1823 and *P. sibirica*, *P. obovata*, and *L. sibirica* trees in the other type of forests also showed growth reduction during this year. Between the 1940s and 2009s, both species showed a rapid decrease and continuous low radial growth.

Larix sibirica trees growing within this stand showed similar growth patterns (Fig. 3.13b) as *P. sylvestris* trees. Except for higher growth fluctuations in the mid 1880s and 1940s, the mean growth of *L. sibirica* continuously decreased until 2009.

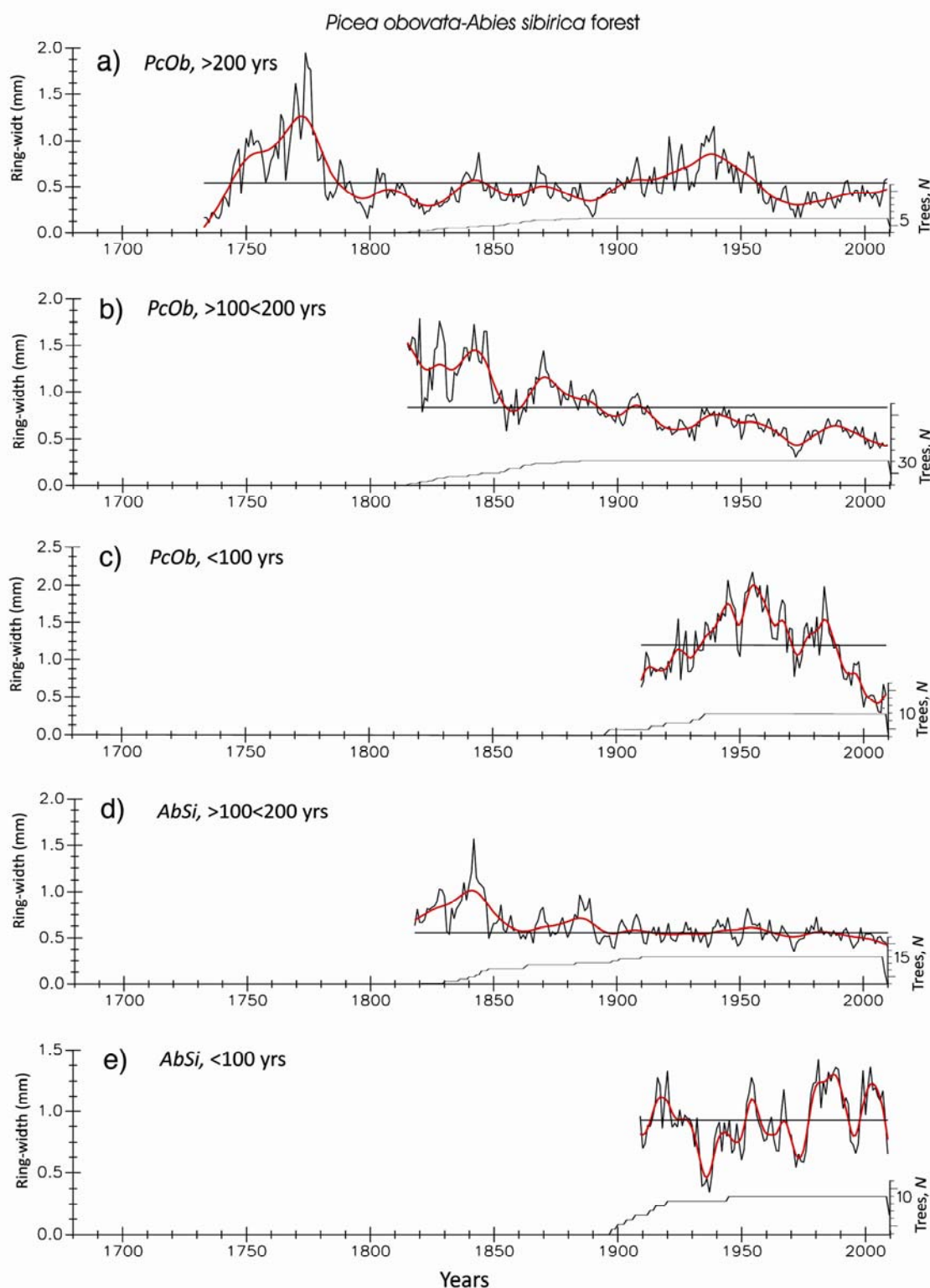


Figure 3.11: Tree-ring chronologies of *Picea obovata* and *Abies sibirica*: a) *Picea obovata*-more than 200 years old; b) *P. obovata*-100 to 200 years old; c) *P. obovata*-less than 100 years old; d) *Abies sibirica*-100 to 200 years old; e) *A. sibirica*-under 100 years old. Y-axis indicates tree ring-width with moving average in red. Y2-axis shows number of samples and the reference line indicates the mean tree-ring width over the dataset.

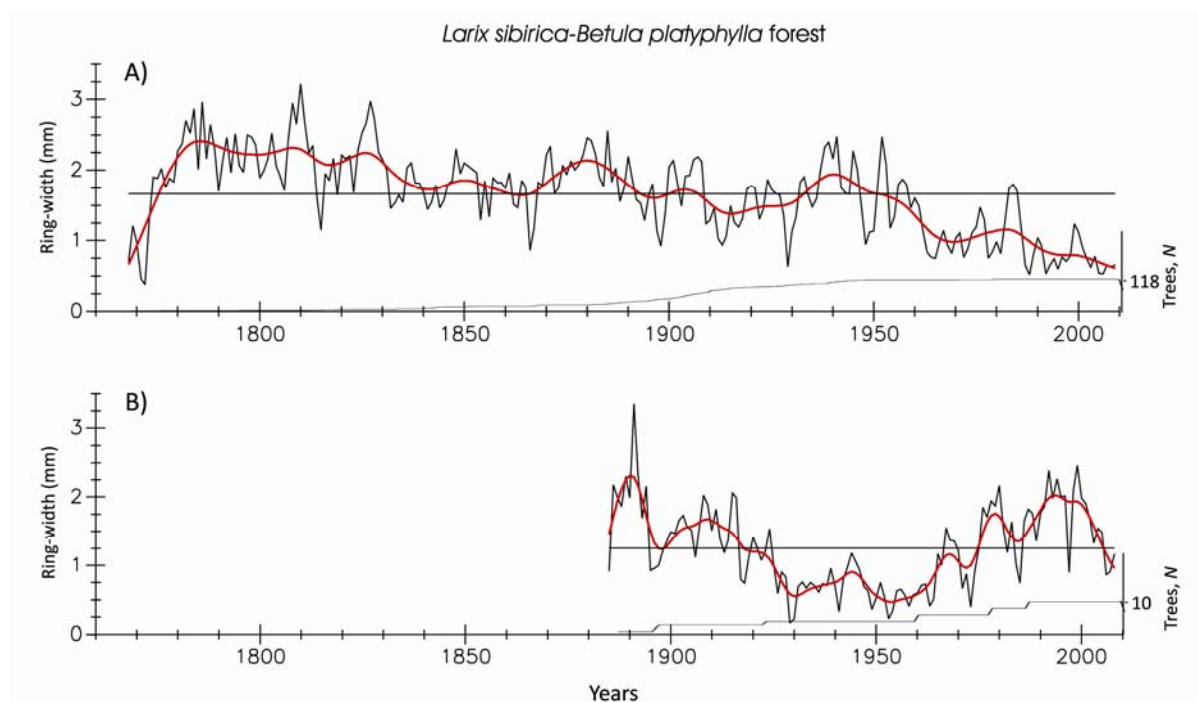


Figure 3.12: Tree-ring chronologies of *Larix sibirica* and *Betula platyphylla*: a) *Larix sibirica*; b) *Betula platyphylla*. Y-axis indicates tree ring-width. Y-axis indicates tree ring-width with moving average in red. Y2-axis shows number of samples and the reference line indicates the mean tree ring width over the dataset.

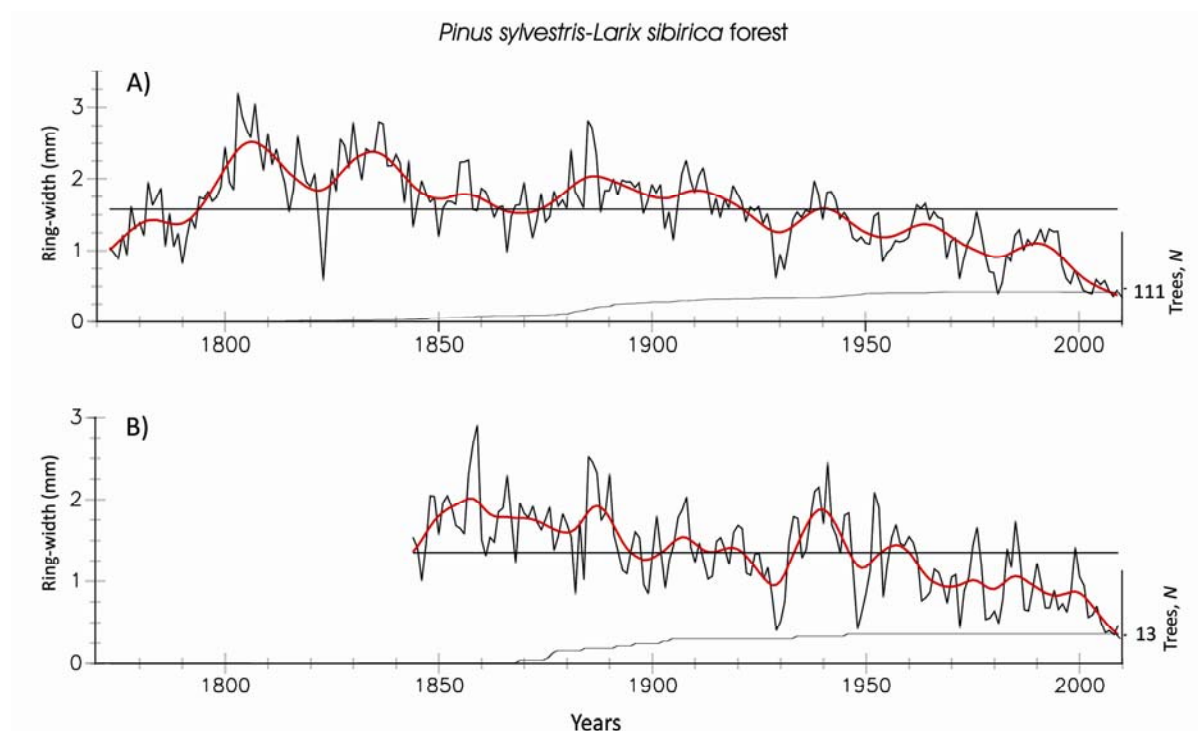


Figure 3.13: Tree-ring chronologies of *Pinus sylvestris* and *Larix sibirica*: a) *Pinus sylvestris*; b) *Larix sibirica*. Y-axis indicates tree ring-width. Y-axis indicates tree ring-width with moving average in red. Y2-axis shows number of samples and the reference line indicates the mean tree ring width over the dataset.

3.3.6. Downed logs

3.3.6.1. Species composition of downed logs

A total of 681.3 logs/ha, with a minimum diameter of >5 cm, occurred in the *PiSi-AbSi* forest (Fig. 3.14a). Species of logs were successfully determined (99%) and *Abies sibirica* logs composed the highest percentage (71.6%), whereas *Pinus sibirica* logs comprised 25.1%. *L. sibirica*, *P. obovata* and unknown species made up only >4% of the total logs. In *PcOb-AbSi* forest a total of 621.3 logs/ha was determined (Fig. 3.14b; Tab. 3.6), which is fairly the same amount of logs when compared to the *PiSi-AbSi* forest. Logs of *A. sibirica* clearly dominated this forest type (72.4%) and logs of other species included *B. platyphylla*, *P. sibirica*, and *P. obovata* comprising 10.7%, 9.2%, and 7.7%, respectively.

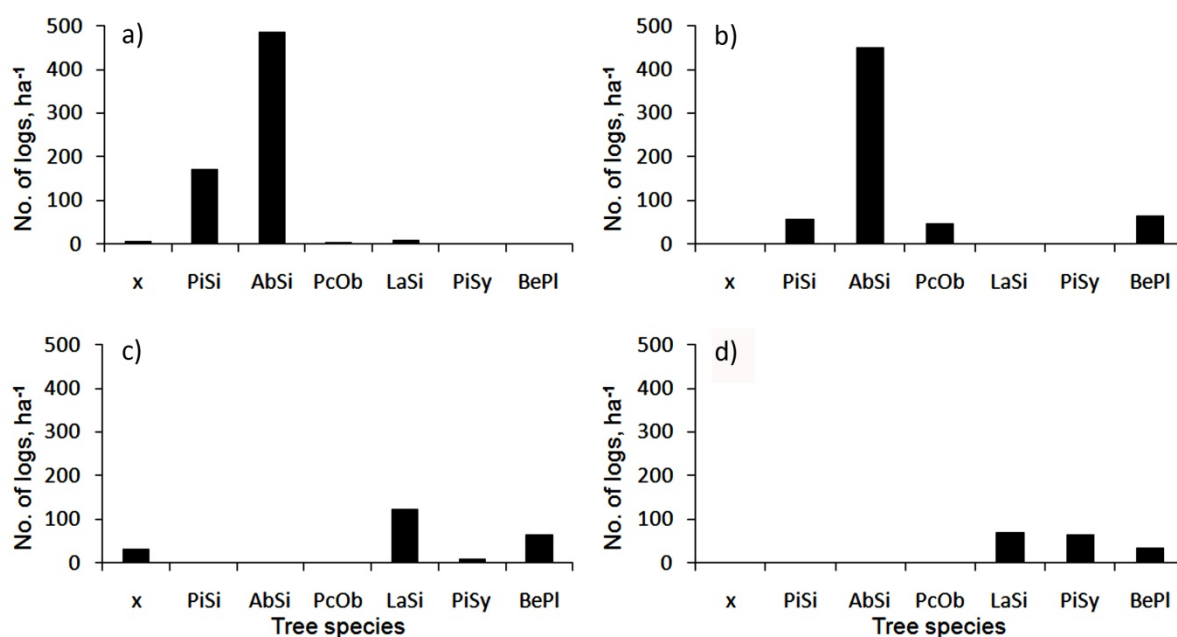


Figure 3.14: Comparison of number of logs and its species distribution in four type of forests: a) *PiSi-AbSi* forest; b) *PcOb-AbSi* forest; c) *LaSi-BePl* forest; d) *PiSy-LaSi* forest. Log species: x – unknown species, PiSi-*Pinus sibirica*, AbSi-*Abies sibirica*, PcOb-*Picea obovata*, LaSi-*Larix sibirica*, PiSy-*Pinus sylvestris*, BePl-*Betula platyphylla*.

A total of 233.1 logs/ha occurred in *LaSi-BePl* forest (Fig. 3.14c). *L. sibirica* logs were the most abundant within this forest type, representing 53.6% of all downed logs. The proportion of *B. platyphylla* logs comprised 28.4% of all, and unknown species and *P. sylvestris* logs made up 13.9% and 4.0%, respectively (Tab. 3.6).

In *PiSy-LaSi* forest a total of 171 downed logs/ha occurred (Fig. 3.14d). The *L. sibirica* logs

composed 41.5% of all logs and the percentage of *P. sylvestris* logs was determined as 37.5%. *B. platyphylla* logs made up 21.1% of the total logs (Tab. 3.6). Density of downed logs in this

Table 3.6: An abundance of the downed logs and species, categorized by forest types.

Forest type	Species												Total Stems /ha		
	x		PiSi		Absi		PcOb		LaSi		PiSy			BePl	
	Stems /ha	(%)	Stems /ha	(%)	Stems /ha	(%)	Stems /ha	(%)	Stems /ha	(%)	Stems /ha	(%)		Stems /ha	(%)
PiSi-Absi	6.3	0.9	171	25.1	487.5	71.5	5.6	0.8	11	1.5	-	-	-	-	681.3
PcOb-Absi	-	-	57	9.1	450	72.4	48.1	7.7	-	-	-	-	66.2	10.6	621.2
LaSi-BePl	32.5	13.9	-	-	-	-	-	-	125	53.6	9.3	4.0	66.2	28.4	233.1
PiSy-LaSi	-	-	-	-	-	-	-	-	71	41.4	64.3	37.4	36.2	21.1	171.8
Total	38.7	2.2	228	13	937.5	54.9	53.7	3.15	206.8	12.1	73.7	4.3	168.7	9.8	1708

forest was much lower compared to *PiSi-Absi* (681 logs/ha) and *PcOb-Absi* (621 logs/ha) forests.

3.3.6.2. Diameter distribution of downed logs

A general feature of *PiSi-Absi* and *PcOb-Absi* forests was the large amount of dead trees. The high quantity of logs recorded in *PiSi-Absi* and *PcOb-Absi* sites (i.e., 681 logs/ha: Fig. 3.15a) makes these forests different from the *LaSi-BePl* and *PiSy-LaSi* forest stands in this region.

Downed logs diameter class distribution was pooled by all species in each forest type and is shown in Figure 3.15. The pattern of DL diameter size distribution was similar in *PiSi-Absi* and *PcOb-Absi* forests. The majority of the downed logs in the *PiSi-Absi* forest belonged to the <10 cm and 21-30 cm dbh classes. The largest downed logs in the *PiSi-Absi* forest belonged to the dbh class of 61-70 cm (4.7% of total logs).

The size distribution of the downed logs (logs) was similar in *LaSi-BePl* and *PiSy-LaSi* forests (Figure 3.15c, d). Most of the logs in the *LaSi-BePl* forest were in the <10 cm and 21-30 cm dbh classes, while the highest number of living trees occurred in 11-20 cm and 21-30 cm dbh classes. The largest logs in this forest belonged to the 51-60 cm dbh class.

Majority of the logs in *PiSy-LaSi* forest occurred in the <10 cm and 31-40 cm dbh classes (4.7% of total logs).

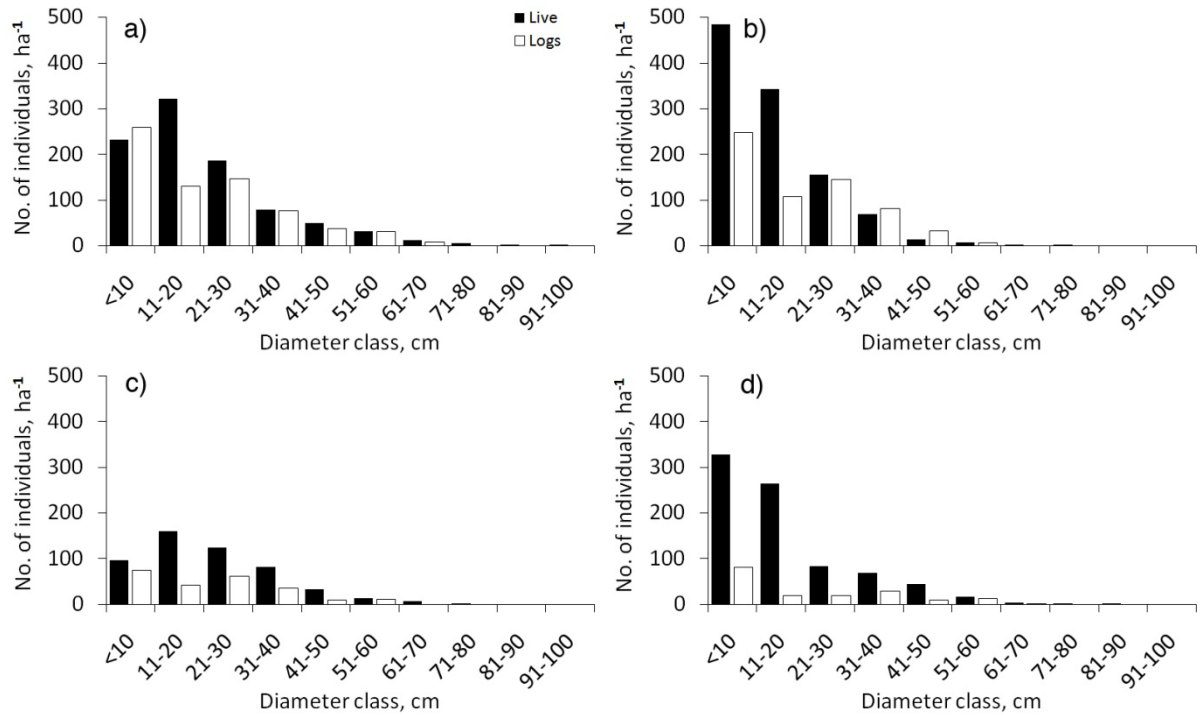


Figure 3.15: Diameter distribution of living trees (filled bars) and logs (open bars) in four types of forests: a) *PiSi-AbSi* forest; b) *PcOb-AbSi* forest; c) *LaSi-BePl* forest; d) *PiSy-LaSi* forest.

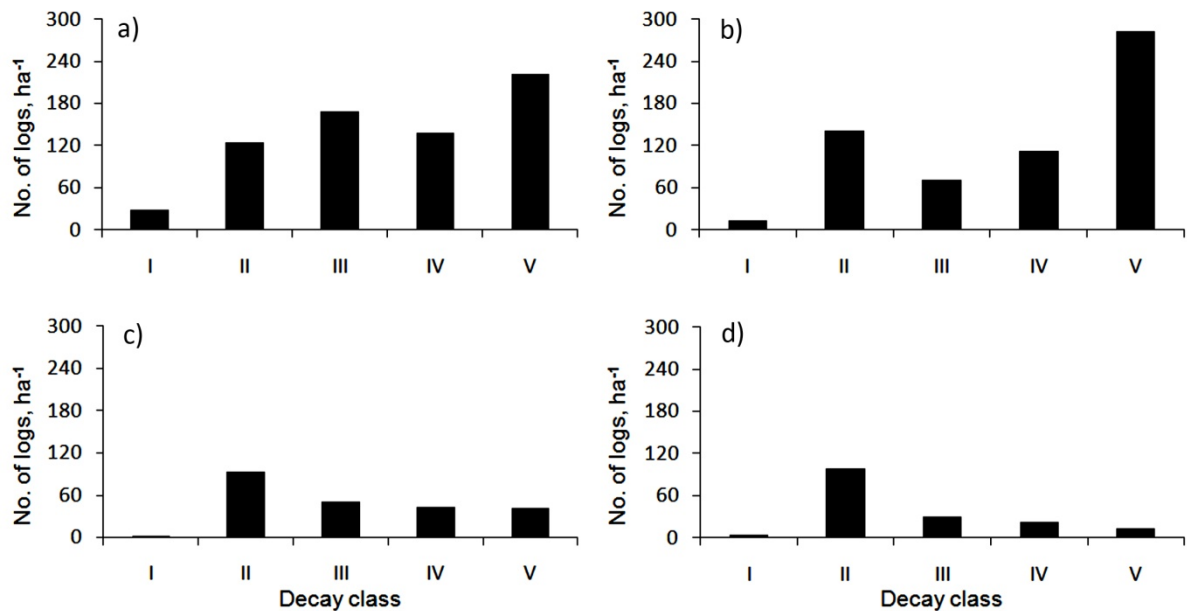


Figure 3.16: Decay class and number of logs in four types of forests: a) *PiSi-AbSi* forest; b) *PcOb-AbSi* forest; c) *LaSi-BePl* forest; d) *PiSy-LaSi* forest.

The density of downed logs among decay classes varied between the forest types (Fig. 3.16). In *PiSi-AbSi* and *PcOb-AbSi* forests, logs were dominating in the decay class-V, whereas the

lowest density of logs was observed in the decay class-I. The number of logs within decay classes increased with increasing decay classes.

In the *LaSi-BePl* and *PiSy-LaSy* forests, the density of logs was relatively low (Fig. 3.16c, d) compared to the log density in *PiSi-AbSi* and *PcOb-AbSi* forests. In *LaSi-BePl* and *PiSy-LaSy* forests, the highest number of logs was observed in decay class-II. The number of logs within decay classes decreased with increasing decay classes, with an exception of decay class-I, where very few logs were observed.

3.4. Discussion

Tree composition

In general, the *Pinus sibirica-Abies sibirica* (*PiSi-AbSi*) forest and *Picea obovata-Abies sibirica* dark taiga forests consisted of more diverse tree species and had different size structures leading to a higher stand complexity, than the *Larix sibirica-Betula platyphylla* and *Pinus sylvestris-Larix sibirica* light taiga forests in the west Khentey Mountains.

The Importance value (IV) gives a total picture of the social structure of species within a forest tree community and can be used to form an association of dominant species. Overall, main tree species which occurred in the research area were present in all the forest types, but they differed by proportion of IV. Although, tree species in *PiSi-AbSi* forest were differed, as well as their IV, diameter distribution, age structure, and radial growth patterns, suggests a different population dynamics between species. *P. sibirica* grew bigger and reached a higher maximum age than other tree species within the same site, while *Abies sibirica* and *Picea obovata* trees were shade tolerant species.

Dominance by a few tree species in light taiga forest types may be related to adverse conditions such as past frequent disturbances (Parthasarathy and Karthikeyan, 1997).

Sapling composition

Quantifying the current sapling population can provide some indication of what the forest of the future could look like. *Pinus sibirica-Abies sibirica* forest had a high number of *Pinus sibirica* (4360.8 saplings/ha, 49.7%) and *Abies sibirica* (4933.8 saplings/ha, 43.9%) saplings,

indicating that a future canopy could remain dominated by the canopy species. Other tree species, such as *Picea obovata* and *Betula platyphylla* which constituted a rather small part of the canopy, were also composed relatively few in the sapling composition.

In *Picea obovata-Abies sibirica* forest, *Picea obovata* saplings made up only 5.8% of sapling composition, while *A. sibirica* saplings made up the highest percentage (53.3%) of total saplings and were followed by *P. sibirica* saplings (31.7%). Also, percentage of *Betula platyphylla* saplings was higher (9.2%) than *P. obovata*. This pattern indicates that the future composition of forest will be different than the present structure.

In *Larix sibirica-Betula platyphylla* forest, *L. sibirica* made up 54.3% of canopy trees, however in the sapling tally, *B. platyphylla* was dominant (77.6%); also it was well distributed in the different height classes of sapling. *L. sibirica* saplings made up only 22.4% of the total saplings indicating that a pioneer stage dominated by *B. platyphylla* trees. Lack of *L. sibirica* regeneration was also observed in the study area (Dulamsuren *et al.*, 2010)

Pinus sylvestris-Larix sibirica forest had a high number of *P. sylvestris* saplings, indicating that a future canopy could remain dominated by the species. However, *B. platyphylla* saplings consisted slightly higher (15.4%) than *L. sibirica* (11.5%), suggesting that these species would compete for the pioneer stage. The sample plots of *Pinus sylvestris-Larix sibirica* forest at the higher elevation (1200 m), consisted of small amounts of *P. sibirica* saplings, indicating that elevation is important for distribution of *P. sibirica* trees.

Johnstone *et al.* (2010) reported that shifts in the dominance of spruce vs. deciduous tree seedlings have long-term consequences for successional trajectories and future forest composition. Although sites with high seedling densities are likely to experience self-thinning (Westoby, 1984), long-term observations indicate that compositional patterns established shortly after fire are good predictors of relative composition, two or three decades later (Johnstone *et al.*, 2004). Therefore, more detailed research is needed to observe post-fire forest composition and seedling establishment after the extreme fire of 2009, which will provide an exceptional opportunity to investigate post-fire recovery across a wide range of landscape and fire conditions. The results of such study will advance our understanding of factors controlling post-fire community recovery by providing an insight into the relative roles of environmental gradients, vegetation legacies, and disturbance effects in driving forest dynamics within the landscapes (Johnstone *et al.*, 2010).

Diameter structure

The diameter-class structure of *Pinus sibirica*-*Abies sibirica* forest trees showed a reverse-J shape distributions when all tree species were combined. However, the dominant *P. sibirica* followed a unimodal diameter distribution, whereas *A. sibirica* was dominant in the smallest through middle diameter classes. *P. obovata* trees were abundant in the smallest and the middle DBH classes. *B. platyphylla* occurred only in the small diameter classes, suggesting that once dark taiga species took a place; *B. platyphylla* could not reach its maximum size. Generally, *B. platyphylla* as a pioneer species is able to rapidly colonize favourable microsites created by fire and treefall disturbances by producing large amount of light wind dispersed seeds and having fast growth rate. However, this was not the case in *Pinus sibirica*-*Abies sibirica* forest. Also, limited distribution of *B. platyphylla* in this forest could be explained by the cold and higher elevation. The high density in the smallest classes indicated that gap disturbance contributes to tree species' coexistence and acts to sustain the mixed tree species composition of the forest (Grubb, 1977; Denslow, 1985; Kuuluvainen *et al.*, 1998). Few *Larix sibirica* trees occurred in small to large diameter classes, thereby indicating that within the dark taiga species, it was not successfully colonized.

Diameter distribution of trees in *Picea obovata*-*Abies sibirica* forest showed reverse-J shape pattern (Fig. 3.3), as mentioned before this shape is characteristic of multi-aged forests. *P. obovata*, *A. sibirica*, and *B. platyphylla* trees are showed similar distribution through the diameter classes, while occurrence of *L. sibirica* increased in the larger diameter classes. Compared to *Pinus sibirica*-*Abies sibirica* forest, in this forest light taiga species such as *L. sibirica* and *B. platyphylla* trees were common in the bigger diameter classes. A dramatic decrease of *P. sibirica* from the sapling stage to the lower diameter classes, suggested the high mortality of young *P. sibirica* trees in this forest. However, *P. sibirica* was dominant from dbh class of 35-40 cm.

Diameter distribution of *Larix sibirica*-*Betula platyphylla* forest trees indicated secondary succession, which means as an indicator of the disturbances, *B. platyphylla* trees colonized in the early stage. However, *L. sibirica* started to dominate from dbh class of 25-30 cm to the largest classes.

Pinus sylvestris-*Larix sibirica* forest *P. sylvestris*, *L. sibirica*, *B. platyphylla*, and *P. sibirica* tree species were present in the smallest diameter classes. None of *B. platyphylla* trees occurred larger than dbh class of 30-35 cm. There was a similar situation in *Larix* dominated forests that as an early successional species *B. platyphylla* were often present in the smaller diameter classes and never reached the larger dbh classes. Dry site condition may have an explanation for the less occurrence of *L. sibirica* trees in this forest.

Tree recruitment

Our results indicated that tree recruitment is varying by forest types. The continuous and stable tree recruitment of the different tree species in *Pinus sibirica* dominated forest suggested that this forest did not experience catastrophic events, such as fire. Also continuous tree establishment suggests that this forest grew without any major disturbances for more than 200 years.

Multi-aged structure is common for the boreal forests of the Northern Hemisphere (Bondarev, 1997). The main questions under discussion are the reasons for the multi-aged structure and the dynamics of these forests. One of possible reasons could be a multi-aged pattern reflecting severe past disturbances within a stand (Kolesnikov, 1947; Ditrich, 1970; Ross *et al.*, 1982; Lorimer, 1985; Stewart, 1986; Despons and Payette, 1992). Post-fire regeneration yields an even-aged forest structure instead of a continuous recruitment that would yield a multi-aged forest.

In early successional stages, a high establishment of saplings and sprouts occurring in forest stands after wildland fire events have been documented by several authors (Bell, 1980; Fox, 1988; Fulé, 1994). Due to the openness of the canopy, light penetrates and warms the forest floor, enhancing the conditions for species diversity in the area. As a response to this fact, the understory growth is stimulated and species with the ability to sprout start to colonize the area (Schneider, 2001). The tree recruitment pattern in *Picea obovata*-*Abies sibirica* forest confirms the explained reaction of vegetation.

In *Larix sibirica*-*Betula platyphylla* forests close to 90% of the importance value were sharing their dominance between *L. sibirica* and *B. platyphylla* (Tab. 3.3, Fig. 3.8). Very few other tree species present in this forest, suggested that a short fire recurrence was responsible for

the absence of any successional changes (Dix and Swan, 1971; Black and Bliss, 1978; Cogbill, 1985; Morneau and Payette, 1989). Although recruitment was possible and uneven-aged stands were observed (Foster, 1985; Foster and King, 1986; Bergeron and Charron, 1994), the understory cohort had a very low probability of reaching the canopy because recruitment was too low, mortality very high and fires too frequent (Johnson, 1992). In *Larix sibirica*-*Betula platyphylla* forest, *B. platyphylla* is abundant only during the first seven to twelve decades. After its decline *P. sylvestris* and *L. sibirica* became the main species. The tree recruitment wave indicates that this forest experienced major disturbances every 40-60 years. In *Pinus sylvestris*-*Larix sibirica* forest, tree recruitment was more or less restricted to *P. sylvestris*, may explained by dry site conditions (Fig. 3.9). The tree recruitment pulses occurred every 20-40 years in this forest.

Growth pattern of trees

Building chronologies and evaluating long-term forest growth trends using those chronologies is one of the most widely used methods for identifying forest growth trends (Mielikäinen and Senov, 1996; Sinkevich and Lindholm, 1996; Spiecker *et al.*, 1996; Spiecker, 1999b; Grudd *et al.*, 2002).

The tree-ring chronologies were divided into three groups based on their age structure, in order to examine growth patterns (Fig. 3.10). The different tree species within same forest type indicated some similarities and differences in radial growth patterns. The middle aged (>100<200 years) *Pinus sibirica* and *Abies sibirica* trees showed similar growth pattern that *ca.* first 100 years mean radial growth of both species increased. When this group reached the peak in radial growth, the oldest *P. sibirica*'s mean growth decreased, which suggests that the middle aged tree group formed the canopy layer. The increased growth of *P. sibirica* trees less than 100 years old indicates this group was established in the gap. On the other hand a few number of samples included in this chronology (Fig. 3.10c) may not present growth pattern of whole group. The mean radial growth of both middle aged and younger *A. sibirica* trees was low compared to *P. sibirica* trees within the same age group. *A. sibirica* is shade tolerant and has an ability to grow under suppression from some years to hundreds of years (Larsen, 1980). In the last 50 to 60 years notable growth decrease was

observed in the both old and younger aged trees. There could be various causes for the general decrease in growth of both of *P. sibirica* and *A. sibirica* trees during the last decade. This gives an opportunity to examine whether it is a natural process or influence of climatic variables. Therefore, we tested the relationship between radial growth of the main tree species in our study area and climatic variables, which is presented in Chapter 4.

The mean radial growths of tree species in *Picea obovata* dominated forest were varied. Overall, growth of most trees in different age groups was low, except *P. obovata* and *A. sibirica* trees in younger age group. The middle aged (Fig. 3.11d) *A. sibirica* trees showed the most significant different growth pattern than other tree species within this forest. The mean radial growth of the *A. sibirica* trees in this group showed constant low rate throughout ca. 200 years, indicating the ability of these trees that grew under suppression for long period. On the other hand *P. obovata* and *A. sibirica* trees (Fig. 3.11e) in the younger age group showed a higher growth rate, suggesting that these cohorts were established in the gap.

The mean radial growth of *Larix sibirica* trees in *Larix sibirica-Betula platyphylla* forest showed continuous decrease through the time, especially in the last 5 decades. The growth decrease in last several decades were also observed within the different tree species in other forest types. Dulamsuren *et al.* (2010) observed that radial growth decline of *L. sibirica* were related to increasing temperature and decreasing precipitation in our study area.

Pinus sylvestris and *Larix sibirica* trees showed similar growth pattern and these species also showed dramatic growth reduction in the last several decades. A strong radial growth decrease in single years greatly fits to the fire event years. Such years are; 1790, 1822, 1866, 1905, 1929, 1948, 1954, 1972, 1981, 1996 and 2009 (Fig. 3.12, Fig. 3.13).

Downed logs

Large amounts of dead and decaying wood have usually been related to old-growth forest ecosystems (Wells, 1998). This was also true in the case of the *Pinus sibirica-Abies sibirica* and *Picea obovata-Abies sibirica* dark taiga forests investigated in the present study. The amount of dead trees and their species composition and distribution among decay classes could give important information on former stand structure. The forests studied in this

research indicate that species composition and number of downed logs consists of dominant tree species. Also, in *PiSi-AbSi* and *PcOb-AbSi* forest number of downed logs was high in higher decay classes which may explain these forests experienced long-term fire cycle. In *LaSi-BePl* and *PiSy-LaSi* light taiga forests were often burned, therefore abundance of downed logs was much lower in these forests as compared to dark taiga types.

CHAPTER 4: TREE GROWTH-CLIMATE RELATIONSHIPS AT THE WEST KHENTEY MOUNTAINS, MONGOLIA

4.1. Objectives

The objective of this chapter is to explore the relationship between radial growth of different tree species and climatic variables.

4.2. Materials and methods

4.2.1. Field methods

The detailed field method of establishment of sample plot stand structure, and fire history studies are described in Chapter 5. In order to obtain the longest possible ring sequences with a minimum of individual variability, core samples for the growth analysis were taken at breast height (1.3 m) using an increment borer. With two cores per tree, a large part of the individual variability can be eliminated through averaging. Also, to determine and compare the growth patterns of different tree species, cores were taken from at least 10 trees in different canopy layers. A total of 1001 core samples (from 650 trees) were collected (Tab. 5.1).

4.2.2 Crossdating and Chronology Construction

Out of 1001 cores, 353 series were used for the chronology development, which are from *Pinus sibirica*, *Abies sibirica*, *Picea obovata*, *Larix sibirica* and *Pinus sylvestris* trees.

Every tenth ring on all series was first dotted from the outermost complete ring to the innermost ring and marker rings were identified (Stokes and Smiley, 1996). All increment cores were then crossdated using skeleton plots and verified using COFECHA software (Holmes, 1983; Grissino-Mayer, 2001a). COFECHA is a computer program used as a tool by dendrochronologists to gauge the quality of crossdating and measurement accuracy of and among tree-ring series (Grissino-Mayer, 2001a). Individual series were analyzed in COFECHA using 50-yr segments lagged successively by 25 yrs. The tree rings on all species increment cores were measured to the nearest 0.001 mm using a LINTAB measuring system (Rinntech, Heidelberg, Germany) for chronology construction. After the increment cores were measured, their measurement files were combined into one text file per site and used as a

working data set. Not all collected increment cores were used in chronology development because of irregular growth patterns that caused some segments to have correlations that fell below the critical correlation coefficient of 0.50 ($p > 0.01$).

Table 4.1: Descriptive statistics for the sampled tree species residual chronologies. Including number of sample trees, length of chronology, mean tree-ring width, values of expressed population signal (EPS), mean sensitivity and first-order autocorrelation (AC1), and interseries correlation (Rbar). (\pm standard deviations). See Figure 2.3 for site locations.

Species	No. series	Length (range)	Ring-width (mm)	EPS	Mean sensitivity	AC1	Rbar
<i>Pinus sibirica</i>	76	167 (95-329)	1.20 \pm 0.51	0.98	0.16 \pm 0.02	0.74 \pm 0.12	0.39 \pm 0.37
<i>Abies sibirica</i>	48	123 (61-306)	1.00 \pm 0.35	0.96	0.16 \pm 0.02	0.85 \pm 0.07	0.36 \pm 0.42
<i>Picea obovata</i>	40	140 (62-277)	1.01 \pm 0.03	0.94	0.15 \pm 0.02	0.63 \pm 0.11	0.29 \pm 0.19
<i>Larix sibirica</i>	118	111 (31-242)	1.50 \pm 0.45	0.99	0.29 \pm 0.04	0.78 \pm 0.08	0.55 \pm 0.21
<i>Pinus sylvestris</i>	111	118 (42-236)	1.05 \pm 0.38	0.99	0.24 \pm 0.05	0.74 \pm 0.08	0.53 \pm 0.15

Each measurement series was then standardized to build a master tree-ring chronology for each site using the program ARSTAN (Cook, 1985). ARSTAN standardizes the raw measurements by fitting a trend line or curve to the individual series being modeled using the ordinary least squares technique (Cook, 1985). Standardization is the correction of ring widths for the changing age and geometry in a tree (Fritts, 1976), and involves dividing the ring width measurement for each year by the value obtained from a negative exponential curve (used for this study), a regression line, or spline fit to the series (Cook and Kairiukstis, 1992). Standardization forms a new time series by removing the trend and creating a mean and variance that are more homogeneous with respect to time (Matalas, 1962; Fritts, 1976). The standardized ring-width indices generally have no positive or negative linear trend, their mean value is one, and the variability exhibited in younger rings (juvenile growth) is made comparable to the slower mature growth (Fritts, 1976). By standardizing, influences such as tree size, stand density, and competition within the stand are minimized (Friend and Hafley, 1989). The descriptive statistics used to characterize the tree-ring chronologies are shown

in Table 4.1. This includes mean sensitivity, a measure of year-to-year variability, standard deviation, a measure of the overall variability, and first-order autocorrelation, a measure of interdependence between the indices of successive years (Fritts, 1976). It is desirable for the mean sensitivity and standard deviation to be high, and the first-order autocorrelation to be low (Dewitt and Ames, 1978; Grissino-Mayer and Butler, 1993). The most important indicator of the validity of both the crossdating accuracy and the strength of the climate signal of a tree-ring chronology is the average interseries correlation. The average interseries correlation gauges the strength of crossdating amongst all series for a site. The expressed population signal (EPS) is one criterion used to evaluate the reliability of tree-ring chronologies in a quantitative sense, with a value exceeding 0.85, considered acceptable by some researchers (Wigley *et al.*, 1984; Cook and Kairiukstis, 1990). The EPS, which partly depends on sample size, measures how well the finite chronology is comparable with a theoretical infinite population. Another useful criterion is the RBar, or average correlation between tree-ring series. R Bar is independent of sample sizes and is an indication of common variance (Cook and Kairiukstis, 1990).

4.2.3. Climate data

The monthly mean temperature, monthly total precipitation and streamflow data of Eröö meteorological station, Mongolia was used to study the relationship of tree growth and climate sensitivity. It is one of the continuously recorded meteorological data available near the study area. The common period for the meteorological data was from 1962 to 2009. Additionally, gridded Palmer Drought Severity Index (PDSI) data of south east Khentey mountain stations was used in the analyses as it captures the effects of both precipitation and mean temperature on radial growth (Dai *et al.*, 2004). The PDSI records for our study covered the period from 1946 to 2005, with calibration period for the Eröö station from 1962 to 2005.

4.2.4. Climate response analysis

The climate response of each population was determined by correlating the residual chronology (Fig. 4.1) against a 17-month climate window from prior April to August of the

current growth year. The correlations were calculated using the PCREG program (PCREG is a FORTRAN program developed by E. Cook and K. Peters at the Lamont–Doherty Geological Earth Observatory, Palisades, NY 10964, USA). Climate during the prior growing season and intervening season can influence the current growth of a tree (Fritts, 1976; Kramer and Kozlowski, 1979; Cook and Kairiukstis, 1990).

Several physiological factors are responsible for the lag between a prior year's climate and growth (Pederson *et al.*, 2004). Species with determinate growth typically flush once during a growing season. Similar to this physiology, some species have preformed shoots in which the number of leaves and amount of growth for the first flush is set during bud formation from the prior year (Kramer and Kozlowski, 1979).

4.3. Results

The statistics describing the five tree-ring residual chronologies indicated a strong common signal (Tab. 4.1). All chronologies met the minimum requirement of $EPS < 0.85$ despite frequent forest disturbance and conservative detrending methods.

4.3.1. Climate response of *Pinus sibirica* tree growth

P. sibirica residual chronology showed significant positive correlation (Fig. 4.2a, b) with October temperature of year prior to ring formation ($t - 1$) and negative correlation with current year's August precipitation (t). No significant correlations were found between PDSI, streamflow values and *P. sibirica* growth (Fig. 4.2c, d).

4.3.2. Climate response of *Picea obovata* tree growth

Picea obovata growth was positively correlated to PDSI in current years growing season (April-July) PDSI (Fig. 4.3d). No significant associations were found between *P. obovata* growth, temperature, precipitation and streamflow values (Fig. 4.3 a-c).

4.3.3. Climate response of *Abies sibirica* tree growth

During the year of ring formation (t) *Abies sibirica* growth was positively correlated with April-May streamflow (Fig. 4.4c). Also, positive correlations observed between *A. sibirica* growth and March-April PDSI (Fig. 4.4d) in the year of ring formation (t). No significant correlations were found between growth of *A. sibirica*, precipitation and temperature (Fig. 4.4a, b).

4.3.4. Climate response of *Larix sibirica* tree growth

Larix sibirica growth was negatively correlated ($p \leq 0.01$) to August temperature in prior year and August temperature in current year (Fig. 4.5a). *L. sibirica* growth was positively correlated ($p \leq 0.05$) to prior year September temperature. Also, positive correlations ($p \leq 0.05$) observed between *L. sibirica* growth and prior year November and current year January-February PDSI. This positive association increased ($p \leq 0.01$) in current year July PDSI. No significant correlations were found between precipitation, streamflow values and *L. sibirica* growth (Fig. 4.5b, c).

4.3.5. Climate response of *Pinus sylvestris* tree growth

Pinus sylvestris growth was positively correlated with prior year August ($p \leq 0.05$) and September ($p \leq 0.01$) precipitation. Also, positive correlations ($p \leq 0.05$) were observed during current year February and June precipitations (Fig. 4.6b). *Pinus sylvestris* growth was significantly correlated ($p \leq 0.01$) with streamflow values of prior year August-December and current year May-August (Fig. 4.6c). Correlation between *Pinus sylvestris* growth and PDSI values were the highest. Significant positive correlations were found between *P. sylvestris* growth and prior year August-December ($p \leq 0.01$) PDSI and current year January-August ($p \leq 0.001$) PDSI values (Fig. 4.6d). No significant correlations were observed *P. sylvestris* growth and temperature.

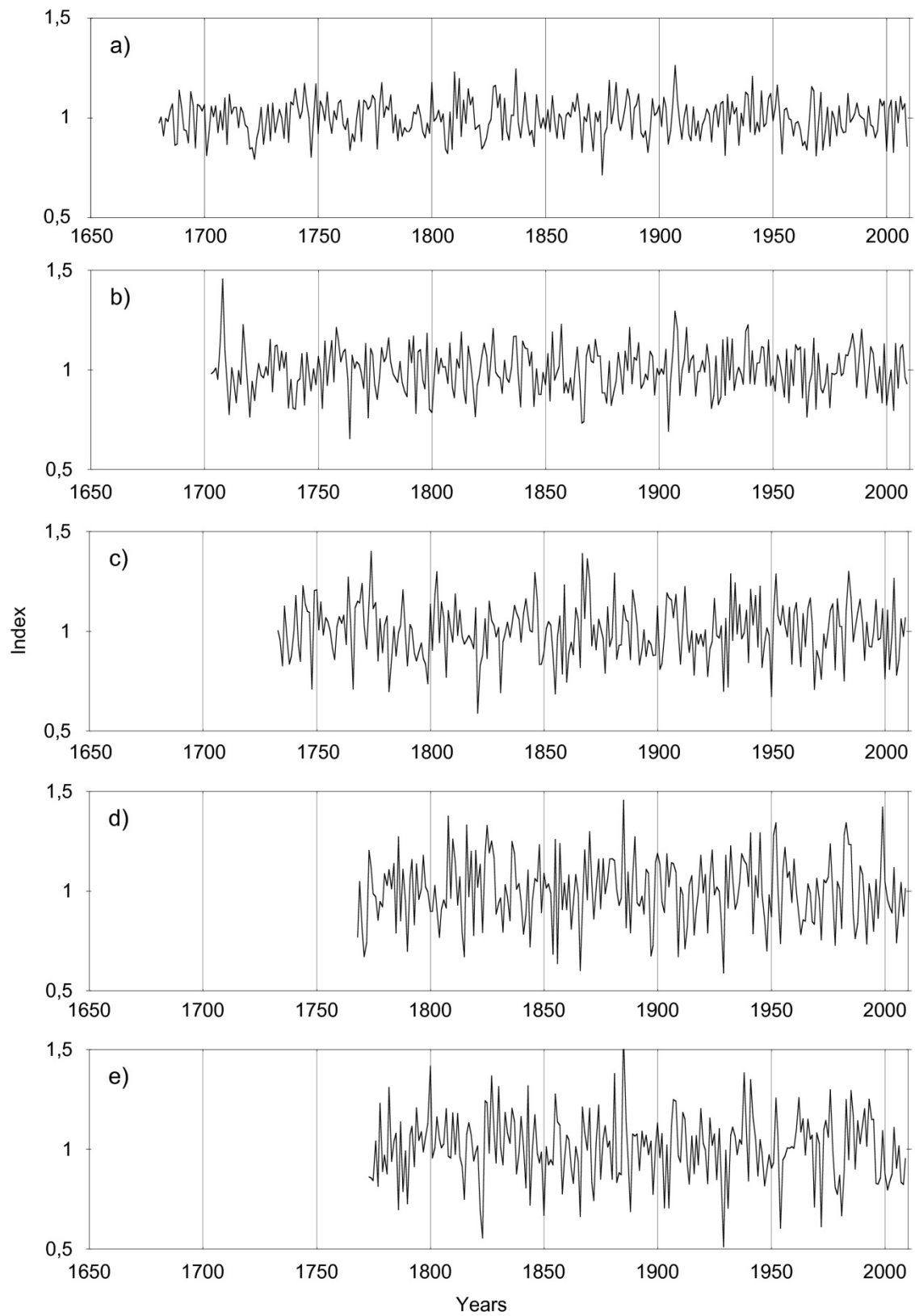


Figure 4.1: Tree-ring residual chronologies: a) *Pinus sibirica*, b) *Abies sibirica*, c) *Picea obovata*, d) *Larix sibirica*, and e) *Pinus sylvestris*.

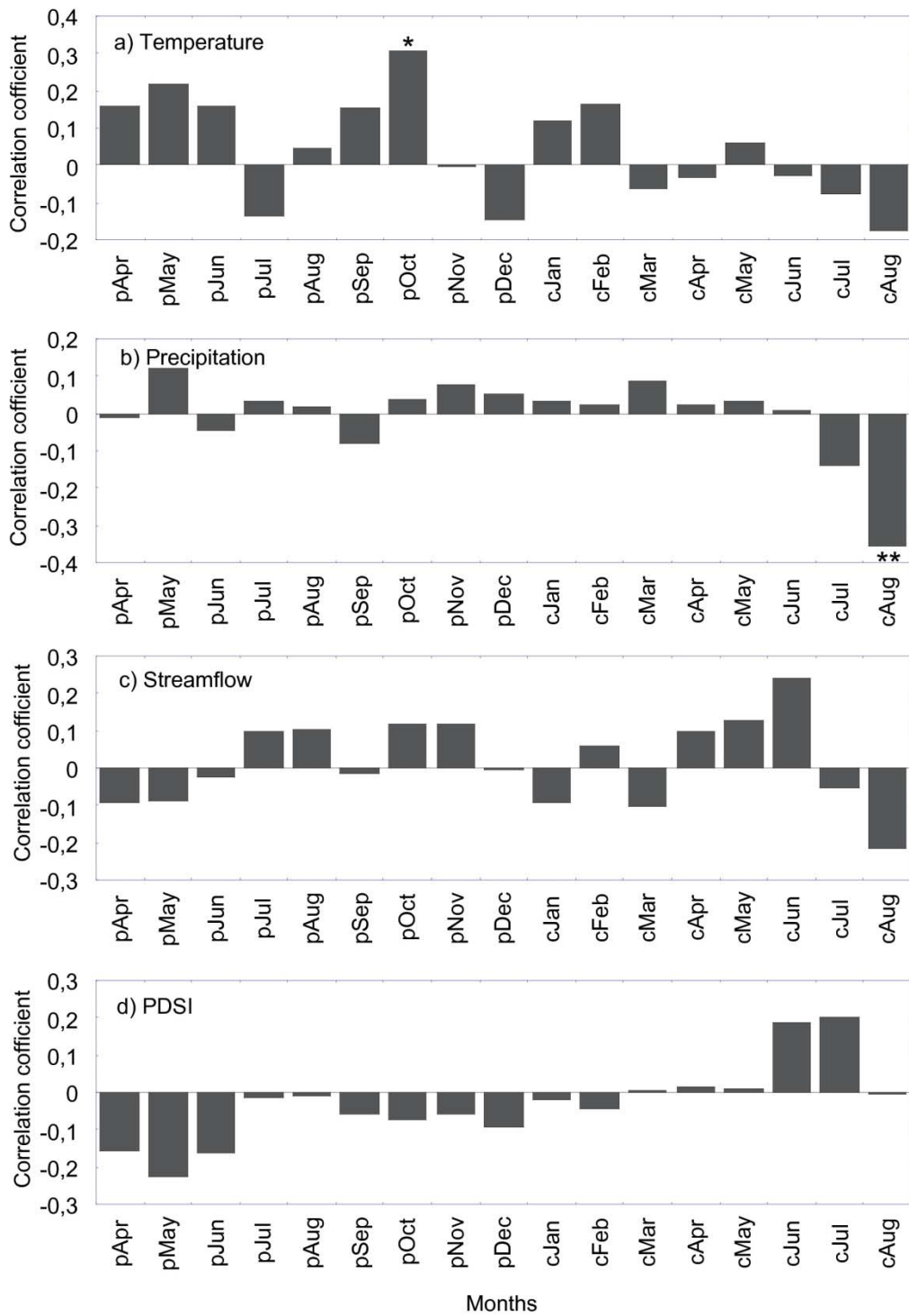


Figure 4.2: Correlation between a) monthly average temperatures, b) monthly total precipitation, c) monthly average streamflow, d) monthly PDSI and residual chronology of *Pinus sibirica* tree (**represents $p \leq 0.01$, and *represents $p \leq 0.05$). The letter “p” refers to months of the year prior to ring formation ($t - 1$), while letter “c” refers to months of the year to ring formation (t).

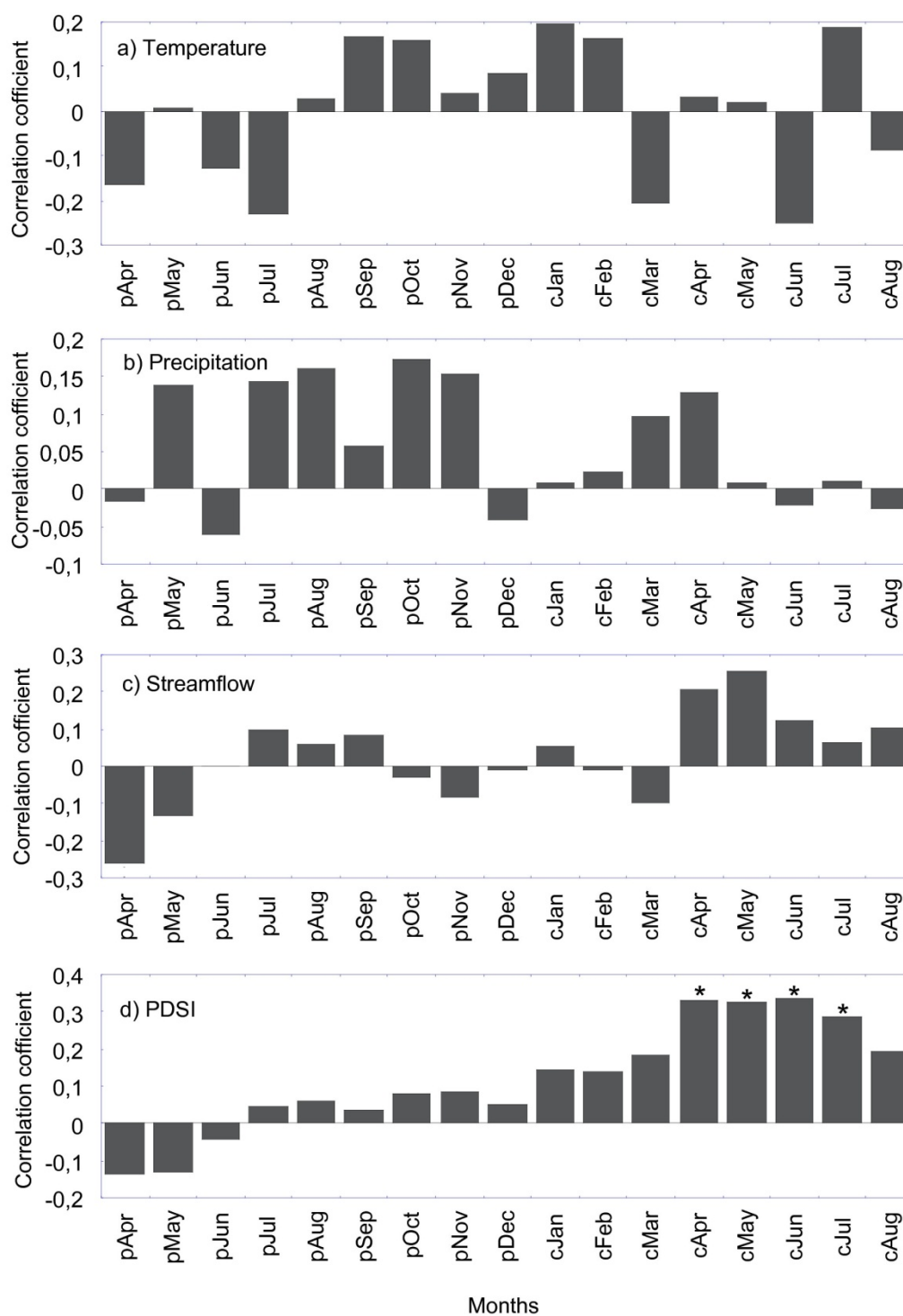


Figure 4.3: Correlation between a) monthly average temperatures, b) monthly total precipitation, c) monthly average streamflow, and d) monthly PDSI and residual chronology of *Picea obovata* tree (*represents $p \leq 0.05$). The letter "p" refers to months of the year prior to ring formation ($t - 1$), while letter "c" refers to months of the year to ring formation (t).

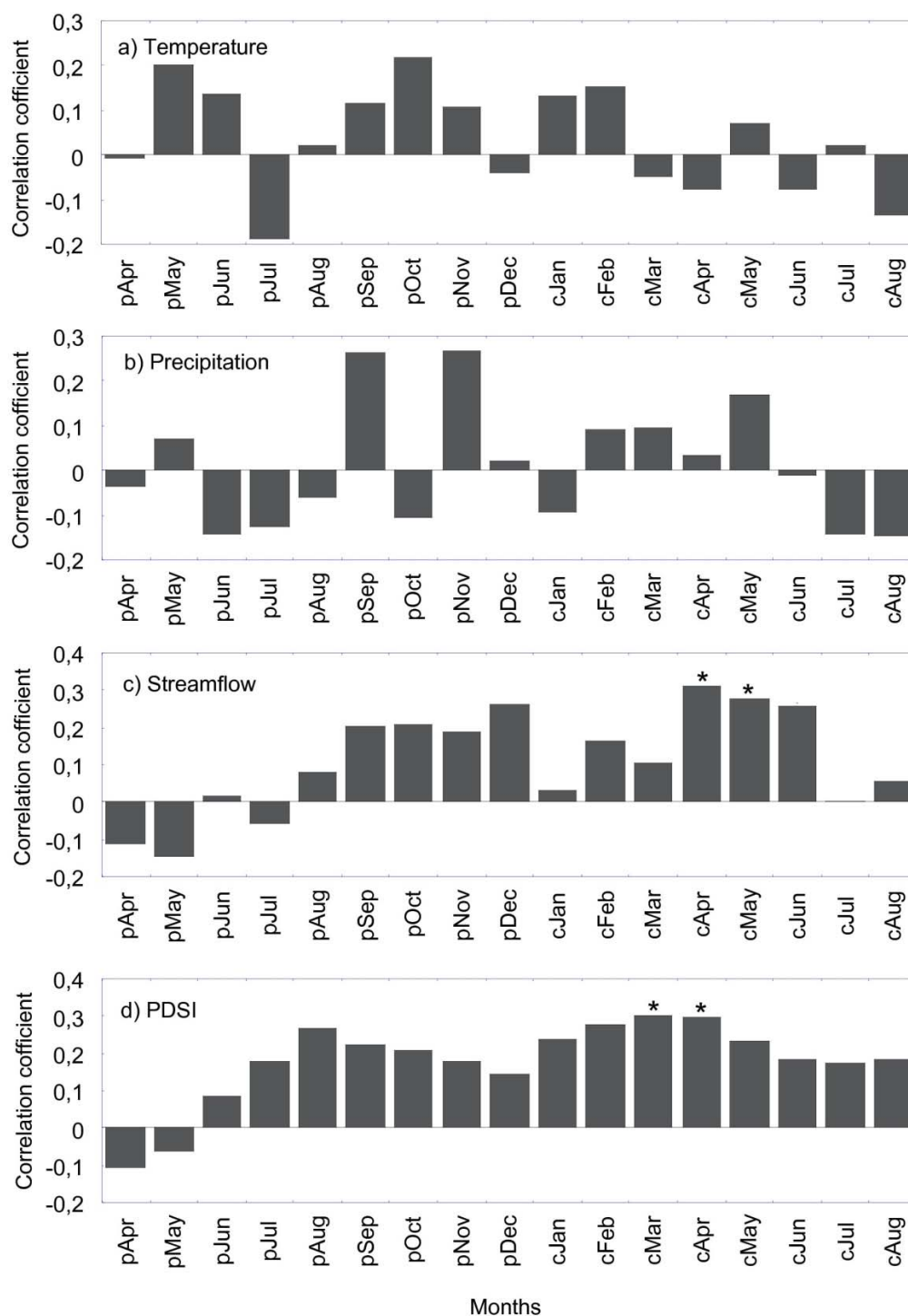


Figure 4.4: Correlation between a) monthly average temperatures, b) monthly total precipitation, c) monthly average streamflow, d) monthly PDSI and residual chronology of *Abies sibirica* tree (*represents $p \leq 0.05$). The letter "p" refers to months of the year prior to ring formation ($t - 1$), while letter "c" refers to months of the year to ring formation (t).

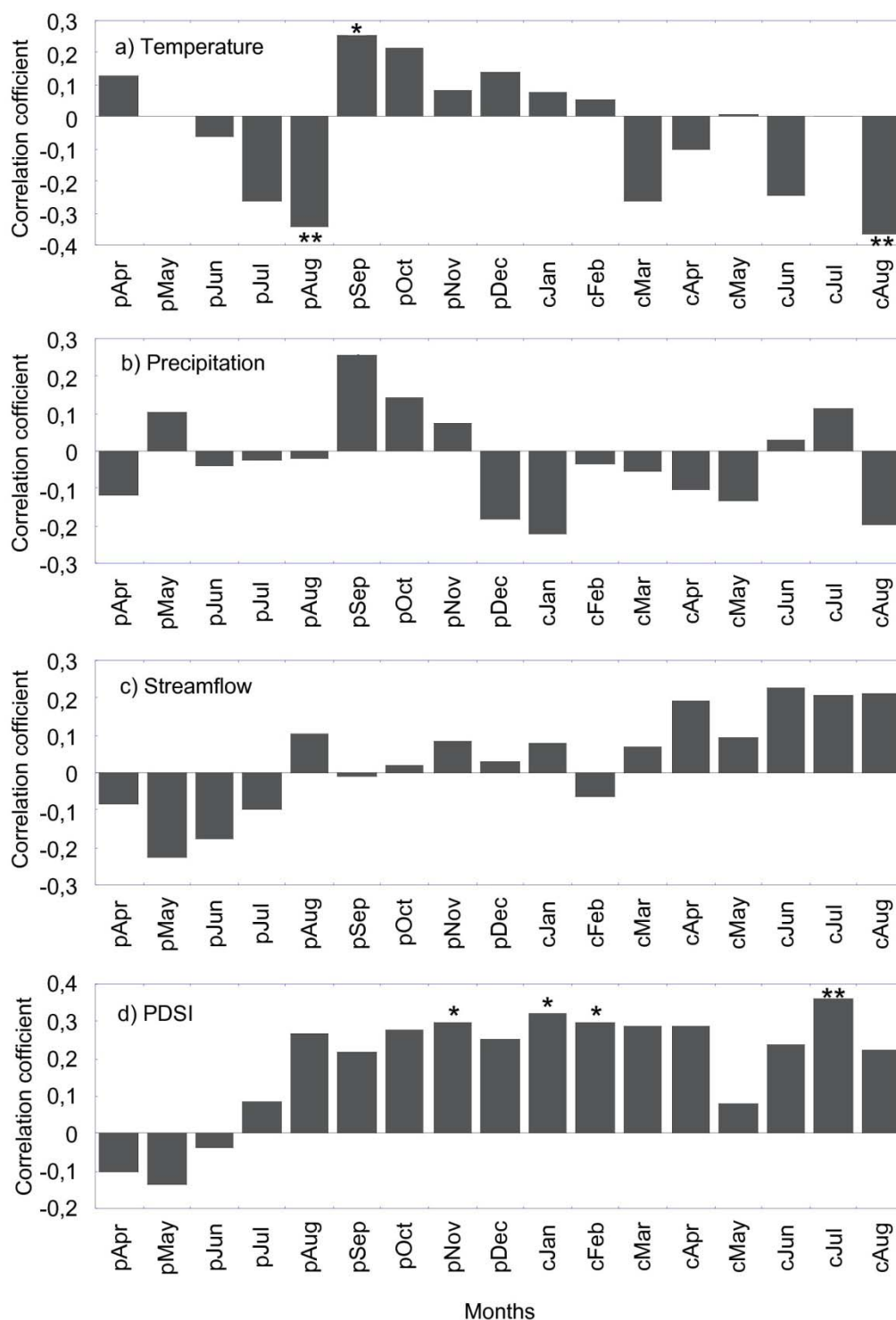


Figure 4.5: Correlation between a) monthly average temperatures, b) monthly total precipitation, c) monthly average streamflow, d) monthly PDSI and residual chronology of *Larix sibirica* tree (**represents $p \leq 0.01$, and *represents $p \leq 0.05$). The letter "p" refers to months of the year prior to ring formation ($t - 1$), while letter "c" refers to months of the year to ring formation (t).

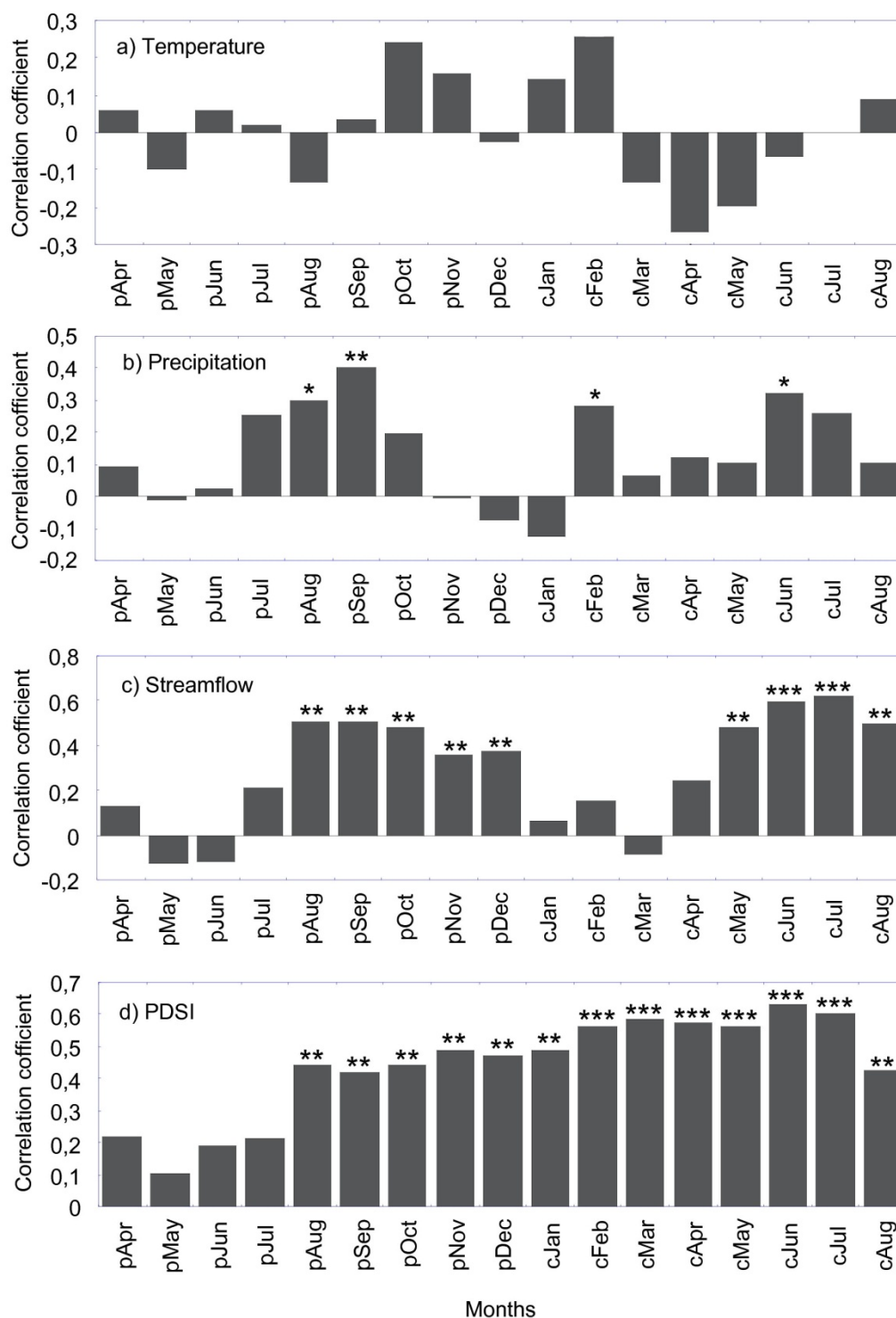


Figure 4.6: Correlation between a) monthly average temperatures, b) monthly total precipitation, c) monthly average streamflow, monthly PDSI and residual chronology of *Pinus sylvestris* tree (***) represents $p \leq 0.001$; ** represents $p \leq 0.01$, and * represents $p \leq 0.05$). The letter "p" refers to months of the year prior to ring formation ($t - 1$), while letter "c" refers to months of the year to ring formation (t).

4.4. Discussion

The overall signal (expressed population signal and mean sensitivity) in the residual chronologies was excellent and similar to that observed in other semi-arid regions (Liang *et al.*, 2001; Bogino *et al.*, 2009, De Grandpré *et al.*, 2011). The commonality of marker rings across the region further indicates regional climatic influences.

Correlation analysis for the five tree species resulted in very different climate signals very likely related to differences in elevation, topography, and microclimate at the sites. On the other hand few climatic variables correlated with the growth of tree species (*Pinus sibirica*, *Abies sibirica*, and *Picea obovata*), which are at the wetter sites perhaps due to a stronger relative influence of non-climatic factors, leading to more individualistic tree growth patterns. The climate of the prior growing season sometimes exert a significant influence on growth that extends into the period in which stems are elongating, i.e. current growing season (Fritts, 1976). The previous growing season is important for carbohydrate uptake and photosynthate production, which explains the influence of climate during the previous year on *P. sylvestris* growth. A wide annual ring generally forms when optimal conditions for the photosynthesis occur during the fall of the previous growing season (Fritts, 1976). This could be a case for statistically significant positive correlation between *P. sibirica* tree growth and prior year October temperature (Fig. 4.2a). Also, negative correlation between current August (*t*) precipitation and radial growth of *P. sibirica* indicates that precipitation is a limiting factor for growth (Fig. 4.2b).

Positive correlations between *A. sibirica* and streamflow in early growing season of current year suggests that watercharge of spring is important for the production of *A. sibirica* growth (Fig. 4.4c).

Absent or some lower correlation values between temperature, precipitation, streamflow and *P. obovata* growth could be explained by growing condition of this forest (Fig. 4.3a-c). The sample sites for this species were at the narrow and wet north facing slopes. However, for the growth of *P. obovata*, current year's growing season PDSI was important (Fig. 4.3d).

Among the all tree species in this study *L. sibirica* growth showed significant negative correlations to prior year and current year's August temperatures (Fig. 4.5a). Also, positive correlation was found in *L. sibirica* growth during prior year September temperature.

Dulamsuren *et al.* (2011) observed similar relationships that significant correlation between *L. sibirica* growth and summer months (June, July, and August) temperatures depending on the plot, whereas significant correlations were not detected in the hottest and most rainy month, July.

In this study, temperature was not significantly correlated to the growth of *P. sylvestris* (Fig. 4.6a). *P. sylvestris* growth was significantly correlated to the prior year August-September and current year February and June precipitations, emphasizing the importance of previous-year water availability for physiological processes, such as carbohydrate storage, for growth of the next year (Kozłowski and Pallardy, 1997). This was further clarified by the significant correlation between *P. sylvestris* growth and prior year August-December and current year May-August streamflow.

The most determinant factor for *P. sylvestris* tree growth is the PDSI from current June (Fig. 4.6d). PDSI integrates soil moisture anomalies over several prior months, strong precipitation anomalies during winter can be carried over to influence the summer conditions. It means mostly that the PDSI is accumulated over the antecedent drought conditions; it increases from month to month if no precipitation occurs. Therefore it carries the information from the previous months. It is not necessarily a correlation with winter months but the effect of precipitation from previous August to winter on growth. If the prior growing season, winter and current spring were dry, current year growth production will be lower.

The high correlations with climatic variables suggests that trees growing on extreme sites, such as *P. sylvestris* forest, are climatically sensitive and represent an important resource for dendroclimatology studies, even in closed-canopy forests (Fritts, 1976; Phipps, 1985; Cook 1987; Abrams and Orwig, 1995). Dulamsuren *et al.* (2009a) studied response of *P. sylvestris*, *L. sibirica* and *P. sibirica* seedlings to summer drought in our study area, by measuring shoot water potentials. The results indicated that *P. sylvestris* trees growing in the forest-steppe ecotone show conservative water consumption with a sensitive stomatal regulation and relatively constant shoot water potentials under dry conditions. Also, their finding suggests that a selective advantage for *P. sylvestris* against increasing aridity is driven by global warming, since the main competitor, *L. sibirica*, often suffers from drought stress even under the current climatic conditions in the study area.

In this study, the high correlation between *P. sylvestris* growth and PDSI suggests that using *P. sylvestris* chronologies from this region would be an important tool for drought reconstructions.

CHAPTER 5: FIRE HISTORY IN DIFFERENT TYPES OF FOREST STANDS IN WEST KHENTEY MOUNTAINS, MONGOLIA

5.1. Introduction

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.*, 2003). The main natural cause of forest fires in the Taiga ecosystems during the summer months is lightning (Chuluunbaatar, 1998). Since the transition to a market economy at the beginning of the 1990s, the duration, frequency and intensity of forest fires have increased significantly. Ninety percent of the forest fires are manmade, and are linked to new livelihood strategies for income generation such as illegal deforestation, and the intensive and unsustainable utilization of non-timber products (NTP), such as collecting deer antlers, pine nuts, herbs and berries in the spring and autumn months. The main causes of forest fires are uncontrolled campfires, smoking, bullets (hunting activities) and sparks from tractor exhausts. 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; Romme, 1982; Knight, 1987).

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.

5.2. Objectives

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. We addressed the following questions:

- What were the characteristics of the past fire regime (fire frequency and variability) within different forest types of the West Khentey Mountains, Mongolia?
- What is the relationship between these forests' fire regimes?
- Were the majority of these fires, spring fires?

5.3. Materials and methods

5.3.1. Field 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. To characterize the stand structure ten (40x40m) 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 1.3m) 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. In order to characterize the under story, circular sub-plots were established within the quadrat plots (10 m radius from the plot center = 31.4 m²) and saplings species, number, height class (I = 50-150 cm, II = 151-250 cm, III = 251-350 cm, IV = >351cm; DBH <5 cm) and condition (live, dying, and dead) were recorded. Also, the species of downed logs, diameter class, length and decay stage within these circular sub-plots were recorded.

Fire scarred specimens were taken from stamps, 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) and Gray and Riccius (1999), or felled, while small diameter trees were felled and sectioned until the area with the highest number of visible scars was located. 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. Additionally, core samples were collected to produce master chronology and create an age structure graphs (Tab. 1.1).

5.3.2. Laboratory methods

After the tree rings from all fire-scarred cross sections were crossdated, calendar years were assigned to all fire scars. Then all data was entered to the FHX2 software (Grissino-Mayer, 1995).

Statistics used to analyze the historical range of variability of fire regimes fall into three general categories (Grissino-Mayer, 1995, 2001b; Georgina, 2007). The first includes measures of central tendency. The mean fire interval (MFI) is the average of all fire intervals (the length of time between successive fire scars), but is generally not used in recent years to describe fire regimes because extremely long fire intervals can cause the distribution to be skewed, usually positively (Baker, 1992; Grissino-Mayer, 1995). To account for this skewness, the Weibull distribution is used to model positively (and negatively), skewed distributions that are common in fire history studies because it provides a superior fit to the distribution of fire intervals than the mean fire interval (Clark, 1989; Johnson, 1992; Baker, 1992; Grissino-Mayer, 1999). The Weibull Median Interval (WMEI) is the interval associated with the 50th (midpoint) percentile of the distribution of fire intervals (Grissino-Mayer, *et al.*, 2004), and is less affected by extremely long fire intervals (Grissino-Mayer, 2001b; Lewis, 2003). Finally, the Weibull Modal Interval (WMOI) represents the fire interval associated with the greatest area under the probability density curve (Grissino-Mayer, 2001b; Lewis, 2003). The second major category includes measures of dispersion about the central value, such as the standard deviation (SD) and the coefficient of variation (CV). The CV is preferred because it allows comparisons of variability in fire interval distributions amongst sites by combining the SD and MFI within one statistic (Grissino-Mayer, 1995; Lewis, 2003). The SD alone does not facilitate easy comparisons because of the variability of the mean fire interval. The variability of the frequency of fire events can have profound implications on

Table 5.1: List of sampled forest sites and number of increment cores and cross-sections taken from each plots

Forest types	Sample Plots (40x40m)	Elevation (m)	Slope (deg)	Aspect	Increment Cores	Cross-Sections
<i>Pinus sibirica</i> - <i>Abies sibirica</i>	SA1	1563	6	W	48	9
	SA2	1542	8	E	36	6
	SA3	1542	6	SE	18	8
	SA4	1536	8	SE	15	7
	SA5	1546	8	E	15	6
	SA6	1543	7	E	18	4
	SA7	1558	6	SE	16	4
	SA8	1572	10	SE	16	5
	GT1	1518	11	E	18	8
	GT2	1584	2	E	20	10
Total	10	-	-	-	178	67
<i>Picea obovata</i> - <i>Abies sibirica</i>	AT1	1020	33	N	17	3
	AT2	983	1	W	18	4
	GA1	1112	21	N	18	9
	GA2	1026	1	NW	17	10
	GA3	1107	20	N	15	4
	GA4	1100	15	N	17	6
	GA5	1101	21	NW	15	6
	GA6	1126	30	NE	17	4
	GA7	1132	25	NW	16	4
	GA8	1115	23	NE	15	5
Total	10	-	-	-	165	57
<i>Larix sibirica</i> - <i>Betula platyphylla</i>	HB1	1081	18	N	14	12
	HB2	985	8	N	19	12
	BA1	958	8	W	20	13
	BA2	1135	19	NW	15	4
	DA	1003	8	NW	19	9
	SD1	1180	20	SE	15	6
	SD2	1058	18	S	15	7
	SD3	1086	20	NW	15	7
	SD4	1115	25	NW	15	5
	SD5	1149	28	NW	13	7
Total	10	-	-	-	160	82
<i>Pinus sylvestris</i> - <i>Larix sibirica</i>	KR1	1102	34	E	15	8
	KR2	1022	30	E	13	8
	KR3	1345	25	SE	16	6
	KR4	1134	32	E	15	5
	KR5	1143	25	SE	15	6
	ST1	1200	20	E	14	6
	ST2	1150	21	E	11	4
	ST3	1151	23	NW	19	6
	ST4	1200	28	SE	15	5
	ST5	1183	18	W	15	6
Total	10	-	-	-	148	60
Grand total	40				651	266

the resulting vegetation. For example, a fire regime with low variability suggests fire events that recur with regular frequency, which may allow enough time for pine seedlings to reach sapling height and therefore escape damage from a succeeding fire (Georgina, 2007).

The third general category includes measures of range and these help to further delimit the historical range of variability in fire regimes (Morgan *et al.*, 1994). The Minimum Fire Interval (MIN) and Maximum Fire Interval (MAX) represent the actual shortest and longest fire-free intervals in the distribution, respectively. The Lower Exceedence Interval (LEI) and Upper Exceedence Interval (UEI) of a distribution represent the intervals that delimit the shortest and longest fire intervals as modeled by the Weibull distribution. The FHX2 software by default uses the ± 1.1 SD level to delimit these intervals because values above or below these two intervals represent 25% of the values considered statistically short (12.5%) or statistically long (12.5%). The Maximum Hazard Interval (MHI) is the maximum theoretical fire-free period that an ecosystem can sustain, where burning is highly probable (Grissino-Mayer, 1995; 1999). For sites with high maximum hazard intervals, such as 1000+ years, the other statistical measures may provide a more accurate representation of the maximum sustainable fire-free interval. In this situation, the upper exceedence interval would be a more accurate representation of the maximum sustainable fire-free interval because it is not easily skewed by high variability or extremely long fire-free intervals (Lewis, 2003). Together, the MAX, UEI, and MHI help assess the degree of fire hazard that currently exists at a site (Grissino-Mayer, 1999; Grissino-Mayer, *et al.*, 2004).

In addition, 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 (Fig. 5.1). This means the fire could have occurred in one of two years. Therefore the fire scars can be attributed to the current year, i.e. the earlywood of the following ring. Early-early season fire scars occur in the first third of the earlywood, while middle-early season fire scars occur in the middle third of the earlywood. Late-early season fire scars occur in the last third of the earlywood, while late season fire scars occur in the latewood portion of the tree ring (Baisan and Swetnam, 1990; Grissino-Mayer, 1995). Assigning a single year to dormant-season scars is difficult because the scar results either from fires that burn in the fall (year x), after the annual ring has formed, or in early spring (year $x+1$), before the new ring begins to form. Recent fire (NEMA, 2009) 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 crossdated were not used in subsequent analysis.

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.

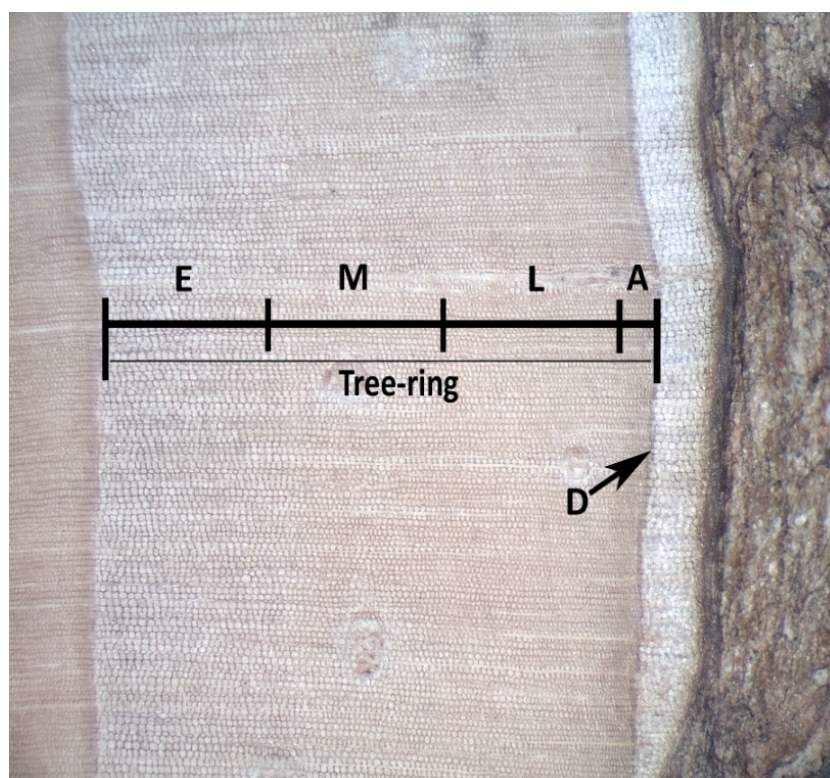


Figure 5.1: Illustration of fire seasons on a fire-scarred *Pinus sibirica* cross-section. Fire seasons include E = early-early season, M = mid-early season, L = late-early season, A = late season, and D = dormant season fires. *Note:* The white incomplete ring at the right side shows that early-early season fire, which occurred in all study forests on 18 May 2009.

5.4. Results

5.4.1. Fire History in the four forest types

5.4.1.1. 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 (Tab. 5.2) 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

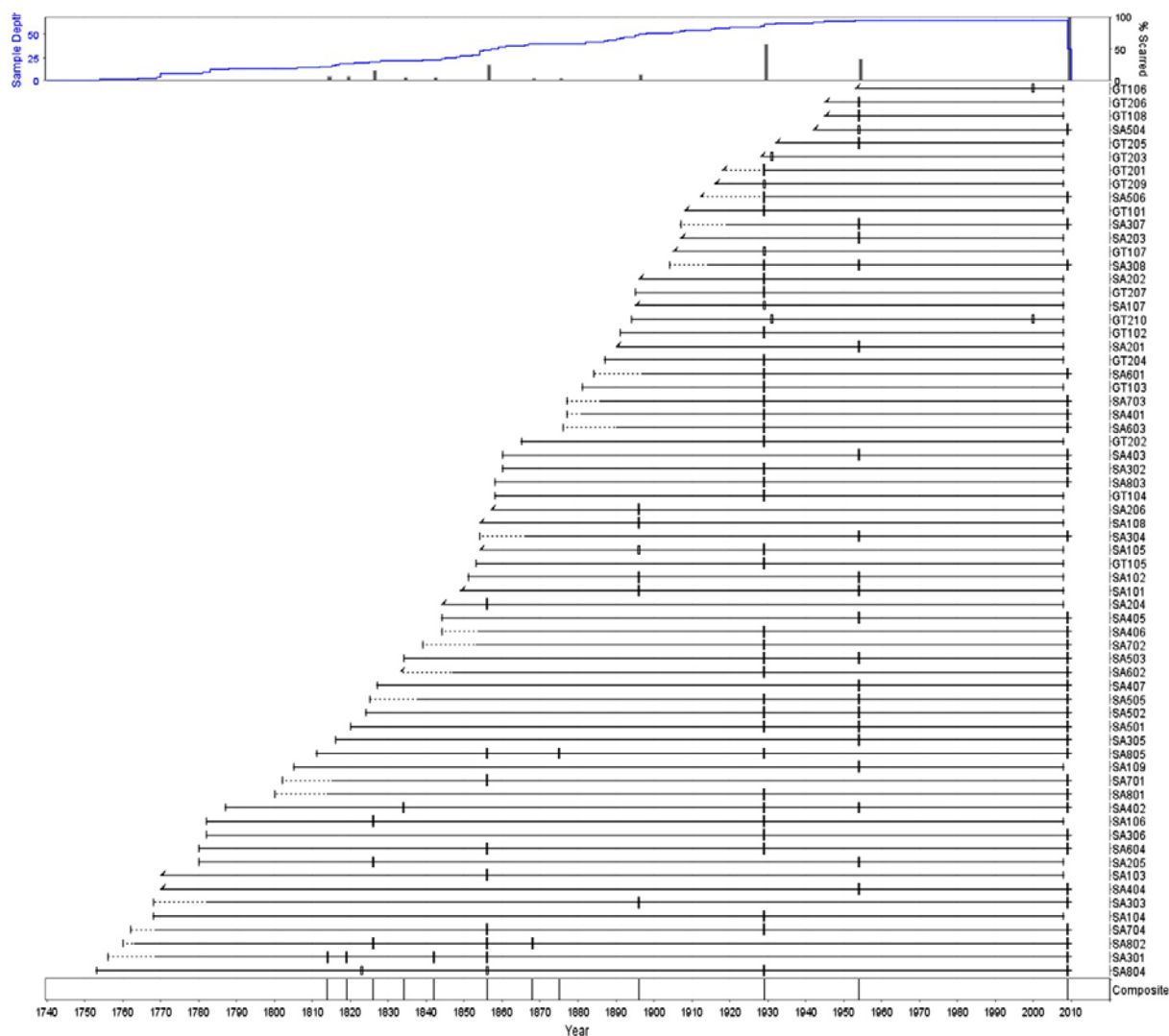


Figure 5.2: *Pinus sibirica*-*Abies sibirica* stand's composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (solid = recorder years, dashed = estimated years to the pith) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event. At the upper part of the chart indicates sample depth and percentage of scarred trees.

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. The maximum hazard interval for the all-scarred class was 420.0 years, and for the 25%-scarred class was 432.17 years. Fires at *Pinus sibirica-Abies sibirica* forest, which are spatially large, extending across several ridges, occurred in 1856, 1929, and 2009 (Fig. 5.2). 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.

5.4.1.2. 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 (Fig. 5.3). The first dated fire in this forest

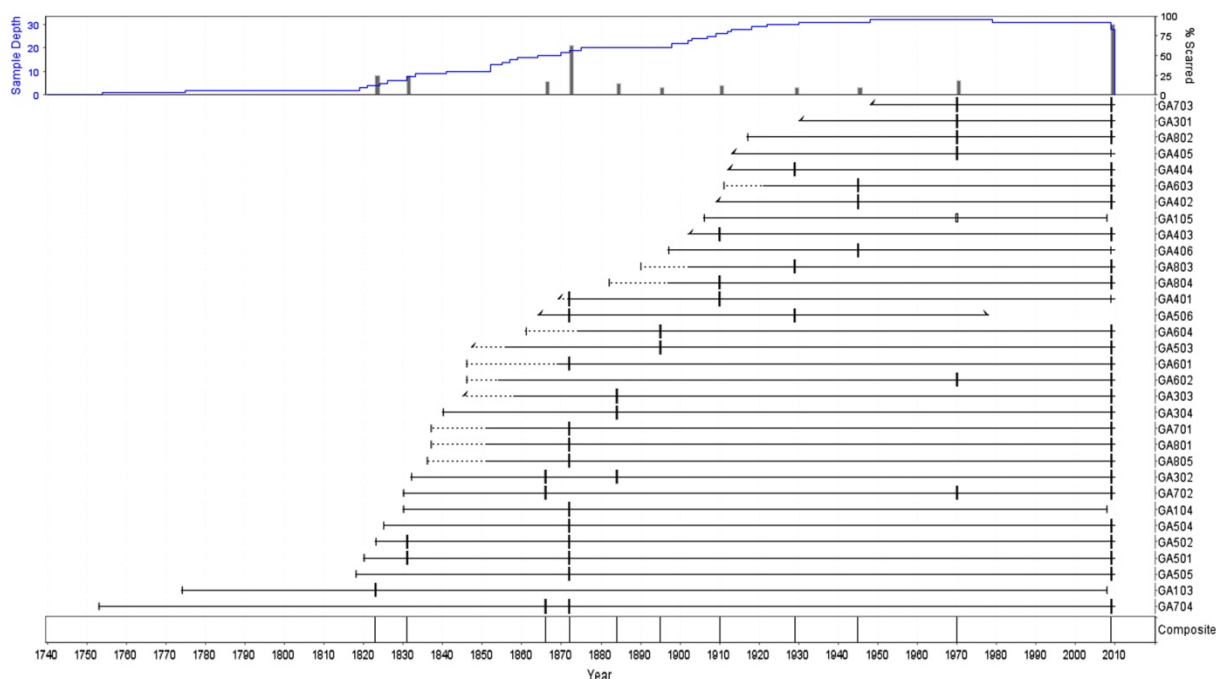


Figure 5.3: *Picea obovata-Abies sibirica* stand's composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (solid = recorder years, dashed = estimated years to the pith) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event. At the upper part of the chart indicates sample depth and percentage of scarred trees.

years for the all-scarred class and 54.18 years for the 25%-scarred class (Tab. 5.2). 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. For the all-scarred class, the maximum hazard interval was 506.59 years and for the 25%-scarred class was 544.47 years. *Picea obovata-Abies sibirica* forest did not experience large fires and the relatively large-scale fire occurred in 1872 (Fig. 5.3). 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 (Tab. 5.2). 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. The maximum hazard intervals were 506.6 years for the all-scarred class and 544.47 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 (Fig. 5.4; 5.5).

5.4.1.3. 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 (Tab. 5.2). 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 maximum hazard interval was 419.18 years for the all-scarred class and 207.43 years 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.

5.4.1.4. 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 (Fig. 5.5). 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

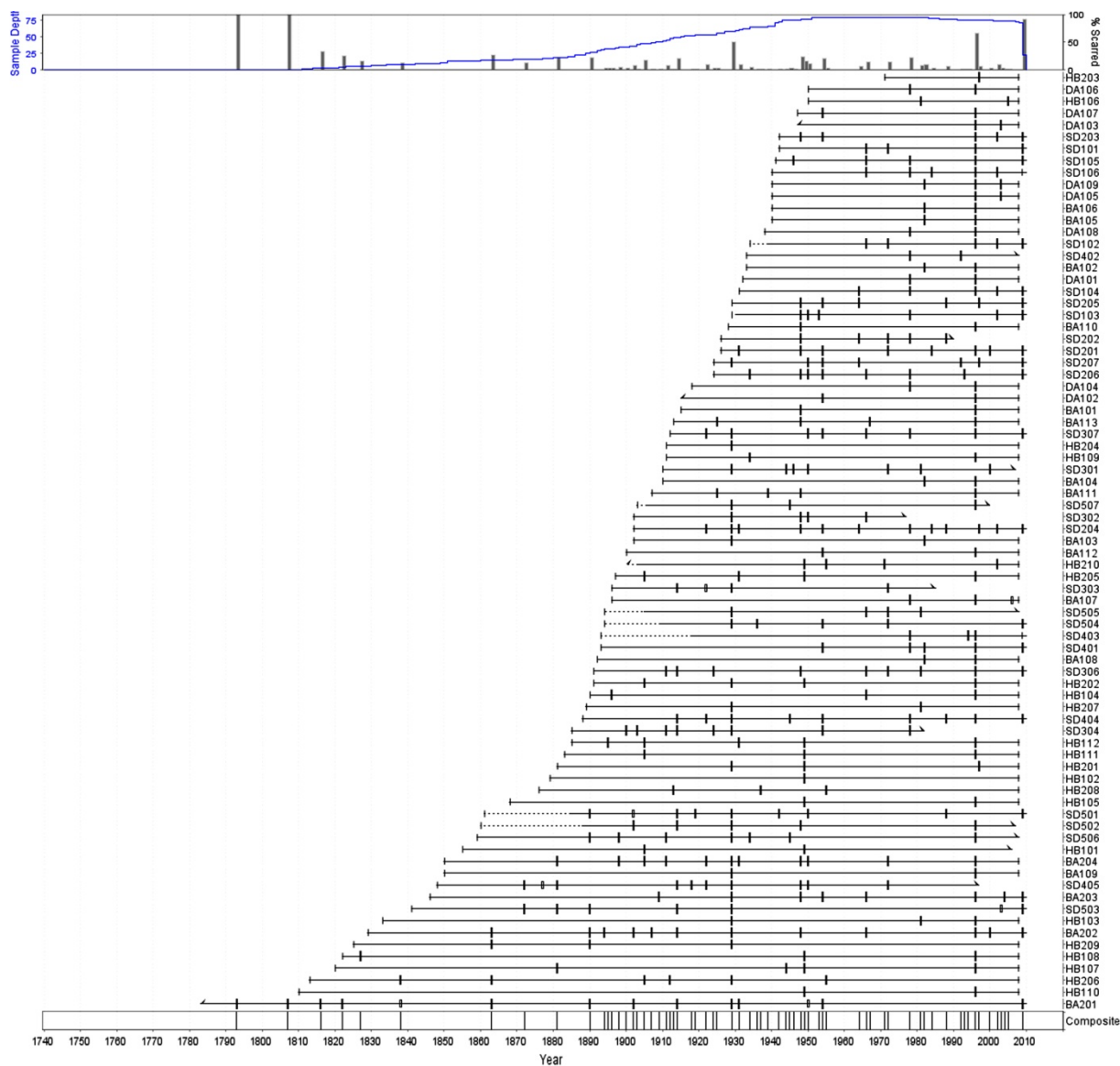


Figure 5.4: *Larix sibirica-Betula platiphylla* stand's composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (solid = recorder years, dashed = estimated years to the pith) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event. At the upper part of the chart indicates sample depth and percentage of scarred trees.

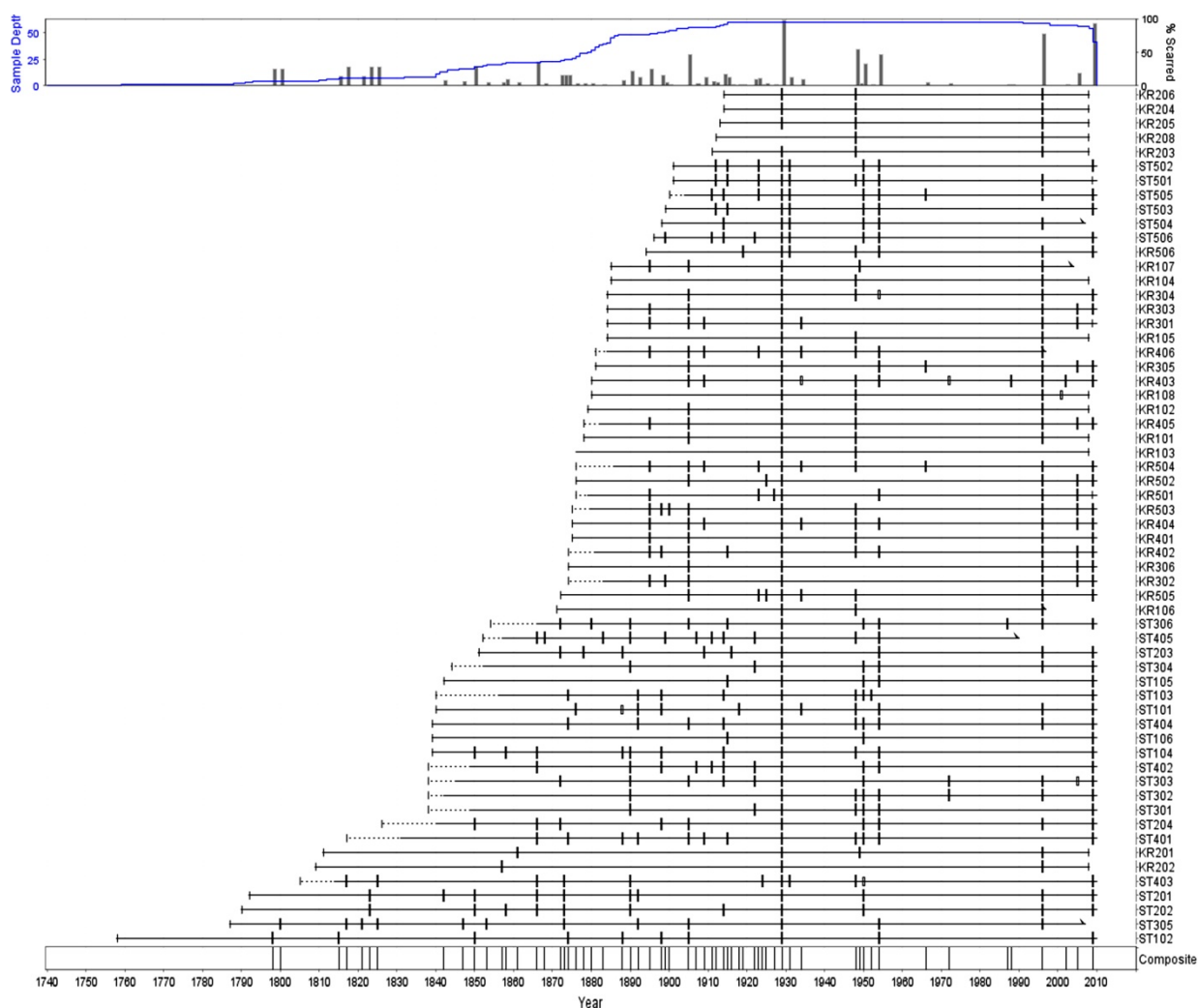


Figure 5.5: *Pinus sylvestris-Larix sibirica* stand's composite fire history chronology. The spatial distribution of fire events is illustrated by the sample identifications on the right while the temporal distribution of fire events is illustrated by the composite axis at the bottom of the chart. Horizontal lines (solid = recorder years, dashed = estimated years to the pith) represent the range of years for the sample listed at the right. Each vertical bar shown on the horizontal lines is a fire event. At the upper part of the chart indicates sample depth and percentage of scarred trees.

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.

The standard deviation can be used to calculate the 95% confidence interval (CI) for the MFI (Grissino-Mayer, 1995). However, the standard deviation cannot be used to calculate the CI for sites with very short values for the measures of central tendency, or for sites with skewed distributions, such as fire interval data, because these situations would yield negative values for the lower bound of the CI. Instead, the coefficient of variation (CV) can be used which is a standardized statistic that combines both the standard deviation and

MFI, allowing intra-site comparison of variability in fire intervals (Grissino-Mayer 1995). This is very important, as comparison would be impossible due to the differences in MFI for each site. By using the coefficient of variation to measure variability, comparisons can be made between two sites with very different MFIs. Higher values for the coefficient of variation indicate more variability in the length of fire intervals.

Table 5.2: 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</i> <i>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
	MHI	420.0	506.59	419.18	690.0
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
	MHI	432.17	544.47	207.43	618.14

*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 Exceedence Interval; UEI = Upper Exceedence Interval; MHI = Maximum Hazard Interval

In general, the coefficients suggest that the variability for the mean fire intervals were fairly consistent for three forests (Tab. 5.2): *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 (Tab. 5.2).

5.4.2. 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 (Tab. 5.3), 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 (Tab. 5.3), 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.

Table 5.3: 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-Abies sibirica</i>	1	72.2	73.2	12.4	14.4	0	26.8
<i>Picea obovata-Abies sibirica</i>	3.6	61.8	65.5	34.5	0	0	34.5
<i>Larix sibirica-Betula platyphylla</i>	0.9	82.8	83.6	12.9	3.4	0	16.4
<i>Pinus sylvestris-Larix sibirica</i>	2	73.2	75.2	19.9	4.9	0	24.8

Fire seasonality in *Larix sibirica*-*Betula platyphylla* forest were also concentrated in the early earlywood (Tab. 5.3) 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.

The seasonality of past fires in *Pinus sylvestris*-*Larix sibirica* forest was similar to the seasonality observed for past fires in other forest types (Tab. 5.3). 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.

5.5. Discussion

Fire history

One of the aims of this research was to determine the frequency of forest fires in the north-west Khentey 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, 2003; Swetnam, 2001a; 2001b). In this research study, the composite master forest fire chronology reconstructed 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 Khentey 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 comparison to the forest fire history studies in Siberia, fire return intervals in both the dark

and light taiga forest types in the Khentey Mountains, showed shorter intervals. For example, the fire return interval in the light conifer (larch, *Larix spp.*, and pine, *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 (Tchebachova, 2009).

Turner (1994) concluded that crown fire ecosystems are probably the best regarded as non-equilibrium systems, because extensive, infrequent fires tend to 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 Hovsgol (Oyunsanaa *et al.*, 2005) 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 Tujyin 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 5.1). 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 Hovsgol 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. Hessel *et al.* (2011) 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, 2002). 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.

CHAPTER 6: SUMMARY AND CONCLUSION

The overall purpose of this study was to investigate the structure, dynamic patterns of different forest types and to specifically examine the present tree species composition, regeneration pattern, size distribution, radial growth pattern of trees, composition and structure of downed logs and fire history within different forest types. This chapter summarizes and concludes the major findings and proposes recommendations for future research.

6.1. Structure and dynamics of forests

The main tree species in the study area were detected within all the four forest types. However, the frequency of their occurrences within the forest types was found to be different. With respect to species composition, it was observed that *Pinus sibirica-Abies sibirica* (PiSi-AbSi) forest and *Picea obovata-Abies sibirica* (PcOb-AbSi) dark taiga forests consisted of more diverse tree species and had different size structures leading to a higher stand complexity, than the *Larix sibirica-Betula platyphylla* (LaSi-BePl) and *Pinus sylvestris-Larix sibirica* (PiSy-LaSi) light taiga forests in the west Khentey Mountains. Dominance by a few tree species in the light taiga forest types were related to adverse conditions such as past frequent fire disturbances.

Quantifying the current sapling population can provide some indication of what the forest in the future could look like. *Pinus sibirica-Abies sibirica* forest had a high number of *Pinus sibirica* (49.7%) and *Abies sibirica* (43.9%) saplings, indicating that a future canopy could remain dominated by the canopy species. Other tree species, such as *Picea obovata* and *Betula platyphylla* which constituted a rather small part of the canopy, were also relatively few with respect to the sapling composition. *Picea obovata-Abies sibirica* forest, *Picea obovata* saplings made up only 5.8% of sapling composition, while *A. sibirica* saplings made up the highest percentage (53.3%) of total saplings and were followed by *P. sibirica* saplings (31.7%). Also, percentage of *Betula platyphylla* saplings was higher (9.2%) than *P. obovata*. This pattern indicates that the future composition of forest will be different than the present structure. In *Larix sibirica-Betula platyphylla* forest, with respect to the sapling tally, *B.*

platyphylla was dominant (77.6%). *L. sibirica* saplings made up only 22.4% of the total saplings indicating that the early stage of the forest is dominated by *B. platyphylla* trees. *Pinus sylvestris-Larix sibirica* forest had a high number of *P. sylvestris* saplings, indicating that a future canopy could remain dominated by the species. However, *B. platyphylla* saplings consisted slightly higher (15.4%) than *L. sibirica* (11.5%), suggesting that these species would compete with each other for the early stage.

The diameter-class structure of *Pinus sibirica-Abies sibirica* forest trees showed a reverse-J shape distribution when all tree species was combined. However, the dominant *P. sibirica* followed a unimodal diameter distribution, whereas *A. sibirica* was dominant in the smallest through the middle diameter classes. *P. obovata* trees were abundant in the smallest and the middle DBH classes. *B. platyphylla* occurred only in the small diameter classes. Few *Larix sibirica* trees occurred in small to large diameter classes, thereby indicating that within the dark taiga species, it was not successfully colonized. Diameter distribution of trees in *Picea obovata-Abies sibirica* forest showed reverse-J shape pattern, which is characteristic of multi-aged forests. *P. obovata*, *A. sibirica*, and *B. platyphylla* trees showed a similar distribution pattern throughout the diameter classes, while occurrence of *L. sibirica* increased in the larger diameter classes. Diameter distribution of *Larix sibirica-Betula platyphylla* forest trees indicated secondary succession, which means as an indicator of the disturbances, *B. platyphylla* trees colonized in the early stage. However, *L. sibirica* started to dominate from dbh class of 25-30 cm to the largest classes. *Pinus sylvestris-Larix sibirica* forest *P.sylvestris*, *L. sibirica*, *B. platyphylla*, and *P. sibirica* tree species were present in the smallest diameter classes. None of *B. platyphylla* trees occurred larger than dbh class of 30-35 cm.

The tree recruitment was varying by forest types. In *Pinus sibirica* dominated forest, the tree recruitment of the different tree species was continuous and stable. Also continuous tree establishment indicates that this forest grew without any stand replacing fire for more than 200 years. In *Larix sibirica-Betula platyphylla* forest, *B. platyphylla* is abundant only during the first seven to twelve decades. After its decline *P. sylvestris* and *L. sibirica* became the main species. The tree recruitment wave indicates that this forest experienced major

disturbances every 40-60 years. In *Pinus sylvestris-Larix sibirica* forest, tree recruitment was restricted to *P. sylvestris*, which could be explained by dry site conditions. The tree recruitment pulses occurred every 20-40 years in this forest.

The tree-ring chronologies were divided into three groups based on their age structure, in order to examine the growth patterns. The different tree species within same forest type indicated some similarities and differences in radial growth rates. The middle aged (>100<200 years) *Pinus sibirica* and *Abies sibirica* trees showed similar growth pattern. The mean radial growth of both middle aged and younger *A. sibirica* trees was low compared to *P. sibirica* trees within the same age group. The mean radial growths of tree species in *Picea obovata-Abies sibirica* forest were varied. Overall, growth of most trees in different age groups was low, except *P. obovata* and *A. sibirica* trees in younger age group. The middle aged (Fig. 3.11d) *A. sibirica* trees showed the most significant different growth pattern than other tree species within this forest. The mean radial growth of the *A. sibirica* trees in this group showed constant low rate throughout ca. 200 years. The mean radial growth of *Larix sibirica* trees in *Larix sibirica-Betula platyphylla* forest showed continuous decrease through the time, especially in the last five decades. Both *Pinus sylvestris* and *Larix sibirica* trees showed similar growth pattern and these species also showed dramatic growth reduction in the last several decades. A strong radial growth decrease in single years greatly fits to the fire event years. Such years are; 1790, 1822, 1866, 1905, 1929, 1948, 1954, 1972, 1981, 1996 and 2009.

The forests studied in this research indicate that species composition and number of downed logs consists of dominant tree species. Also, in *PiSi-AbSi* and *PcOb-AbSi* forest number of downed logs was high in higher decay classes which may explain these forests experienced long-term fire cycle. In *LaSi-BePl* and *PiSy-LaSi* light taiga forests were often burned, therefore abundance of downed logs was much lower in these forests as compared to dark taiga types.

6.2. Tree growth and climate relationships

The objective of this chapter is to explore the relationship between radial growth of different tree species and climatic variables. Correlation analysis for the five tree species indicated

very different responses to climatic variables likely related to differences in elevation, topography, and microclimate at the sites. On the other hand few climatic variables were found to be correlated with the growth of tree species (*Pinus sibirica*, *Abies sibirica*, and *Picea obovata*), which are at the wetter sites perhaps due to a stronger relative influence of non-climatic factors, leading to more individualistic tree growth patterns. Positive correlation was found between *A. sibirica* and streamflow in early growing season of current year. For the growth of *P. obovata*, current year's growing season PDSI was important. Among the all tree species in this study *L. sibirica* growth showed significant negative correlations to prior year and current year's August temperatures. Also, positive correlation was found in *L. sibirica* growth during prior year September temperature. *P. sylvestris* growth was significantly correlated to the prior year August-September and current year February and June precipitations, emphasizing the importance of previous-year water availability for physiological processes, such as carbohydrate storage, for growth of the next year. The most determinant factor for *P. sylvestris* tree growth is the PDSI from current June. *Pinus sylvestris* showed high responses to precipitation, streamflow and drought indices. In conclusion, based on the analysis of tree growth to climatic responses, *Larix sibirica* and *Pinus sylvestris* could be considered to be a suitable species for climate studies in this area.

6.3. Fire history of four types of forests

The objective of this study is to determine the fire regimes and seasonality within different forest types. 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 comparison to the forest fire history studies in Siberia, fire return intervals in both the dark and light taiga forest types in the Khentey Mountains, showed shorter intervals. 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. 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%). 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. In *Larix sibirica-Betula platyphylla* forest fire scars were concentrated in the early-earlywood 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%). In *Pinus sylvestris-Larix sibirica* forests 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%). Late-wood fire was recorded in none of the four forests types. In conclusion, dark taiga and light taiga forests differed in fire intervals. Fire seasonality did not change and the majority of fires occurred during the beginning of growing season.

6.4. Recommendations for Future Research

Further research should be continued in the following five areas: (1) to study changes in the structure of these forests after the fire of 2009, (2) chronology development and extension back in time, (3) reconstructions of climate history using *P. sylvestris* chronologies, (4) expanding the number of sample sites in the area to better understand spatial characteristics of past fires in the west Khentey Mountains, and (5) improved analyses to better understand the impacts of climate on fire occurrence in Central Mongolia.

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APPENDIX

Appendix Table 1: Statistics of the tree species basal area (m² /ha) in *Pinus sibirica*-*Abies sibirica* forest

Tree species	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
<i>AbSi</i>	15.89	11.91	19.87	7.94	23.84	31.00	5.56	35.0	1.76
<i>BePl</i>	0.04	-0.02	0.11	0.00	0.26	0.00	0.09	219.3	0.03
<i>LaSi</i>	3.20	0.84	5.56	0.00	10.28	10.90	3.30	103.1	1.04
<i>PcOb</i>	3.93	0.30	7.57	0.00	14.48	25.90	5.08	129.3	1.61
<i>PiSi</i>	24.17	16.56	31.77	4.42	36.18	113.00	10.63	44.0	3.36
<i>Salix spp.</i>	0.01	-0.02	0.05	0.00	0.14	0.00	0.04	316.2	0.01
Total	47.24	40.03	54.46	30.71	63.82	101.7	10.09	21.3	3.19

Appendix Table 2: Statistics of the tree species basal area (m² /ha) in *Picea obovata*-*Abies sibirica* forest

Tree species	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
<i>AbSi</i>	6.47	3.27	9.66	0.10	14.52	20.00	4.47	69.2	1.41
<i>BePl</i>	4.80	2.57	7.04	0.00	10.23	9.73	3.12	64.9	0.98
<i>LaSi</i>	2.43	1.26	3.59	0.00	6.27	2.66	1.63	67.1	0.51
<i>PcOb</i>	7.93	2.05	13.82	1.40	24.33	67.66	8.22	103.7	2.60
<i>PiSi</i>	4.85	0.78	8.92	0.00	18.34	32.35	5.68	117.2	1.79
<i>Salix spp.</i>	0.01	-0.02	0.04	0.00	0.13	0.00	0.04	316.2	0.01
Total	26.55	21.58	31.52	15.1	37.50	48.25	6.94	26.2	2.19

Appendix Table 3: Statistics of the tree species basal area (m² /ha) in *Larix sibirica*-*Betula platyphylla* forest

Tree species	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
<i>AbSi</i>	0.01	-0.01	0.03	0.00	0.09	0.00	0.03	316.2	0.01
<i>Alnus</i>	0.00	-0.00	0.01	0.00	0.02	0.00	0.01	316.2	0.00
<i>BePl</i>	7.34	3.58	11.09	0.62	19.15	27.60	5.25	71.6	1.66
<i>LaSi</i>	20.56	15.10	26.03	7.15	31.60	58.40	7.64	37.2	2.42
<i>PiSi</i>	0.15	-0.01	0.31	0.00	0.58	0.05	0.23	149.5	0.07
<i>PiSy</i>	0.43	-0.15	1.00	0.00	2.10	0.64	0.80	187.5	0.25
<i>PpTr</i>	0.04	-0.05	0.12	0.00	0.36	0.01	0.11	316.2	0.04
Total	28.52	26.03	31.02	22.60	33.31	12.19	3.49	12.2	1.10

Appendix Table 4: Statistics of the tree species basal area (m² /ha) in *Pinus sylvestris*-*Larix sibirica* forest

Tree species	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev.	Coef.Var	Std. Error
<i>BePl</i>	2.99	1.52	4.47	0.56	5.77	4.24	2.06	68.7	0.65
<i>LaSi</i>	3.47	2.42	4.52	0.86	5.74	2.17	1.47	42.4	0.47
<i>PiSi</i>	0.00	-0.01	0.02	0.00	0.05	0.00	0.02	316.2	0.01
<i>PiSy</i>	23.16	17.21	29.11	13.61	41.57	69.28	8.32	35.9	2.63
<i>PpTr</i>	0.00	-0.00	0.01	0.00	0.03	0.00	0.01	316.2	0.00
Total	29.70	24.07	35.33	19.00	44.67	61.88	7.87	26.5	2.49

Appendix Table 5: Basal areas (m² /ha) of snag and live trees in *Pinus sibirica*-*Abies sibirica* forest

Tree condition	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
Broken	0.22	-0.18	0.61	0.09	0.40	0.03	0.16	74.47	0.09
Dead	7.26	3.11	11.42	1.66	16.75	33.78	5.81	80.02	1.84
Dead and Broken	1.66	0.56	2.77	0.51	5.21	2.39	1.55	92.88	0.49
Live	38.25	29.92	46.58	21.34	55.48	135.7	11.65	30.46	3.68
Total	47.24	40.03	54.46	30.71	63.82	101.7	10.09	21.35	3.19

Appendix Table 6: Basal areas (m² /ha) of snag and live trees in *Picea obovata*-*Abies sibirica* forest

Tree condition	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
Dead	1.61	0.07	3.15	0.24	5.83	3.39	1.84	114.3	0.65
Dead and Broken	0.78	-0.23	1.79	0.28	1.71	0.40	0.63	81.1	0.31
Live	24.95	20.08	29.82	14.26	36.97	46.30	6.80	27.3	2.15
Total	26.55	21.58	31.52	15.15	37.50	48.25	6.94	26.2	2.19

Appendix Table 7: Basal areas (m²/ha) of snag and live trees in *Larix sibirica*-*Betula platyphylla* forest

Tree condition	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
Broken	0.24			0.24	0.24				
Dead	2.35	0.73	3.97	0.12	7.19	4.45	2.11	89.69	0.70
Dead and Broken	0.30	0.06	0.54	0.04	0.79	0.08	0.29	96.41	0.10
Live	26.15	22.81	29.49	19.80	32.79	21.78	4.67	17.85	1.48
Total	28.52	26.03	31.02	22.60	33.31	12.19	3.49	12.24	1.10

Appendix Table 8: Basal areas (m²/ha) of snag and live trees in *Pinus sylvestris*-*Larix sibirica* forest

Tree condition	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
Broken	0.32	-2.29	2.93	0.11	0.52	0.08	0.29	91.1	0.21
Dead	2.83	0.96	4.70	0.52	9.33	6.84	2.61	92.5	0.83
Dead and Broken	0.66	-0.21	1.53	0.09	3.05	1.08	1.04	157.8	0.37
Live	26.28	20.37	32.20	16.79	43.95	68.41	8.27	31.5	2.62
Total	29.70	24.07	35.33	19.00	44.67	61.88	7.87	26.5	2.49

Appendix Table 9: Length of downed logs (m/ha) by diameter classes in *Pinus sibirica*-*Abies sibirica* forest

Diameter class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef. Var	Std. Error
<10 cm	581.24	192.16	970.32	0.0	1489.69	295827.9	543.90	93.58	172.00
11-20 cm	534.77	243.79	825.74	0.0	1066.35	165449.9	406.76	76.06	128.63
21-30 cm	747.40	222.54	1272.26	0.0	2307.77	538324.7	733.71	98.17	232.02
31-40 cm	428.13	78.38	777.88	0.0	1273.25	239036.3	488.91	114.20	154.61
41-50 cm	109.82	-8.07	227.71	0.0	509.30	27157.5	164.80	150.06	52.11
51-60 cm	218.04	-103.18	539.27	0.0	1209.59	201635.0	449.04	205.94	142.00
61-70 cm	0.00			0.0	0.00	0.0	0.00	0.00	0.00
Total	2619.4	1286.6	3951.8	0.0	4854.28	3469322.9	1862.61	71.11	589.01

Appendix Table 10: Length of downed logs (m/ha) by diameter classes in *Picea obovata*-*Abies sibirica* forest

Diameter class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef. Var	Std. Error
<10 cm	561.82	164.36	959.28	0.0	1241.42	308701.8	555.61	98.89	175.70
11-20 cm	413.81	67.39	760.23	0.0	1352.83	234507.6	484.26	117.03	153.14
21-30 cm	664.64	183.09	1146.19	0.0	1820.75	453147.5	673.16	101.28	212.87
31-40 cm	351.74	71.90	631.57	0.0	1050.43	153023.8	391.18	111.21	123.70
41-50 cm	205.31	-172.24	582.86	0.0	1687.06	278552.4	527.78	257.06	166.90
51-60 cm	165.52	-120.46	451.51	0.0	1241.42	159820.9	399.78	241.52	126.42
61-70 cm	0.00			0.0	0.00	0.0	0.00	0.00	0.00
Total	2362.84	819.52	3906.17	0.0	5140.76	4654466.5	2157.42	91.31	682.24

Appendix Table 11: Length of downed logs (m/ha) by diameter classes in *Larix sibirica*-*Betula platyphylla* forest

Diameter class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std. Dev	Coef. Var	Std. Error
<10 cm	403.62	52.08	755.17	0.0	1623.40	241500.7	491.43	121.75	155.40
11-20 cm	244.15	43.93	444.36	0.0	859.45	78334.4	279.88	114.64	88.51
21-30 cm	191.94	26.40	357.49	0.0	732.12	53553.0	231.42	120.56	73.18
31-40 cm	225.68	-60.94	512.30	0.0	1254.16	160533.5	400.67	177.53	126.70
41-50 cm	101.22	-27.61	230.06	0.0	477.47	32436.6	180.10	177.92	56.95
51-60 cm	168.71	-47.06	384.48	0.0	795.78	90977.2	301.62	178.79	95.38
61-70 cm	0.00			0.0	0.00	0.0	0.00	0.00	0.00
Total	1335.33	739.32	1931.33	0.0	2864.82	694143.1	833.15	62.39	263.47

Appendix Table 12: Length of downed logs (m/ha) by diameter classes in *Pinus sylvestris-Larix sibirica* forest

Diameter class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef. Var	Std. Error
<10 cm	360.33	36.56	684.10	0.0	1480.16	204844.2	452.60	125.61	143.12
11-20 cm	159.79	-14.41	334.00	0.0	668.46	59300.8	243.52	152.40	77.01
21-30 cm	211.68	40.51	382.84	0.0	557.05	57250.6	239.27	113.04	75.66
31-40 cm	301.76	175.47	428.05	0.0	636.63	31166.7	176.54	58.50	55.83
41-50 cm	98.68	-48.68	246.03	0.0	636.63	42432.0	205.99	208.75	65.14
51-60 cm	148.97	-25.18	323.12	0.0	732.12	59264.8	243.44	163.42	76.98
61-70 cm	15.92	-20.09	51.92	0.0	159.16	2533.1	50.33	316.23	15.92
Total	1297.13	694.29	1899.97	0.0	3119.47	710165.8	842.71	64.97	266.49

Appendix Table 13: Length of downed logs (m/ha) by decay classes in *Pinus sibirica*-*Abies sibirica* forest

Decay class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
1	150.56	-123.82	424.94	0.0	1209.59	147117.2	383.56	254.75	121.29
2	483.52	77.16	889.87	0.0	1890.76	322680.3	568.05	117.48	179.63
3	891.28	348.35	1434.21	0.0	2451.01	576024.6	758.96	85.15	240.01
4	408.08	101.62	714.53	0.0	1238.23	183525.3	428.40	104.98	135.47
5	685.97	130.98	1240.95	0.0	2212.28	601887.3	775.81	113.10	245.33
Total	2619.40	1286.96	3951.83	0.0	4854.28	3469322.9	1862.61	71.11	589.01

Appendix Table 14: Length of downed logs (m/ha) by decay classes in *Picea obovata*-*Abies sibirica* forest

Decay class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
1	66.85	-62.17	195.86	0.0	572.96	32525	180.35	269.79	57.03
2	549.09	41.47	1056.71	0.0	1782.56	503536	709.60	129.23	224.40
3	184.62	10.61	358.64	0.0	668.46	59173	243.25	131.76	76.92
4	619.12	109.68	1128.56	0.0	1814.39	507149	712.14	115.03	225.20
5	943.16	168.44	1717.88	0.0	3358.21	1172851	1082.98	114.82	342.47
Total	2362.84	819.52	3906.17	0.0	5140.76	4654466	2157.42	91.31	682.24

Appendix Table 15: Length of downed logs (m/ha) by decay classes in *Larix sibirica*-*Betula platyphylla* forest

Decay class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
1	28.65	-36.16	93.45	0.0	286.48	8207.2	90.59	316.23	28.65
2	635.04	291.03	979.04	0.0	1496.07	231254.6	480.89	75.73	152.07
3	211.68	47.56	375.80	0.0	636.63	52634.7	229.42	108.38	72.55
4	257.83	15.83	499.84	0.0	865.81	114448.3	338.30	131.21	106.98
5	202.13	9.64	394.61	0.0	642.99	72401.8	269.08	133.12	85.09
Total	1335.33	739.32	1931.33	0.0	2864.82	694143.1	833.15	62.39	263.47

Appendix Table 16: Length of downed logs (m/ha) by decay classes in *Pinus sylvestris*-*Larix sibirica* forest

Decay class	Mean	CI -95.0%	CI 95.0%	Min	Max	Variance	Std.Dev	Coef.Var	Std. Error
1	38.20	-48.21	124.61	0.0	381.98	14591	120.79	316.23	38.20
2	704.11	219.58	1188.64	0.0	2116.78	458770	677.33	96.20	214.19
3	245.10	67.48	422.72	0.0	668.46	61650	248.29	101.30	78.52
4	238.10	67.79	408.40	0.0	572.96	56678	238.07	99.99	75.28
5	71.62	-53.13	196.37	0.0	557.05	30411	174.39	243.49	55.15
Total	1297.13	694.29	1899.97	0.0	3119.47	710166	842.71	64.97	266.49

Appendix Table 17: Statistics of the diameter (DBH 1.3 m) distribution of *Pinus sibirica*-*Abies sibirica* forest tree species. The mean, max and min diameters and their standard deviations are included.

Tree species	Mean DBH, cm			Max DBH, cm			Min DBH, cm		
	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.
<i>AbSi</i>	16.8	11.9-19.8	2.3	38.7	32.0-58.0	9.1	5.7	5.0-7.5	0.8
<i>BePl</i>	2.0	0-11.0	4.3	3.5	0-17.5	7.3	1.1	0-5.5	2.2
<i>LaSi</i>	33.1	0-61.4	24.0	39.8	0-74.5	29.4	23.6	0-52.3	20.7
<i>PcOb</i>	16.2	0-25.1	6.6	31.4	0-50.7	16.5	7.5	0-14.5	3.9
<i>PiSi</i>	32.2	21.5-37.9	4.6	71.4	49.5-92.0	12.7	6.9	5.0-11.0	2.1
<i>Salix spp.</i>	1.7	0-17.0	5.4	1.7	0-17.0	5.4	1.7	0-17.0	5.4
Grand mean	21.8	16.0-26.4	3.3	72.9	50.7-92.0	12.8	5.7	5.0-7.5	0.8

Appendix Table 18: Statistics of the diameter (DBH 1.3 m) distribution of *Picea obovata*-*Abies sibirica* forest tree species. The mean, max and min diameters and their standard deviations are included.

Tree species	Mean DBH, cm			Max DBH, cm			Min DBH, cm		
	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.
<i>AbSi</i>	12.3	5.1-18.7	4.5	33.4	7.0-51.7	13.7	5.1	3.4-8.0	1.2
<i>BeP</i>	12.9	0.0-17.8	5.0	31.2	0-41.5	11.5	4.6	0-7.3	2.1
<i>LaSi</i>	41.3	0.0-75.4	22.4	50.9	0-76.5	23.3	31.6	0-75.4	27.0
<i>PcOb</i>	16.2	9.3-24.0	4.1	40.8	30.4-70.5	12.3	6.3	2.5-9.8	2.3
<i>PiSi</i>	22.5	0-39.6	12.0	37.2	0.0-62.8	22.1	9.3	0-15.5	5.8
<i>Salix</i>	1.6	0-16.0	5.1	1.6	0-16.0	5.1	1.6	0-16.0	5.1
<i>Unknown spp.</i>	2.9	0-22.0	7.1	3.6	0-28.0	8.9	2.3	0-16.0	5.2
Grand mean	15.4	11.8-19.4	2.6	61.2	39.5-76.5	13.2	4.7	2.5-7.3	1.4

Appendix Table 19: Statistics of the diameter (DBH 1.3 m) distribution of *Larix sibirica*-*Betula platyphylla* forest tree species. The mean, max and min diameters and their standard deviations are included.

Tree species	Mean DBH, cm			Max DBH, cm			Min DBH, cm		
	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.
<i>BePl</i>	18.2	12.6-22.0	3.0	38.0	25.8-59.0	10.5	7.72	3.0-12.6	3.4
<i>LaSi</i>	29.9	10.7-47.3	9.9	59.4	34.5-78.2	11.8	9.48	3.0-21.0	5.5
<i>PiSi</i>	6.4	0.0-16.0	7.0	7.3	0-16.5	7.9	5.57	0-16.0	6.4
<i>PiSy</i>	10.0	0-41.9	16.9	13.4	0-64.6	23.5	6.55	0-40.0	12.9
<i>PpTr.</i>	2.7	0-27.0	8.5	2.7	0-27.0	8.5	2.70	0-27.0	8.5
Grand mean	24.1	14.9-30.3	4.7	63.0	52.0-78.2	7.3	6.49	3.0-11.0	2.8

Appendix Table 20: Statistics of the diameter (DBH 1.3 m) distribution of *Pinus sylvestris*-*Larix sibirica* forest tree species. The mean, max and min diameters and their standard deviations are included.

Tree species	Mean DBH, cm			Max DBH, cm			Min DBH, cm		
	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.	Mean	Range	Std. Dev.
<i>BePl</i>	13.1	8.6-23.4	4.4	24.8	18.0-34.6	6.8	5.8	3.8-11.0	2.2
<i>LaSi</i>	19.1	9.4-30.8	6.5	43.3	22.9-56.3	9.2	5.6	3.1-8.5	1.6
<i>PiSi</i>	0.4	0-4.0	0.5	0.0	5.4-1.7	0.3	0	3.1-1.0	
<i>PiSy</i>	24.3	12.3-29.9	6.0	64.7	54.3-93.3	12.1	5.1	3.4-7.4	1.3
<i>PpTr</i>	0.7	0-7.2	2.3	0.7	0-7.2	2.3	0.7	0-7.2	2.3
<i>Unknown spp.</i>	3.7	0-37.4	11.8	3.7	0-37.4	11.8	3.7	0-37.4	11.8
Grand mean	19.9	10.9-27.2	5.9	64.8	54.3-93.3	12.0	4.8	3.1-7.4	1.4

Appendix Table 21a: Composition and number of the sapling species (per ha) in *Pinus sibirica*-*Abies sibirica* forest

Sapling height class	Species						Grand Total
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>	<i>BePl</i>	
51-150 cm	3246.8	2737.5	477.5				6461.7
151-250 cm	795.8	2005.4	95.5			31.8	2928.5
251-350 cm	318.3	191.0				31.8	541.1
Total	4360.8	4933.8	573.0			63.7	9931.3

Appendix Table 21b: Proportion (%) of the sapling species in *Pinus sibirica*-*Abies sibirica* forest

Sapling height class	Sapling species						Grand Total
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>	<i>BePl</i>	
51-150 cm	32.7	27.6	4.8				65.1
151-250 cm	8.0	20.2	1.0			0.3	29.5
251-350 cm	3.2	1.9				0.3	5.4
Total	43.9	49.7	5.8			0.6	100.0

Appendix Table 22a: Composition and number of the sapling species (per ha) in *Picea obovata*-*Abies sibirica* forest

Sapling height class	Sapling species						Grand Total
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>	<i>BePl</i>	
51-150 cm	1209.6	668.5	95.5			254.6	2228.2
151-250 cm		413.8	127.3				541.1
251-350 cm		509.3				95.5	604.8
>351 cm		445.6					445.6
Total	1209.6	2037.2	222.8			350.1	3819.7

Appendix Table 22b: Proportion (%) of sapling the species in *Picea obovata*-*Abies sibirica* forest

Sapling height class	Sapling species					Grand Total	
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>		<i>BePl</i>
51-150 cm	31.7	17.5	2.5			6.7	58.3
151-250 cm		10.8	3.3				14.2
251-350 cm		13.3				2.5	15.8
>351 cm		11.7					11.7
Total	31.7	53.3	5.8			9.2	100.0

Appendix Table 23a: Composition and number of the sapling species (per ha) in *Larix sibirica*-*Betula platyphylla* forest

Sapling height class	Sapling species					Grand Total	
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>		<i>BePl</i>
51-150 cm				423.0		732.1	1155.1
151-250 cm						509.3	509.3
251-350 cm						222.8	222.8
Total				423.0		1464.2	1887.2

Appendix Table 23b: Proportion (%) of the sapling species in *Larix sibirica*-*Betula platyphylla* forest

Sapling height class	Sapling species					Grand Total	
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>		<i>BePl</i>
51-150 cm				22.4		38.8	61.2
151-250 cm						27.0	27.0
251-350 cm						11.8	11.8
Total				22.4		77.6	100.0

Appendix Table 24a: Composition and number of the sapling species (per ha) in *Pinus sylvestris-Larix sibirica* forest

Sapling height class	Sapling species						Grand Total
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>	<i>BePl</i>	
51-150 cm	63.7			95.5	541.1	95.5	795.8
151-250 cm						31.8	31.8
Total	63.7			95.5	541.1	127.3	827.6

Appendix Table 24b: Proportion (%) of the sapling species in *Pinus sylvestris-Larix sibirica* forest

Sapling height class	Sapling species						Grand Total
	<i>PiSi</i>	<i>AbSi</i>	<i>PcOb</i>	<i>LaSi</i>	<i>PiSy</i>	<i>BePl</i>	
51-150 cm	7.7			11.5	65.4	11.5	96.2
151-250 cm						3.8	3.8
Total	7.7			11.5	65.4	15.4	100.0

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