

Forest Age Distribution and Traces of Past Fires in a Natural Boreal Landscape Dominated by *Picea abies*

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Wallenius, T. 2002. Forest age distribution and traces of past fires in a natural boreal landscape dominated by *Picea abies*. *Silva Fennica* 36(1): 201–211.

Forest age distribution and occurrence of traces of past fires was studied in a natural *Picea abies*-dominated landscape in the Onega peninsula in north-west Russia. Forest age (maximum tree age) was determined and charcoal and fire scars were searched for in 43 randomly located study plots. In 70% of the study plots (30/43) trees older than 200 years existed. The largest 50-year age class consisted of plots with 251–300 year old forests. Traces of fires were found in all types of study plots, in forests on mineral soil as well as on peatlands. However, fire has been a rare disturbance factor, as traces of fires could not be found in 35% of the study plots (15/43). Estimated from the forest age class distribution, the fire rotation time for the whole area has been at least 300 years, but possibly considerably longer. This fire rotation time is much longer than fire history studies (largely based on examination of fire scars) commonly have reported for the average time between successive fires in Fennoscandia and Northwest Russia. The results suggest that the often stated generalisations about the importance and natural frequency of fire disturbance in boreal forests do not apply in landscapes dominated by *Picea abies*.

Keywords boreal forest, disturbance dynamics, fire refugia, tree age

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Received 1 November 2000 **Accepted** 30 January 2002

1 Introduction

Forest age distribution and disturbance regime are central characteristics of forest landscapes. Forest age distribution gives an idea of what kind of forests there exists in a landscape and what are the proportions of different forest successional stages. At the stand scale, tree size distribution

and species composition change with forest age and stand succession. Forest age and disturbance history also affect the amount and quality of decaying trees, which are important for species diversity in forests (Ohlson et al. 1997, Sturtevant et al. 1997). An adequate knowledge about the variability of disturbance dynamics and structure of natural forests is the foundation for ecologi-

cally sound forest management and conservation of protection areas (Landres et al. 1999, Bergeron et al. 2002, Kuuluvainen 2002).

In Scandinavian countries, intensive forest management and forest fire suppression have considerably changed the structure and dynamics of the forests. The age of managed forest stands do not usually exceed the economical rotation time, which is typically 80–120 years in the boreal vegetation zone. For example, in Finland 13.5% and in Sweden only 11% of forests are older than 120 years (Metsätilastollinen vuosikirja 2000, Skogsstatistisk Årsbok 1998). Usually forests are clear-cut before they come even close to the biological maximum age of the most common Fennoscandian boreal tree species.

In addition to human influence, the age structure of a tree stand, as well as the forest age structure of a landscape, are influenced by natural disturbances such as forest fires, storms and outbreaks of insects and pathogens (White 1979). In general, fire is considered to be the most important natural forest-renewing factor in the boreal zone (Rowe and Scotter 1973, Goldammer and Furyaev 1996). Several studies have shown that even peatlands can burn fairly frequently (Tolonen 1985, Segerström et al. 1994, Pitkänen et al. 1999). Nevertheless, some studies indicate that there are forested sites, which have not been burnt for very long periods (Steijlen and Zackrisson 1987, Hörnberg et al. 1995, Zackrisson et al. 1995, Kuuluvainen et al. 1998). Some evidence exists that *Picea* forest probably burn more seldom than *Pinus* forests (Zackrisson 1977, Engelmark 1987). In addition, forests with a dense *Picea* undergrowth can burn more severely than open forests (Granström et al. 1995). However, the relations of forest site type, tree species composition and fire frequency are still largely unresolved (cf. Zackrisson 1977, Engelmark 1987, Lehtonen 1997, Pitkänen 1999, Niklasson and Granström 2000) and the extent and characteristics of the fire refugia in natural forest landscapes are not known (Vanha-Majamaa 1998, Ohlsson and Tryterud 1999).

Forest age distribution of a natural forest landscape has seldom been measured. Modelling approaches to landscape forest age distribution and landscape dynamics have been more common. Van Wagner (1978) introduced a theory,

predicting that forest age class distribution of a landscape has the form of a negative exponential function, implying a domination of young forest age classes (see Pennanen 2002, Fig. 4). The assumptions of the theory are that a landscape is composed of forest patches with different ages and that more or less equal area of the forests in the landscape is renewed by random stand-replacing fire events every year. Johnson (1979) presented the Weibull model, which also accounted for the change of fire ignition risk with stand age. These models predict that, in a landscape where stand-replacing fires dominate, the size (area) of forest age classes diminishes with age and the form of the forest age distribution is approximately constant over time when viewed over a sufficiently large area.

Cumming et al. (1996) tested the theory of a stationary forest age distribution using fire data in a near natural forest landscape in Canada. They found that the forest age distribution of a large (>70 000 km²) boreal mixedwood forest landscape was not stationary. The theoretical work by Boychuck et al. (1997) also indicated that forest age distribution may not be stationary even in large areas. The ratio of maximum size of disturbance patches to landscape size determines if the forest age distribution is stable (Cumming et al. 1996). In general, crown-fire dominated landscapes are supposed to be non-equilibrium systems, where the proportions of young and old forests fluctuate over time (Turner and Romme 1994). On the other hand, equilibrium landscape structures could exist where small-scale disturbances are the rule (Kuuluvainen et al. 1998).

In North America as well as in continental Siberia and China, forest fires are often severe and affect large areas, killing trees in areas up to thousands of square kilometres (Wein and MacLean 1983, Johnson 1992). In Fennoscandian boreal forests, large crown fires may not have been common even in ancient times, because of the climatic conditions, characteristics of the tree species, and the large proportion of swamps and lakes in the landscape (Vanha-Majamaa 1998). However, Pitkänen (1999) estimated, based on paleoecological data, that in northern Karelia before significant human influence, approximately half of the fires may have been stand-replacing.

In Scandinavian countries, forest age distribution and landscape dynamics of natural forests cannot be empirically examined because of the extensive human influence. Fortunately, feasible natural reference landscapes exist in Northwest Russia (Angelstam and Borgegård 1993). For this study I selected an area locating in the Onega Peninsula, Northwest Russia, representing a large forest area dominated by *Picea abies* (L.) Karst. with minimal human influence. The purpose of this study was to examine the forest age distribution and evaluate the importance of fires in a natural boreal landscape dominated by *Picea abies*.

2 Material and Methods

2.1 Study Area

The study was carried out in the Northwestern half of the Onega peninsula in Northwest Russia (Fig. 1). This area consists of about 5000 km² of roadless taiga. The population of only 1300 permanent inhabitants lives in seven small villages on the coast of the peninsula. The inland area has remained uninhabited. Until the 17th century, salt extraction from seawater demanded large amounts of firewood and at this time the forests near the coast have probably been extensively harvested. Presently, any traces of human influence on forests and peatlands are very infrequent in the inner parts of the peninsula. A large national park in the peninsula has been proposed.

The study area is situated in the middle boreal vegetation zone (Ahti et al. 1968). The average July temperature in Arkhangelsk in 1813–1988 was 15.7°C and the average yearly rainfall in 1852–1989 was 491 mm (The Global Historical Climatology Network, <http://www.worldclimate.com>). The topography of the Onega peninsula is gently sloping or flat with a few steep river ravines. The altitude in the inner peninsula is mostly between 100–150 m above sea level.

Peatlands, largely open bogs dominated by *Pinus sylvestris* L., cover approximately 30% of the land area of the peninsula. Forests on mineral soil are generally dominated by *Picea*. *Bet-*

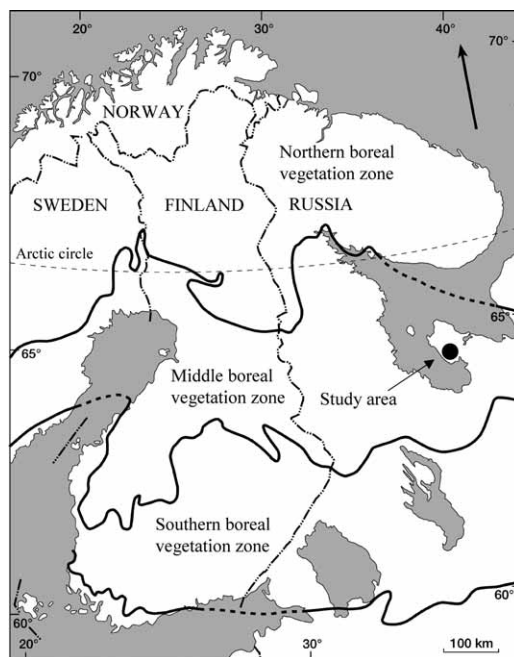


Fig. 1. The location of the study area in Onega peninsula, north-west Russia. Vegetation zones are according to Ahti et al. (1968) in Russia and according to Kalela (1961) in Finland.

ula-dominated forests are rare, but some *Betula pubescens* Ehrh. typically grow under the dominant coniferous trees.

On mineral soil, *Vaccinium myrtillus* L. is the dominant field layer species but *Gymnocarpium dryopteris* (L.) Newm and *Maianthemum bifolium* (L.) F. W. Schmidt are also abundant. The field layer of damp and more or less paludified sites are dominated by *Sphagnum* spp. On drier sites *Dicranum* spp. and *Pleurozium schreberi* (Brid.) Mitt. are the typical moss species.

Pinus-dominated peatlands are covered by *Sphagnum* spp. mosses. *Eriophorum vaginatum* L. is the most abundant herbaceous species. Other common plant species on *Pinus* bogs are *Vaccinium uliginosum* L., *Vaccinium oxycoccus* L. and *Carex globularis* L. *Picea* dominated peatlands are dominated by *Sphagnum* spp. and *Polytrichum commune* Hedw. mosses. *Rubus chamaemorus* L. and *Vaccinium myrtillus* are the most prevalent herbaceous plants on those sites.

2.2 Sampling

A study area of 9 km × 15 km (64°55'N, 37°39'E) was selected from the interior parts of the Onega peninsula (Fig. 1). Locations of sixty study plots with a radius of 20 m were randomly distributed over the study area. Randomisation was done with the ArcView GIS (Geographic Information System) software. However, all the randomised study plots could not be investigated due to a lack of time in the field. Altogether 47 study plots were examined beginning from the west side of the study area. Four study plots of the 47 turned out to be in lakes, leaving 43 valid study plots. The study plots were located with a measuring tape and a GPS (Global Positioning System) satellite navigation device. First, a point was looked for where the GPS device showed the first time coordinates that were 30 m away from the coordinates of the study plot. Secondly, the remaining 30 m distance was measured with a tape. This was done to avoid any possible influence of forest openings on the GPS positioning.

2.3 Recording of Site and Stand Characteristics

The recorded site characteristics were fertility, dampness and the occurrence of peat deposits. The area of the study plots was divided into different vegetation types, if necessary. Only the area of the dominating vegetation type in the study plot was studied. This limitation was set so that fire history in the studied plot area would be as uniform as possible.

In order to determine the tree species composition and to estimate the tree cover in the study plots, the basal area (m²/ha) of living trees and dead standing trees was measured by species with a relascope. This was done in three places, in the centre of the study plot and in two points 20 m apart from the centre in opposite directions, assuming they were in the dominating vegetation type.

2.4 Determination of Forest Age

In this study forest age was defined as the highest

age of living trees in a forest patch. In order to determine forest age, 2–7 trees were sampled in each study plot. If the age structure of trees in the study plot was not obvious (e.g. there were not only a few large trees or the oldest tree was not evident) the sampling procedure was as follows. First the three oldest looking trees were selected and then the three trees nearest to the centre point of the study plot belonging to the dominant canopy layer (irrespective of species) were sampled. Estimation of the tree age for sampling was based on tree size, health and appearance of the bark (Volkov et al. 1997). Sampling was not restricted to the dominant tree species of the site. In *Picea* dominated sites, also *Pinus* were sampled and vice versa.

Large trees were cored with an increment corer and from small trees, disks were taken with a handsaw. Samples were taken about 30 cm above the root collar. In a few cases trees were sampled higher due to badly rotten heartwood at stump level. Altogether 209 trees were sampled and analysed. Year rings of the core and disk samples were counted in the laboratory with a microscope. Samples were prepared with a razor blade for better visibility of the year rings. In some cases, when the latest year rings could not be distinguished and counted, the first years were dated with the marker year method (Douglas 1941, Niklasson et al. 1994). Only one fourth of the sample cores had a pith. The number of missing year rings in the pith was estimated by considering the curvature and thickness of the innermost rings (Arno and Sneek 1977). Additionally, five years was added to the age of each sample tree because samples were taken from stump level. Five years can be used as a reasonable estimate of mean tree age at 30 cm height (Oinonen 1968). However, especially *Picea* may grow very slowly at the seedling stage (Niklasson 1998). Thus the maximum tree ages presented here (forest ages) are in many cases underestimates of the actual ages.

2.4 Determination of Fire Occurrence

The occurrence of past fires was studied using a combination of three methods. First, charcoal particles were looked for in the humus layer and on top of mineral soil by digging five subplots

with a spade in each study plots. Subplots were situated along a straight line crossing the centre of the study plot, 2.5 m apart from each other in the dominant vegetation type. The size of each subplot was approximately 0.2 m × 0.2 m. Whether or not there was charcoal was determined in the field. Only large (> 1–2 mm) thoroughly black particles that could be crumbled by fingers were identified as charcoal. Second, visible charcoal layers in peat deposits were searched for and the depth of the layers was measured, if the dominant vegetation type of the study plot was on peatland. Charcoal layers in peat deposits can provide evidence of several successive fires (Tolonen 1985, Wein et al. 1987). Samples were taken by a Russian type peat sampler (sample size 5 cm × 50 cm) to a depth of one meter, when possible. Sampling was done in the same positions (the five subplots) where charcoal under humus layer was studied on mineral soil. Peat samples were analysed in the field as well. Third, fire scars and charred stumps were looked for in the study plots. A wedge was sawn from the fire scars for dating the fires (Arno and Sneek 1977).

3 Results

3.1 Forest Age Distribution

The observed forest age distribution was bimodal (Fig. 2). The largest 50-year age class was the 251–300 year old forests. Forests of 51–100 year old formed another peak in the age class distribution. Forest younger than 50 years of age did not exist in the study plots. In 86% of the study plots (37/43) trees older than 120 years existed and 70% of the study plots (30/43) had trees older than 200 years. Taking all plots into account, the oldest tree was a *Pinus* approximately 408 years old (401 counted tree rings, plus stump level age 5 years, plus the estimated number of rings in the pith, 2 years). This *Pinus* tree grew in a *Picea*-dominated site, where the oldest *Picea* were over 300 years. The tree age distribution in the study plots was not measured. However, judging from the appearance of the forest structure, it appeared likely that both single-cohort stands as well stands, where no dominating cohort could

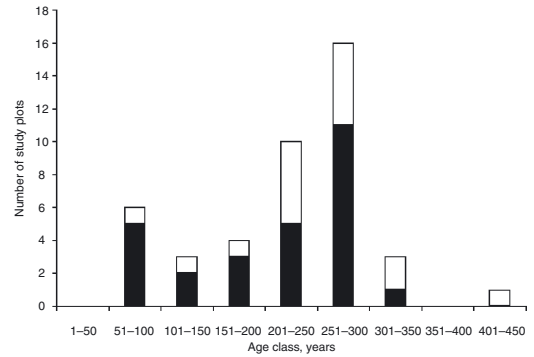


Fig. 2. The forest age class distribution of the study plots. Black area indicates study plots with signs of fire.

Table 1. Forest age statistics for different type of study plots.

	N	Average forest age	Max	Min	StDev
<i>Picea</i> dominated	27	259	408	82	64
<i>Pinus</i> dominated	13	173	239	77	78
<i>Betula</i> dominated	3	154	284	66	85
Peatland	15	202	291	66	79
Mineral soil	28	238	408	77	82
Burned	28	208	348	66	79
Unburned	15	257	408	85	79
All study plots	43	225	408	66	82

be detected, existed. However, it appeared that multi-cohort stands were rare.

On average, forests were younger on peatland than on mineral soil (Table 1). The youngest forests were *Betula*-dominated and the oldest *Picea*-dominated except some rare *Pinus* dominated sites on mineral soil. Forests were older in fertile than in poor sites (data not shown). A relatively large proportion of young forests was situated in the south-west part of the study area (Fig. 3).

3.2 Occurrence of Past Fires

Overall, traces of past fires were found in 65% of studied plots (28/43) (Table 2). All types of study plots had burned, i.e. forests on mineral soil as well as on peatlands. Signs of fires were most

Table 2. Traces of past fires in different type of study plots.

Study plot vegetation	Macroscopic charcoal under humus	Fire layer in peat	Charred wooden pieces	Fire scars	Number of study plots
Forest on mineral soil	X	-	X	X	1
Forest on mineral soil	X	-	X	-	8
Forest on mineral soil	X	-	-	-	9
Forest on mineral soil	-	-	-	-	10
Pine bog	-	X	X	-	5
Pine bog	-	X	-	-	2
Pine bog	-	-	X	-	1
Pine bog	-	-	-	-	2
Spruce swamp	-	X	-	-	2
Spruce swamp	-	-	-	-	3

common on relatively open *Pinus* bogs, eight of ten study plots on this site type had burned. However, fires had also occurred on mineral soil where 18 of 28 plots (64%) had burned and 2 of 5 plots (40%) in *Picea* swamps.

Macroscopic charcoal particles under the humus layer and in peat deposits were the most

prevalent signs of fire. Most of the charcoal layers in peat were in the upper 0.5 m layer. The depth of charcoal layers in the peat varied between 8–56 cm. Charred stumps and other wooden pieces were common especially in *Pinus* bogs. Fire scars were very rare in the landscape, as fire scars were only found in one study plot. This forest was

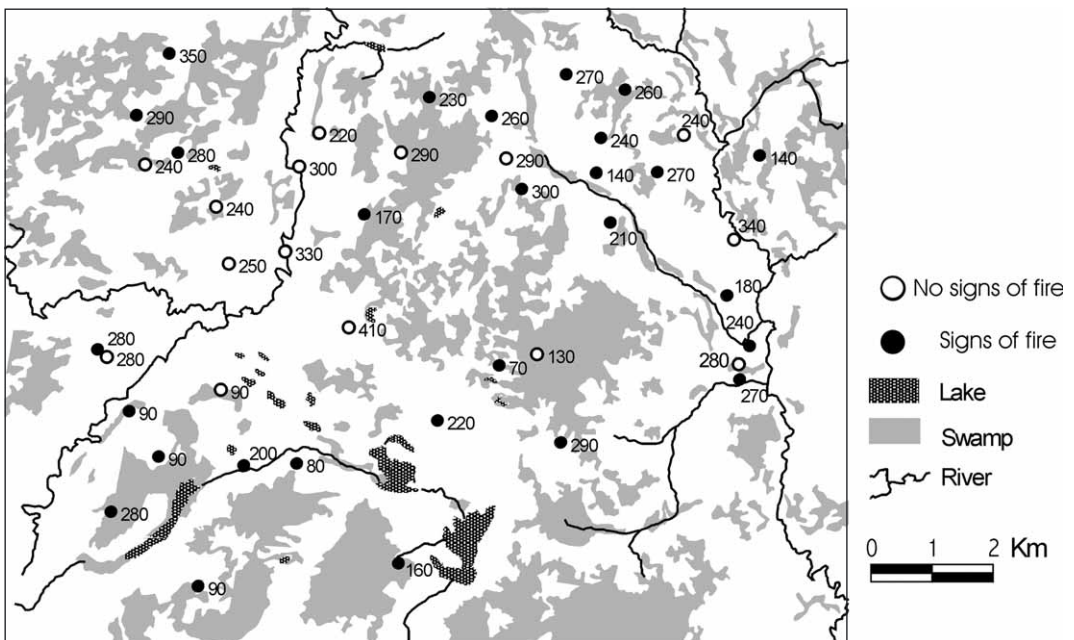


Fig. 3. The location of the study plots in the landscape. Study plots which included traces of past fires are marked with black dots, open circles mark unburned study plots. Forest ages are beside the study plots.

burned in 1927/1928. This open *Pinus*-dominated forest was located on a dry site type, where the forest floor vegetation consisted mainly of lichen and feather moss.

About one third of the study plots lacked traces of past fires (Table 2). There was no distinct category of study plots, which exclusively lacked signs of fire, with the exception of the two herb-rich forest plots near a river, which had no signs of fire. However, the study plots lacking traces of fires were concentrated in the north-west quarter of the study area (Fig. 3).

4 Discussion

4.1 Evaluation of the Method

The age of the forest in the study plots was determined by taking samples from the oldest trees. Subjectively selecting the oldest trees in the study plot proved to be difficult. In 18 plots the subjectively selected oldest-looking trees were the oldest sampled trees. However, in 10 plots the oldest of the cored trees was found among the trees sampled systematically nearest to the centre of the study plot. In one plot the oldest of the subjectively and systematically selected trees had the same age. In the remaining 14 plots only a few trees were cored due to small number of trees or due to clearly even aged structure of the young cohort.

In the ten study plots where subjective selection of the oldest tree failed, the difference between the age of the oldest subjectively selected tree and the oldest systematically selected tree was on average 23 years. This large average difference was due to one plot where the difference was 91 years. It is probable that, if every tree in every study plot had been sampled, a few years or at maximum a few decades older trees would have been found in many plots than had been found now. However, coring of all trees would have not been a feasible method in the allocated time in the wilderness circumstances. Moreover, the percentual error of the methods used is not large, since the age of the forests was on average 225 years.

The finding of traces of past fires evidently depends on the effort out into searching for them. This can be deduced from the fact that in one

case a charred stump was found in a study plot although no fire layer was detected in the peat cores (Table 2). Accordingly, the proportion of study plots with signs of fire would probably have been larger if more peat cores and subplots in the humus layer had been analysed. However, the absence of apparent charcoal and the old age of the forests suggest that the sites have not experienced fire for a very long time.

4.2 Forest Age Distribution and Traces of Fires

Compared with managed forests, forests in the study area were old. The lack of young forests (<50 years) and recent fire areas may be due to strengthened fire control since the 1950s in Russia (Pyne 1996). On the other hand, since fires seem to be rare in the landscape, it can just by coincidence be that there have been no fires in the last 50 years. However, even if the lack of young forest is due to fire suppression, and is excluded from the analysis, the observed forest age distribution does not fit the negative exponential distribution predicted by the models of van Wagner (1978) and Johnson (1979). This suggests that the forest age distribution in the landscape is not stationary in the scale studied. It can be argued that this is due to the fact that the landscape was small compared with the size of fires. This is a relevant argument, but on the other hand Russian forestry maps substantiate that a major part of the north-western half of the Onega peninsula (ca. 5000 km²) is covered by similar old forests as the studied area.

The peak in the forest age distribution in the 251–300 year old forest could be explained by the occurrence of large forest fires in the beginning of the 18th century. On the other hand, the forest age distribution may have a peak in this age class because *Picea* seldom lives longer than 300 years (Sirén 1955). If this is the cause of the observed forest age distribution, this distribution may be a stationary one. Sirén's (1955) observation that *Picea* stands in northern Finland start to 'deteriorate' after reaching the age of 220–260 years, is in accordance with this hypothesis. The younger age of forests on peatlands could be due to floods that occasionally kill trees.



Fig. 4. A small forest opening in a mineral soil forests with no signs of fire. The age of the oldest trees in the study plot was approximately 250 years. Photo: Mariko Lindgren.

Although forests with signs of fire were on average younger than forests with no signs of fire, the occurrence of traces of past fires was not strongly related to forest age. Almost all the plots with young forest had traces of fires, but charcoal was also found in plots with older forest. This is probably due to the long persistence of charcoal in the forest floor and in peat deposits (Tolonen 1985, Zackrisson et al. 1996). Also charred stumps seem to be very resistant to decay and fragmentation.

The tree species composition and the rarity of fire scars in the examined *Picea* dominated landscape also indicate that fires have been rare and mostly stand-replacing. *Picea* is known to be more sensitive to fire than *Pinus*. A high frequency of fires would have favoured *Pinus* and *Betula* at the expense of *Picea* (Lehtonen 1997, Pitkänen 1999, Niklasson and Drakenberg 2001).

Approximately one-third (34%) of the plots had no traces of past fires. The forests of these sites were quite old (average forest age 257 years, Table 1, Fig. 4). It is evident that most of these

sites have avoided fires for several centuries. Engelmark (1983) studied the occurrence of fires in the large Muddus National Park in northern Sweden, using methods similar to this study. He found no evidence of fire in 25% of the study plots (19/75) in the mixed coniferous – deciduous forest landscape. The mean age of the oldest trees (forest age) in his plots with no signs of fire was 240 years. Engelmark (1983) discovered that the unburned sites were mainly situated on islands of mineral soil within mire complexes. In the present study, sites with no signs of fire existed also within large continuous forest areas. Rather than being aggregated to certain type(s) of sites, the occurrence of study plots with no signs of fire was related to their location in the landscape. Half of the plots lacking traces of fires were located in the north-west quarter of the study area within a large, possibly continuous area, which had escaped fires for a very long time (Fig. 3). In the south-west quarter, the signs of fire and the occurrence of young forest suggest the occurrence of fires about 90 years ago. This

spatial distribution of burned sites, and sites with no signs of fire as well as the wide spread of the occurrence of fire marks in different vegetation types suggest that only a few real fire refugias existed in the study area. This is in accordance with the view of Granström et al. (1995).

In conclusion, traces of fires were found in all types of plots, in forests on mineral soil as well as on peatlands. However, fire has obviously been a rare disturbance factor in the natural *Picea* dominated landscape. The question whether or not the forest age class distribution of the *Picea* dominated landscape is stationary remains unsolved. The age class distribution can be stationary if large catastrophic fires do not occur. The observed age class distribution is close to a situation, where the forest age is determined by the maximum biological age of the trees. A low-intensity fire regime could be also the cause of this kind of forest age distribution (Pennanen 2002). However, no evidence for the occurrence of frequent sub-lethal fires was found in the area. The results of this study suggest, that it is very unlikely that the forest age-class distribution of a natural *Picea*-dominated landscape would conform to the theoretical negative exponential distribution, where young forest age classes are dominating. On the contrary, the results of the study suggest that in most cases natural *Picea*-dominated landscapes are dominated by old-growth forests (see also Kuuluvainen 2002, Fig. 2).

It is obvious that variations in the disturbance regimes exist within the landscape. Nevertheless, it can be roughly estimated from the forest age class distribution that the latest fire rotation time for the whole area (i.e. the time in which the cumulative sum of the burnt area equals to the whole area) has been at least 300 years, but possibly much longer. This is considerably more than fire history studies commonly have reported for the average time between successive fires in Fennoscandia (Zackrisson 1977, Haapanen and Siitonen 1978, Tolonen 1978, Tolonen 1985, Lehtonen 1997, Pitkänen 1999, Niklasson and Granström 2000, Lehtonen and Kolström 2000, Niklasson and Drakenberg 2001).

The scarcity of traces of fires in the studied landscape compared to earlier studies is probably mainly due to two interrelated factors: the poorly flammable vegetation of the *Picea* forest and the

scarcity of ignitions. Surface fires do not easily proceed in the *Picea* dominated forests, where *Sphagnum* spp., *Dicranum* spp. and *Polytrichum commune* Hedw. together with *Vaccinium myrtillus* form a considerable proportion of the forest floor vegetation. The low number of ignitions apparently reflects the low level of human impact in the peninsula.

It has been recommended that fire should be reintroduced to boreal forests under effective fire prevention (Heinselman 1973, Angelstam and Rosenberg 1993). However, most of the fire history studies in northern Europe have been done in forests where *Pinus* forms a large proportion of the forest and fire scars are abundant. Dating fires from fire scars yields more accurate fire frequencies than estimating the fire cycle from forest age distributions, but the use of the fire scar method as the only method restricts the study to forests which burn more often than those lacking fire scars. This study implies that the often stated generalisations (largely based on fire scar studies) about the importance and natural frequency of fire disturbance in boreal forests (e.g. Heinselman 1973, Esseen et al. 1997) do not apply in landscapes dominated by *Picea abies*.

Acknowledgements

I thank Professor Emeritus Rauno Ruuhijärvi for giving me the idea of visiting the Onega Peninsula. I am grateful to all the friendly people that we met on the trip and who helped us to reach our goals during the expedition to Onega. In addition, Serguei Torkhov and Mike Konoplev from the Arkhangelsk Forest Inventory Expedition patiently answered my questions and gave me a digital map of the area. My special thanks go to my assistants Heikki Koponen and Eeva Putro, with whom I did the exhaustive field expedition. I'm indebted to docent Timo Kuuluvainen, Dr. Aki Pitkänen, Dr. Mats Niklasson and one anonymous referee who gave me valuable comments for the manuscript. The Ministry of the Environment funded the journey to the Russia and a grant from the Faculty of Natural Sciences of the University of Helsinki made the indoor work with the samples and data possible.

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