Wildfires in northern Siberian larch dominated communities

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Abstract. The fire history of the northern larch forests within the permafrost zone in a portion of northern Siberia (~66ºN, 100°E) was studied. Since there is little to no human activities in this area fires within the study area were mostly caused by lightning. Fire return intervals (FRI) were estimated based on burn marks on tree stems and dates of tree natality. FRI values varied from 130 yr to 350 yr with 200±50 yr mean. In southerly larch dominated communities FRI was found to be shorter (77±20 yr at ~61°N, and 82±7 at 64°N), and longer at the northern boundary (~71°) of larch stands (320 ±50 yr). During the Little Ice Age period in the 16th to 18th centuries FRI was approximately twice as long as recorded in this study. Fire caused changes in the soil including increases in soil drainage and permafrost thawing depth and a radial growth increase of about 2 times (with more than 6 times observed). This effect may simulate the predicted warming impact on the larch growth in the permafrost zone.

Keywords: wildfires, larch forests, fire return interval, climate change

1. Introduction

Larch (*Larix spp*.) forests compose about 43% of Russian forests. Larch stands are dominants from the Yenisei ridge on the west (~92°E longitude) to the Pacific Ocean and from Baikal Lake to the south to 73rd parallel to the north. Wildfires are typical for this area with the majority occurring as ground fires due to low forest crown closure. Larch is a pyrophytic species; since fires promote the establishment of larch regeneration and reduces between species competition. Mineralized burned surfaces, enriched with nutrients are favorable for germination of the small and light weight larch seeds. The expanse of larch forests is at present considered to be a carbon sink (Shvidenko *et al* 2007). However, an increase in fire frequency in response to observed climate changes in the area may result in conversion of this area to a source for greenhouse gases (IPCC 2007). Changes in air temperature, permafrost depth and extent may affect wildfire frequency (Kharuk et al, 2008). In spite of the fact that larch dominated forests occupy about 70% of permafrost areas in Siberia, data on fire occurrence in larch forests is presented by only a few publications (Vaganov and Arbatskaya 1996, Kovacs et al 2004; Kharuk et al 2005, 2008; Schepaschenko et al, 2008; Wallenius et al, 2011). For larch dominated areas of Central Siberia average FRI was found 82±7 years (~64°N latitude), and 77±20 years for the southward "larch-mixed taiga" ecotone. For the northern boundary of larch forests (~71°N) FRI value was estimated to be 320 ±50 years (Kharuk et al 2011). For the north-east larch forests of Siberia FRI was found to be, depending on site, 50-80 and 80-120 yr (Schepaschenko et al, 2008). For southern Central Siberia Wallenius et al. (2011) reported a gradual increase of FRI from 52 years in the 18th century to 164 years in the 20th.

The purpose of this work is to investigate wildfire occurrence in the central part of larch dominated communities (figure 1).

2. Study area

The test sites were located within the Kochechum River watershed. The Kochechum River is a tributary of the Nizhnyaya (lower) Tunguska River which turns northwest and flows into the Yenesei River. This is area is the northern part of the central Siberian plateau with gentle hills with elevations up to 1000 m (figure 1).

This is a permafrost area with a severe continental climate. Mean summer (JJA) and winter (DJF) temperatures are +12°C and –35°C respectively. Mean summer and annual precipitation are 180 and 390 mm, respectively (these values are means over the years 1997–2006 averaged for 1.5º x 2.5º grid cells and covering all test sites; figure 1; WWW1).

The forests are composed of larch (*Larix gmelini* Rupr.) with a mixture of birch (*Betula pendula* Roth). Typical ground cover is composed of lichen and moss. Bushes were represented by *Betula nana*, *Salix* sp, *Ribes* sp, *Rosa* sp., *Juniperus* sp, *Vaccinium* sp, and *Ledum palustre L.* (Labrador tea).

The wildfires across this landscape occur as ground fires due to low crown closure. The seasonal fires distribution is a single-mode (late May–June) with rare late i.e., (August–early September) fires (Sofronov *et al* 1999, Kharuk *et al* 2007). Periodic stand-replacing fires cause a mosaic of the (semi) even-age stands, embedded with older trees that survived the fire.

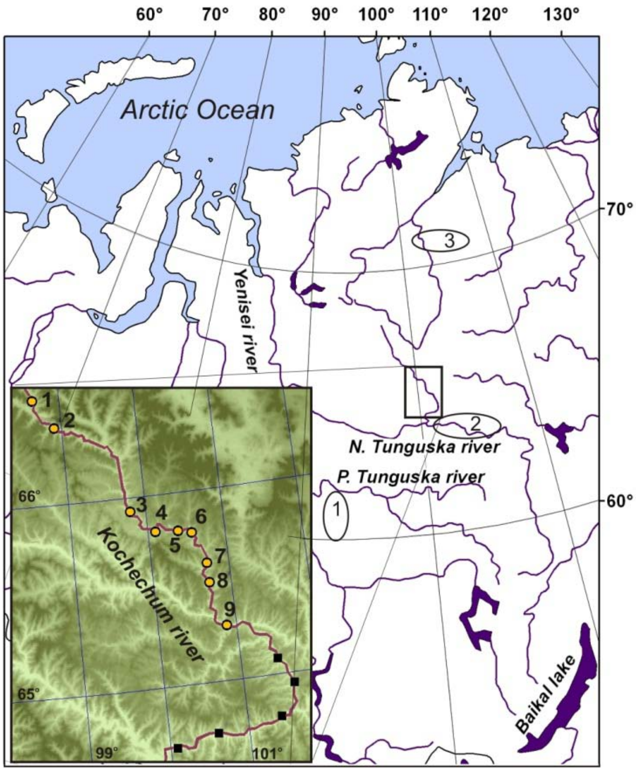

Figure 1. Map of north central Siberia with the area of this investigation shown as a rectangle. Areas marked 1–3 are sites of earlier studies (Kharuk *et al* 2007, 2008, Kharuk *et al* 2011). Inset: Landsat image

showing locations (1–9) of test sites along the Kochechum River. Measurements of older trees from a study of long term wildfire trends were acquired in areas denoted by boxes.

3. Materials and method

3.1. Tree sampling

The samples were collected in 2001 and 2007 within the burned areas of larch forests along the river. There are no roads within the study area, and rivers provide the best access (figure 1). Temporary test sites were established within burned areas within about 1.0 km from the river and within a 160–420 m elevation range. Disks of larch bole cross sections for tree ring analysis were cut at the root neck level. Sampled trees included specimens of the dominant (even-age) trees, as well as older trees that survived stand replacing fires.

Trees within test sites 1–9 (figure 1) were sampled and used for the fire return interval (FRI) analysis. In addition to this, older trees on supplementary sites were sampled (figure 1) for the purpose of estimation of long-term trends in fire frequency. The sample consisted of 58 trees.

3.2. Sample analysis

Tree ring widths were measured with a precision of 0.01 mm using the well-known LINTAB-III instrument. The dates of fires were estimated based on a master chronology constructed for northern larch forests (Naurzbaev *et al* 2004). Mean correlation with the master chronology was 0.54 which is satisfactory for our purposes. The COFECHA (Holmes 1983) and TSAP (Rinn 1996) programs were used to detect double counted and missing rings. Fire-caused tree ring deletions were found only for 3 cases (out of about 75 analyzed). Relevant dates of fire events were adjusted based upon the master chronology.

3.3. Fire return interval calculation

Fire return intervals (FRI) were routinely estimated by tree ring calculation between consecutive fire scars: $D_i – D_{i-1}$, where D_i, D_{i-1} – dates of i and $i-1$ fires. Since many sampled trees have only a single burn mark, the dates of tree natality were included into the FRI calculation where appropriate as described below.

It is known that within larch-dominated communities fires are mostly stand-replacing, and promote the formation of even-aged stands. Fresh burns with mineralized soil are quickly occupied by dense regeneration. Over time, development of a thick moss and lichen cover limits larch regeneration, (Kharuk *et al* 2008). Larch produce seeds annually with good harvests occurring on 5–7 year cycles (Forest Ecosystems 2002). Furthermore, 2–3 year old cones are known to be viable seed sources (Sofronov *et al* 1999). Importantly, ground fires regularly do not damage cones, leaving fire-killed stands as a source of seed. Thus both, tree natality dates and the dates of fires were used for FRI calculations. FRI were determined for each individual tree within test sites and then the mean FRI for a given site was calculated.

Long-term history was based on fire events were for the period spanning the 17th century to 2007. To exclude the impact of a decreasing sample size for older stands i.e., "fading effect" the sample size was adjusted by tree age within groups. Stand replacing and non-stand replacing fires were investigated.

Along the burnmarks, "tree ring width growth accelerations" were also determined. "Growth accelerations" were identified by the following procedure. 1. Expert visual analysis of increase in tree ring width.2. Calculation of the mean tree ring width 20 years before and 20 years after the increases began. This reference period (20 yr) approximately corresponds to the period of post-fire tree ring increment increases. 3. If the ratio (mean tree ring width after begining of tree width increase/mean tree ring width before tree width increase) > 2.0, the observed "growth acceleration" was considered significant. 4The date of the "growth increase" was compared with the air temperature record. It is known that for the boreal-forest zone, radial growth has been closely connected with temperature variability (Esper et al., 2010) . If that date coincided with air temperature increase, that particular "growth increment increase" was excluded from furthur analysis (because of the possibility of climate-driven tree ring increase). The above-mentioned "growth acceleration" dates were considered as a possible additional indirect sign of wildfire impact. It's known that trees that survive fires (including those which do not have burnmarks) experienced a period of growth increase (e.g., Sofronov et al, 1999).

Error analysis

Including the tree natality date into FRI analysis increased errors due to the 0–5 years lag of the post-fire tree establishment. The natality date also has to be adjusted to the "stump age", i. e., the difference of real and measured stump height tree age. Even if a tree was cut at the root neck level, this difference can be 2–5 yr. In some cases disks sampled at the root neck level were not suitable for analysis; in these cases disks were sampled higher up the bole. This procedure entailed about 5 additional years of uncertainty. The post-fire regeneration had a high growth increment the first 15–20 yr, which gradually decreased due to increasing competition and decreasing active root layer depth (Sofronov *et al* 1999). In summary, the maximum total error was estimated to be 15 years.

4. Results

4.1. Fire return intervals

Dates of tree natality and fire events are presented in figure 2. FRI values for different test sites are considerably variable, i.e, from 131 to 349 years (with mean of 200±51 year; table 1).

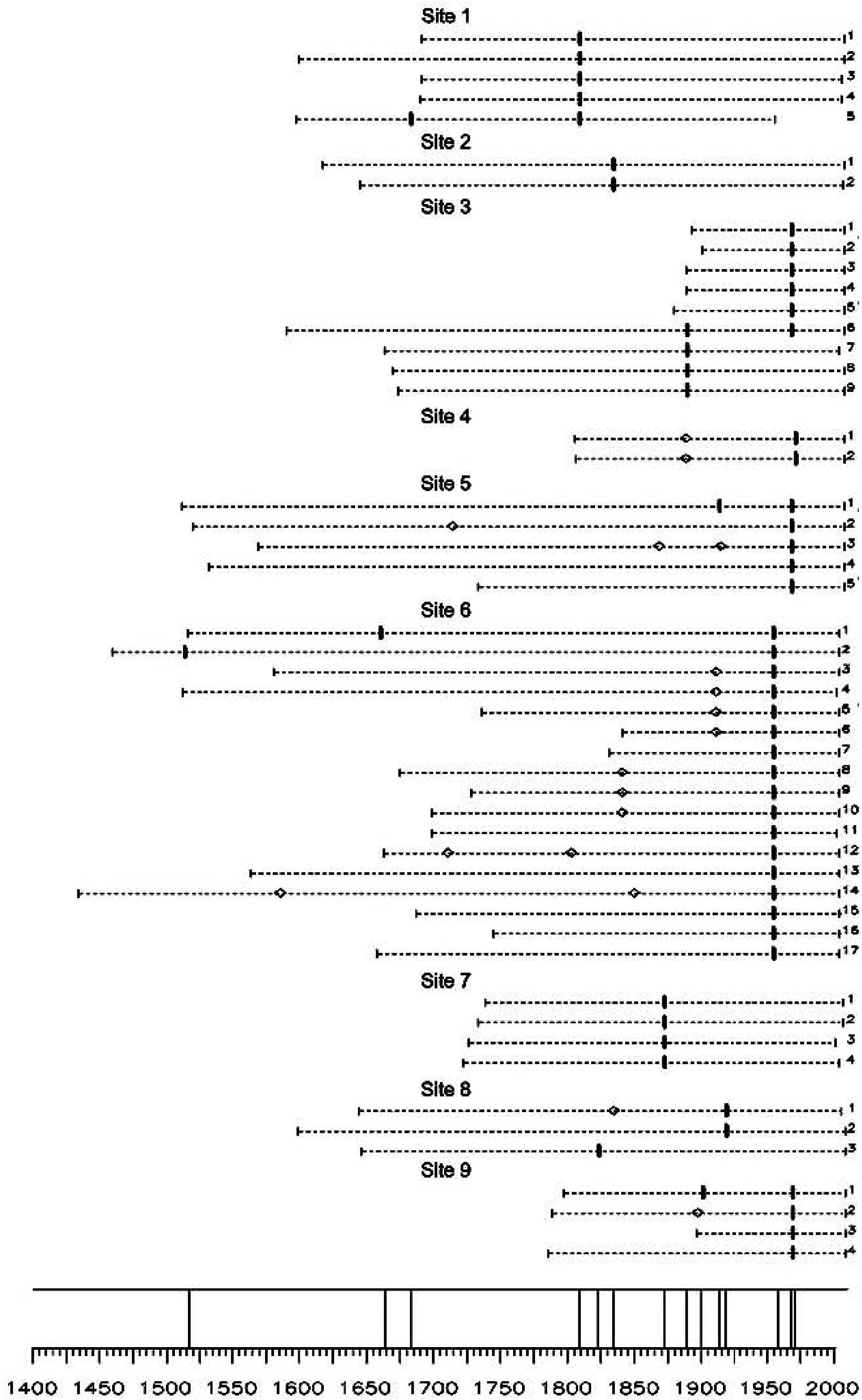

Figure 2. Fire events chronology for the test sites 1–9 (locations are shown in figure 1). Light bars indicate tree natality dates, heavy bars indicate fire events, and diamonds indicate dates of initiation of radial growth acceleration.

Table 1. Mean FRI for nine study sites.

Test sites #	Mean FRI	Sample size (N)
1	134	5
2	203	2
3	138	9
4	165	2
5	349	5
6	278	17
7	142	4
8	256	3
9	131	4
Overall Mean	200±51 ($p \geq 0.05$)	

4.2. Long-term fire events history

The long-term fire event history (for the 17th through 20th centuries) was developed based on data for trees with natality dates before 1800, 1700 and 1600 yr, respectively (figure 3, table 2). To exclude the fading effect data were adjusted for tree natality dates: >200 yr, >300 yr and >400yr for 19th to 20th, 18th to 20th, and 17th to 20th century comparisons, respectively.

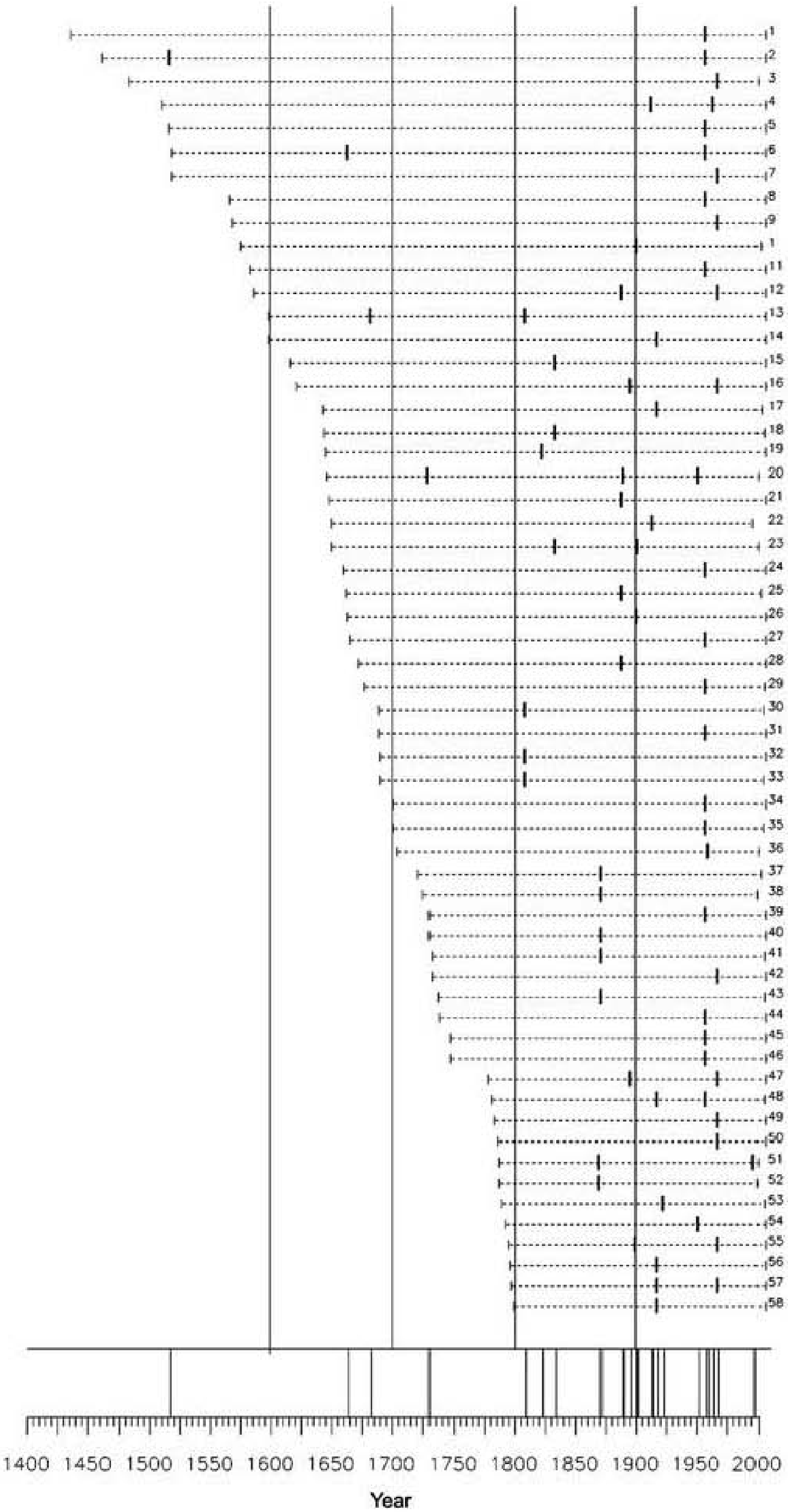

Figure 3. The data set (N=58) for comparison of number of fire events for different time periods. Light and heavy bars show dates of natality and fire events, respectively. Synchronous fire events were counted as a single fire event. The vertical lines along the abscissa denote all fire occurrences.

The number of wildfires in the 20th century increased relative to the 19th century (13 vs 8) (table 2; N=58). For 18th, 19th and 20th centuries (N=33) fires number were 1, 6 and 9, respectively (table 2; N=33). Results for period 17th–20th centuries also showed an increase of fire events from the 17th to 20th centuries (table 2; N=14). The minimum number of wildfires coincided with the air temperature decrease during the Little Ice Age period (i.e., early 17th to early 19th centuries; figure 4).

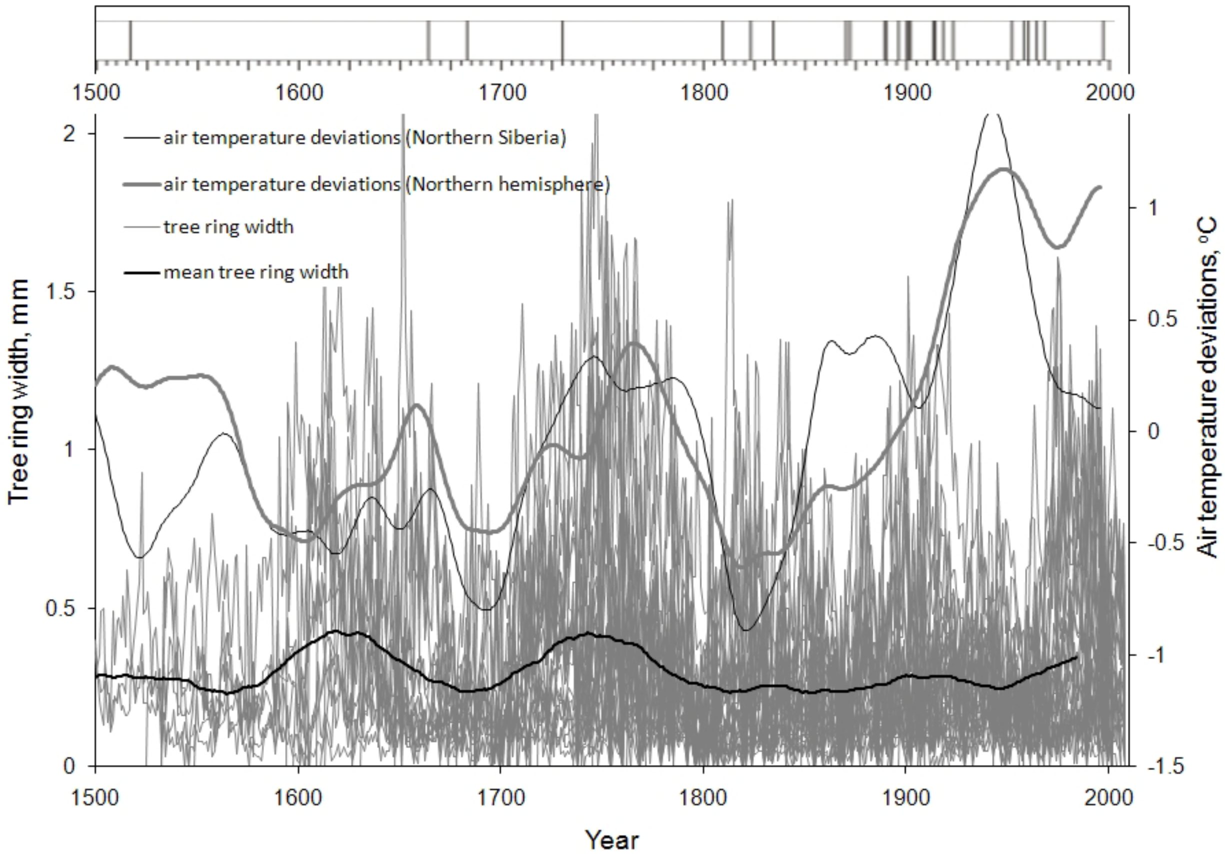

Figure 4. Individual (gray lines) and running mean (with 50 yr window; dense solid line) radial increment data of sampled trees (N=58), dates of fire events (upper scale), and air temperature deviations for the northern Siberia and northern hemisphere (grey thin and bold solid lines; Briffa 2000).

Table 2. Number of wildfires during 17^{th} – 20^{th} centuries

Century	Number of wildfires during

	a given century		
20th	13	9	6
19th	8	6	2
18th	-	1	0
17th	-	-	2
Sample size (N)	58	33	14

5. Discussion

5.1. FRI

The majority of the fires in the larch communities we studied are stand-replacing. This was revealed by the fine-grained mosaic of (semi) even age stands within forested landscapes. For the types of forest communities the mean FRI can only be reconstructed using age-class analysis or fire records (Sannikov and Goldammer 1996, Johnson and Miyanishi 2001). However, in our case the presence of fire scars indicated that non-stand replacing fires also occurred (figure 2).

FRI data for different sites within the study area (figure 1) differed by more than two times, from 131 to 349 years with a mean of 200±51 years (table 1). The reason for this is that fires are rare events within the investigated area. The other cause is the non-uniformity of the topography and land cover within the study area. It is known that fire frequency is different for sunlit and shadowed slopes, as well as for bog areas (Beaty and Taylor 2001, Rollins *et al* 2002; Kharuk *et al* 2005, 2008). Meanwhile, even the lowest FRI value (131 years) considerably exceeds reported data for adjacent southward forests (80–90 years; Vaganov and Arbatskaya 1996, Kharuk *et al* 2005). Mean FRI values (200±51yr) exceeds published FRI values for the boreal conifer forests (60–150 years: Payette 1992, Larsen 1997, Swetnam 1996, Sannikov and Goldammer 1996). Very long FRIs (up to 300 years) were reported for fire-protected forests in Europe and North America (Weir *et al* 2000, Heyerdahl *et al* 2001, Bergeron *et al* 2004, Buechling and Baker 2004). Evidently this is not the case, because within our study area fires were never suppressed. Low fire frequency is not favorable for the larch forests, because fires promote larch regeneration growth, i.e., larch is a ‘‘pyrophytic’’ species. The main tree growth constraints are permafrost thawing depth and soil drainage. Depth of seasonal thawing is dependent on exposition, moss-and-lichen layer thickness, and fire history. Fires not only increase permafrost thawing depth but also increase soil drainage which is very important to larch growth. With time, an increase in the thermal insulator layer composed of the on-ground moss and lichen cover caused upward migration of the permafrost layer, and compression of the active root zone within a progressively decreasing upper layer. Fires also thin regeneration, decreasing within-species competition, and, thus, promoting tree growth because larch is an extremely shade-intolerant species.

5.2. Long-term trends in wildfire number

The advanced age of some sampled trees (>400 years; figure 3) allows estimation of the fire history within the study area back to the Little Ice Age period. Dendrochronology data showed that cooling during the Little Ice Age period caused depression in the tree annual radial growth (figure 4). Fire event numbers since the 17th century approximately coincided with air temperature deviations, increasing with warming since the second half of 19th century (figure 4, table 2). For example, fires numbers increased from 8 in the 19th century to 13 in the 20th century. This phenomenon could not be attributed to decreased samples of older trees, i.e., “fading effect”, since sample sizes were adjusted by the natality dates.

Local asynchrony of radial increment growth and temperature deviations on Fig. 4 could be attributed to the fire-induced increase of radial growth, as well as to the increment decrease during lag between fire event and increment increase begin (which is about 7-10 yr, Fig. 5). Thus, in the middle of 20th century wildfires were observed within the majority of the test sites (Fig. 2). The other reason is a “divergence phenomenon”, i.e. growth-vs.-temperature divergence (D'Arrigo et al, 2008; Esper et al, 2010).

These estimates coincide with earlier reported data on fire frequency increase in the 20th vs 19th centuries for the southerly larch and mixed forests (sites 2 and 1 on the figure1, respectively; Kharuk *et al* 2008). The causes of this trend can be both, natural and anthropogenic. Earlier it was shown that for site 1 (figure 1) the FRI decrease was caused by both, natural (warming) and anthropogenic causes. On site 2 (figure 1) FRI decrease was attributed to temperature increase mainly because the leading factor of fire ignition on the remote northern forests is lightning (>90% of cases in the northern Evenkia, whereas within southern forests >80% of fires are anthropogenic-caused; Kovach *et al* 2004). This is also true for our study site since the remoteness of the area, as well as low population density in general; most of the fires are of natural origin. Similar observations (FRI increase since Little Ice Age) were made for the northern boundary of larch forests (site 3 on figure 1; Kharuk *et al* 2011). All these data support the suggestion that observed climate change will lead to an increase in fire frequency (Gillett *et al* 2004, Bergeron *et al* 2004, Girardin *et al* 2009). Comparison of FRI along the meridian (figure 1) showed a northward increase of FRI: 77±20 years at ~61°N (site 1), 82±7 at 64°N (site 2), 200±51 years at about 66°N, and 320±50 years at the northern boundary of larch dominant communities (71°N, site 3). The main reason of the northward FRI increase is less incoming solar radiation and, consequently, shortening of the fire-danger period.

5.3. Burns as a "simulator" of future warming

Areas experiencing wildfires may be considered as a simulator of predicted warming impacts on northern forests. Indeed, in addition to soil enrichment with nutrients and decreased competition, fires cause an increase of permafrost thawing depth by a factor of 3 to 5 (Kharuk *et al* 2008), and increased soil drainage. Trees that survived wildfire showed an approximately double (1.93; $p>0.95$) increase of radial increment (figure 5). Comparison was made for the period for 25 (20[kjr1]??) years before and after the fire (periods of +/-5 yr around zero were deleted to exclude effects of direct fire damage on trees. Some trees showed an extremely high response to fire affects. For example, the tree cross section shown on figure 5 showed an increase of radial growth about ten times in comparison with background observations. This tree was sampled at a latitude near the Polar Circle.

Generally speaking, growth increases following fire scars should be measured along radii very most distant from the wound itself. But in our case we compare 37 specimens with the same pattern of fire damage; one of which shows outstanding increment growth (about ten times higher than background set; Fig. 5). The basic difference of this specimen with others sampled was the depth of soil thawing (about 1.5 m vs <0.3-0.5 m for the other specimens), and good drainage since that tree was growing on the southern river bank. It is known that larch prefer drained soils (Schepaschenko et al, 2008). The observed radial growth increase (and, consequently, increased carbon sequestration) may be an alternative to the scenario of forests in climate-induced permafrost transformation areas becoming a greenhouse gases source (IPCC 2007). Thus, the vegetation dynamics and productivity of the burned areas deserves future investigations.

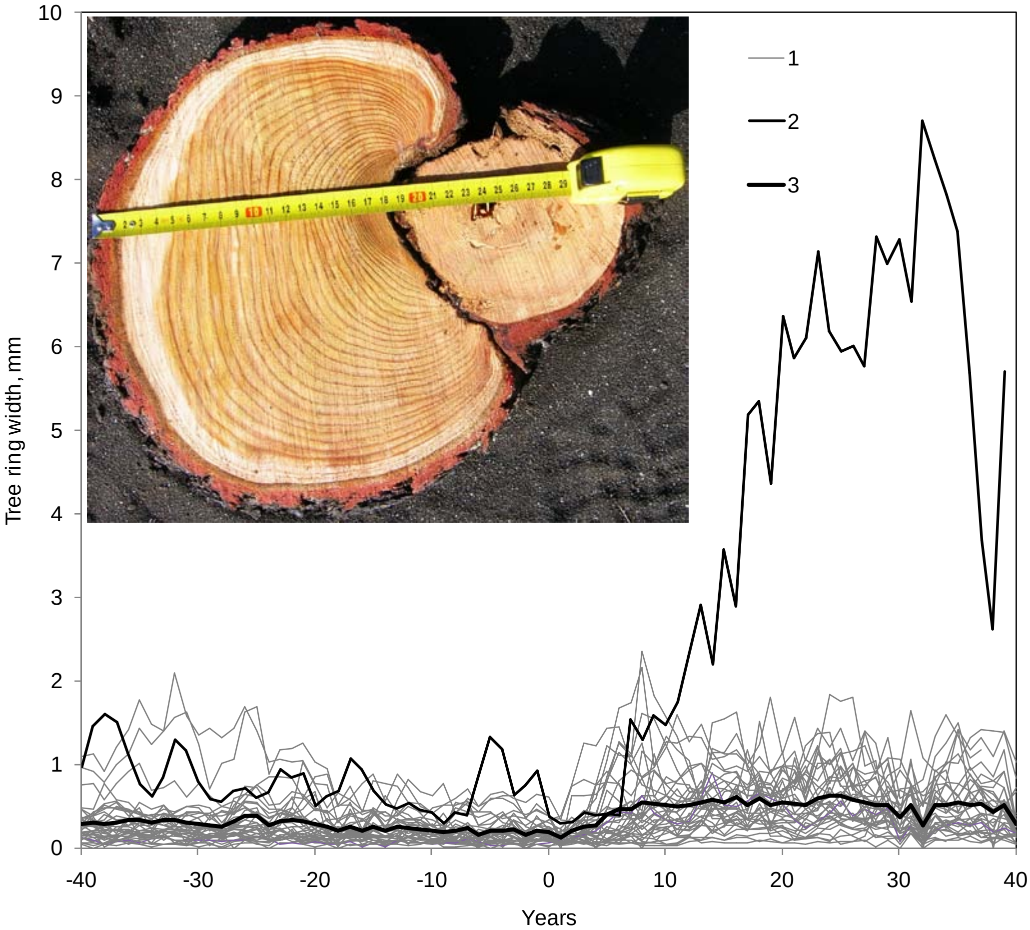

Figure 5. Diagrams for (1) individual tree ring widths (N=36) and (3) mean tree ring widths before and after fire; (2) – tree ring width for a specimen with an extremely high post-fire growth increment (inset). Data were compiled based on fires in 20th century (figure 2). Dates of fires were set to “zero” point. Note that post-fire growth increase has a lag about 7-10 yr.

5.4. Indirect sign of wildfires

Tree ring growth history showed periods of radial growth accelerations (i.e., tree ring width increase; figure 2–4). These increases are commonly considered to be climate driven (e.g., Shiyatov 2003) and may also contain information on fire events. The observed growth accelerations may also be caused by the above mentioned fire-caused soil melioration. Differentiation of these effects could be made based on the comparison with air temperature anomalies. The fire-induced origin of the acceleration is supported by the fact that in some cases the date of accelerations coincides with the burn marks on the trees from the same test site (figure 2).These effects deserved future investigations based on a larger sample sizes.

6. Conclusions

FRI on the study area is considerably longer than in southerly territories. Along the 100 degree meridian (figure 1) FRI values increased northward, 77±20 years at ~61°N (site 1), 82±7 years at 64°N (site 2), 200±51 years at about 66°N, and 320 ±50 years at the northern boundary of larch stands (~71°N). The number of fire events during the Little Ice Age period (17–18th centuries) was approximately half the number observed in 19–20th centuries. Fire-caused soil melioration (basically soil drainage and thawing depth increases) caused a radial growth increase about 2 times (with >6 times in extremes). This effect may simulate predicted warming impact on the larch growth in the permafrost zone.

Acknowledgments

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References

Beaty R M and Taylor A H 2001 Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California, USA *Journal of Biogeography* **28**(**8**) 955–966

Bergeron Y, Gauthier S, Flannigan M and Kafka V 2004 Fire regimes at the transition between mixed wood and coniferous boreal forest in Northwestern Quebec *Ecology* **85(7)** 1916–1932

Briffa K R 2000 Annual climate variability in the Holocene: interpreting the message of ancient trees. In: *Quaternary Science Reviews* **19** 87–105

Buechling A, and Baker L 2004 A fire history from tree rings in a high-elevation forest of Rocky Mountain National Park *Canadian Journal of Forest Research* **34(6)** 1259–1273

D'Arrigo R, Wilson R, Liepert B, and P. Cherubini, 2008 On the 'Divergence Problem' in Northern Forests: A review of the tree-ring evidence and possible causes *Global and Planetary Change* **60**, 289 – 305

Esper J, Frank D, Buentgen U, Verstege A, Hantemirov R and Kirdyanov A 2010 Trends and uncertainties in Siberian indicators of 20th century warming *Global Change Biology* **16(1)**

386-398

Gillett N P, Weaver A J, Zwiers F W and Flannigan M D 2004 Detecting the effect of climate change on Canadian forest fires *Geophys. Res. Lett.* **31** L18211 doi:10.1029/2004GL020876

Girardin M P, Ali A A, Carcaillet C, Mudelsee M, Drobyshev I, Hely C and Bergeron Y 2009 Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s *Global Change Biology* **15(11)** 2751–2769

Forest ecosystems of the Yenisei meridian 2002 ed F I Pleshikov (Novosibirsk: Novosibirsk Publ. House of SB RAS) p 356 (in Russia)

Heyerdahl E K, Beubaker L B and Agee J K 2001 Spatial controls of historical fire regimes: a multiscale example from the interior west, USA *Ecology* **82** 660–678

Holmes R L 1983 Computer-assisted quality control in tree-ring dating and measurement *Tree-Ring Bulletin* **43** 69–78

IPCC 2007 *Climate Change 2007: Synthesis Report* (Valencia, Spain)

Johnson E A, Miyanishi K 2001 *Forest Fires - Behavior and Ecological Effects* (San Diego: Academic Press) p 594

Kharuk V I, Dvinskaya M L, Ranson K J and Im S T 2005 Expansion of evergreen conifers to the larch-dominated zone and climatic trends *Russian Journal of Ecology* **36** 164–170

Kharuk V I, Kasischke E S, Yakubailik O E 2007 The spatial and temporal distribution of fires on Sakhalin Island, Russia *International Journal of Wildland Fire* **16(5)** 556–562

Kharuk V I, Ranson K J and Dvinskaya M L 2008 Wildfires dynamic in the larch dominance zone *Geophysical Research Letters* 35 ARTN L01402

Kharuk V I, Dvinskaya M L and Ranson K J 2011 FRI within the Northern Boundary of the Larch Forest *Scandinavian J. Forestry* (in review)

Kovacs K, Ranson K J, Sun G and Kharuk V I 2004 The relationship of the Terra MODIS fire product and anthropogenic features in the Central Siberian landscape *Earth Interactions* **8(18)** (available at http://earthinteractions.org)

Larsen C P S 1997 Spatial and temporal variations in boreal forest fire frequency in northern Alberta

Journal of Biogeography **24(5)** 663–673

Naurzbaev M M, Hughes M K and Vaganov E A 2004 Tree-ring growth as sources of climatic information *Quaternary Research* **62** 126–133

Payette S 1992 Fire as a controlling process in the North American boreal forest *A systems analysis of the boreal forest* Ed H H Shugart, R Leemans and G B Bonan (Cambridge University Press: Cambridge) pp 144–169

Rinn F 1996 Tsap V 3.6 Reference manual: computer program for tree-ring analysis and presentation (Germany: Bierhelderweg 20, D-69126, Heidelberg) pp 263

Rollins M G, Morgan P and Swetnam T 2002 Landscape-scale controls over 20(th) century fire occurrence in two large Rocky Mountain (USA) wilderness areas *Landscape Ecology* **17(6)** 539–557

Sannikov S N, Goldammer J G 1996 Fire ecology of pine forests of Northern Eurasia *Fire in Ecosystems of Boreal Eurasia* (vol 48) Ed J G Goldammer and V V Furyaev (Dordrecht: Kluver Academic Publishers) pp 151–167

Schepaschenko DG, Shvidenko AZ, and VS Shalaev 2008 Biological productivity and carbon budget of larch forests of Northern-East Russia. Moscow: Moscow State Forest University. 296 pp. [In Russian].

Shiyatov S G 2003 Rates of change in the upper treeline ecotone in the Polar Ural Mountains *Pages News* **11** 8–10

Shvidenko A, Schepaschenko D, McCallum I and Nilsson S 2007 *Russian Forests and Forestry* (Laxenburg, Austria: International Institute for Applied Systems Analysis and the Russian Academy of Science) (CD-ROM)

Sofronov M A, Volokitina A V and Kajimoto T 1999 Ecology of wildland fires and permafrost: their interdependence in the Northern part of Siberia *Proceedings of the eighth symposium on the joint Siberian permafrost studies between Japan and Russia in 1999* pp 211-218

Swetnam T W 1996 Fire and climate history in the central Yenisey Region, Siberia *Fire in ecosystems of boreal Eurasia* ed J G Goldammer and V V Furyaev (Dordrecht, Boston, London: Kluwer Academic Publisher) pp 90–104

Vaganov E A and Arbatskaya M K 1996 Climate history and wildfire frequency in the central part of Krasnoyarsky krai. I. Climatic conditions in growing season and seasonal wildfires distribution. *Siberian J. of Ecology* **3(1)** 9–18

Wallenius, T, Larjavaara, M, Heikkinen, J, Shibistova 2011 Declining fires in Larix-dominated forests in northern Irkutsk district. International Journal Of Wildland Fire 20 (2) 248-254

Weir J M H, Johnson E A and Miyanishi K 2000 Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada *Ecological Applications* **10(4)** 1162–1177

WWW1, available: http://climexp.knmi.nl