Larch Forests of Middle Siberia: Long-Term Trends in Fire Return Intervals

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Abstract Fire history within the northern larch forests of Central Siberia was studied (65+°N). Fires within this area are predominantly caused by lightning strikes rather than human activity. Mean fire return intervals (FRI) were found to be 112 ± 49 years (based on fire scars) and 106 ± 36 years (based on fire scars and tree natality dates). FRI were increased with latitude increase, and observed to be about 80 years at 64°N, about 200 years near the Arctic Circle, and about 300 years nearby the northern range limit of larch stands (~71°+N). Northward FRI increase correlated with incoming solar radiation (r = - 0.95). Post Little Ice Age (LIA) warming (after 1850) caused approximately a doubling of fire events (in comparison with a similar period during LIA). The data obtained support a hypothesis of climate-induced fire frequency increase.

Keywords fire ecology, fire history, fire frequency, Siberian wildfires, larch forests, climate change

Introduction

Larch (*Larix spp*.) dominated forests are an important component of the global circumpolar boreal forest. In Russia, larch is the widest-spread species and is found from the tundra zone in the north to the steppes in the south. The zone of larch dominance ranges from the Yenisei ridge west to the Pacific Ocean, and from Baikal Lake on the south to 73° north latitude. On its southern and western margins in Central Siberia, larch is mixed with evergreen conifers (*Pinus sibirica* Du Tour, *Pinus sylvestris* L., *Picea obovata* L., *Abies sibirica* L.) and soft broadleaved species (*Betula pendula* Roth., *Populus tremula* L.; Koropachinsky and Vstovskaya 2002). Larch forms high closure stands as well as open forests, the latter, which are found mainly over permafrost, where other tree species barely survive. The proportion of permafrost in Russia is about 65% of total territory and located mainly in Siberia, where larch occupies about 70% of the permafrost area.

Average annual burning rate of wildfires in Russia was estimated (based on remotely sensed data only) as 2–17 million ha (or 0.22–1.9% of the forested area) with the majority of fires in larch forests (Krylov et al. 2014). According to official statistics (http://www.gks.ru), annual area of wildfires in Russia since 1990 was 0.55–2.4 Mha (or 0.07–0.27% of forested area) with mortality on 0.17–0.7 Mha.

Within larch communities in Siberia wildfires occurred mostly as ground fires due to low crown closure. Because of shallow larch root system (caused by permafrost) ground fires were mostly stand-replacing with the exception of early summer surface fires, when fuel materials have typically dried to depths <10 cm (Sofronov et al. 1999). Fuel materials were composed mostly of lichen and moss with estimated dry mass of about 4–8 kg m^{-2}. These are sufficient for maintaining severe ground fires over huge areas, which promotes even-age post fire larch stands (Sofronov et al. 1999). Thus, during low-precipitation and high air temperature periods ground fires may spread over tens to hundreds of kilometers. Thus, for the period since 1996 annual area of fires in Siberia was within the 1.0 to > 20 Mha range and the number of fires was within 100-8000 yr^{-1}. (Ponomarev and Kharuk 2016). Similar data were reported by Kukavskaya et al. (2013). During the first decade of the 21st century the annual burned estimates in Siberia ranged from 1.1 to 17.6 Mha. Data analysis based on the NOAA/AVHRR, Terra/MODIS and air-survey observations since 1969 revealed significant positive trends in both fire frequency and area burned (Ponomarev and Kharuk 2016). Data about fire return intervals (FRI) within larch-dominated communities are scarce. Vaganov and Arbatskaya (1996) found that at the latitude of Tura (Figure1) were about 82 years. For the same area according to Sofronov et al (1998) FRI were within 80–90 years. Similar values (82 years) were reported for middle flow of N. Tunguska river (Figure 1, site II; Kharuk et al. 2008). In eastern Siberia (~61°N, 106°E) FRI was found to be about 160 years (Wallenius et al. 2011). Actually, within the huge permafrost area northward of 64°N fire history is poorly studied.

The Eurasian taiga, including larch forests and the northern forest-tundra ecotone, is expected to become more prone to forest fires (e.g., Goldammer 2013; Shvidenko and Schepaschenko 2013). This may result in an increase in both fire frequency and carbon emissions, and may convert this area to a source for greenhouse gases (IPCC 2014). In northern larch stands (i.e., at >65°N) wildfires are mainly (>90 %) of natural origin (Kharuk et al. 2008), and therefore northern wildfires are a sensitive indicator of climate impacts. On the other hand, northward climatic gradient should affect fire return intervals, and FRI changes along the meridian may simulate future climate-induced changes in FRI within northern territories. There is a general understanding that FRI is dependent on latitude (e.g., Korovin 1996). However, there are no quantitative data on such dependence neither for Russian forests in whole or for the area of larch dominance in particular.

Our study objectives were to (i) understand wildfire history (based on fire return intervals, FRI) within northern larch stands of Central Siberia, and (ii) determine changes in FRI northward starting from mid-Siberian larch stands (~64°N) to the northern limit of closed larch stands (~72°N; Fig. 1). We hypothesize that FRI in larch communities is dependent on geographical latitude.

Materials and methods

Study area

The study area was located within the northern part of the central Siberian plateau. The area is typical of Siberian Traps topography with gently sloping, flat topped hills with elevations exceeding 900m above mean sea level. Study sites were established within the Embenchime River watershed (total number = 8; Fig. 1). The seasonal fire distribution is unimodal with most fires in June and July) and only rare fires in August and early September (Sofronov et al. 1999). Periodic stand-replacing ground fires create a mosaic of mostly even-age stands encompassing older surviving trees (Fig. 1, insert). Within the study area fires were not suppressed. This area also has no pest outbreaks and minimal anthropogenic impacts (e.g. hunters, fishermen and prospectors).

Climate

The study area is located within the permafrost zone with a severe continental climate. Mean summer, winter and annual temperatures are +11°C, –34°C and –12°C respectively. Mean summer, winter and annual precipitation totals are 190, 60, and 440 mm, respectively (reference period 1960–2009). The analyzed parameters were air temperature, precipitation (obtained from weather station at Tura, Fig. 1), and drought index SPEI (the Standardized Precipitation-Evapotranspiration index; cell size was 0.5° x 0.5°). SPEI () can measure drought severity according to its intensity and duration, and can identify the onset and end of drought episodes. The SPEI uses the monthly difference (*D*) between precipitation (*P*) and potential evapotranspiration (*PET*) (Vicente-Serrano et al. 2010):

$$D = P - PET$$

Climate variables for the period of reliable meteorological observations were presented on Fig. 2. SPEI was calculated for the entire study area (contour on Fig. 1)

Vegetation

Forest stands (with crown closure of about 0.2) were composed of larch (*Larix gmelinii* Rupr.) rarely mixed with birch (*Betula pendula* Roth). Mean height, diameter breast height and age from field measurements were 8.5 m, 12.5 cm and 250 yr., respectively. These biometric data were obtained from inventory measurements, which were part of on-ground studies. The inventory work was conducted on about 70 test plots and included all types of burns. Shrubs present were *Betula nana* L., *Duschekia fruticosa* (Rupr) Pouzar, *Ledum palustre* L., *Ribes rubrum* L., R. *nigrum*

L., *Ledum palustre* L. *Rosa acicularis* Lindl., *Juniperus sibirica* Burgsd., *Vaccínium uliginósum* L. Ground cover typically consisted of lichens *Cladonia stellaris* (Opiz) Pouzar & Vězda and mosses (*Pleurozium schreberi* (Brid.) Mitt.).

Field measurements

Investigations were conducted on larch stands within the Embenchime River watershed (Fig. 1). Test sites [TS] were preliminary selected randomly and georeferenced within old or new burns along the expedition route (about 250 km with centerpoint coordinates 65°30′ N, 98°30′ E). The burns were identified based on Landsat satellite scenes analysis. During the field work, TS (*n* = 8) were selected within the burned areas at a distance of 50 m to 200 m from the river. On each TS trees with fire-scars were selected. *Larix gmelinii* known by its ability to cover firescars by bark; thus, in some cases firescars were not explicit. In the latter case fire-scars were identified visually by the presence of "irregular" (often concave) surface. We tried to select trees with multiple fire scars to construct the longest possible stand fire chronology. In spite of periodic wildfires some trees of considerable (>300 yr.) age were present. Typically, there were only one or two fire-scars (with rare exception of three fire-scars). Trees were sampled until at least 12 samples were collected. The purpose of getting 12 samples was to ensure our data set could be used for satisfactory statistical analysis and also have a "reserve" if part of the samples were found later not good for analysis. Based on previous experience, the minimal sample set was 5–7 samples. The mean TS area from which samples were obtained was about 1.0 ha. The total sample set consisted of 114 disks. Sampling deadwood and snags often provides the longest possible fire chronology, but not within our study area. We used snags in the analysis, but a maximum of two firescars were found on sampled snags (Fig. 3). The overall low number of snags may be attributed to tree fall resulting from the shallow rooting depth caused by the thin active layer (≤0.3 m with the exception of deeper sandy soils on south facing slopes). In addition, larch roots were often found partially within the lichen and moss fuel layer. Thus, trees with a fire-killed root system were easily blown down. Sample size extension by felled dead trees and subfossils found on moss and lichen ground cover was also limited by poor wood preservation.

Dendrochronological analysis

The surface of each sampled disks was sanded. The widths of tree rings were measured with 0.01 mm precision using a linear table instrument (LINTAB-III). The TSAP (DOS Version) and COFECHA (Version 6.02P) computer programs were used in tree ring analysis (Rinn 1996). Individual ring width series were "detrended" by exponential approximation (Cook and Kairiukstis 1990). A master chronology method (Fritts 1991) was used for determining wildfires dates, as well as dates of tree mortality. Trees with minimal signs of fire damage (N = 18) were selected for master chronology development and further crossdating of the remaining samples. Absent rings were detected and localized by using COFECHA software (Holmes 1983). Sample disks that were not possible to crossdate (N=12) were removed. Thus, the final sample set included 102 disks.

FRI calculations

FRI was determined based on dates of tree natality and fire scars on the tree boles. It is known that ground fires within larch-dominant zone regularly cause stand mortality resulting in even-age tree cohorts (e.g., Sofronov et al. 1999). Typically, fresh burns are quickly covered by dense larch regeneration (Fig. 1, insert). Consequently, post-fire tree cohort natality approximate the date of the fire. The cohort natality date was calculated as a mean tree natality within a given cohort. Then, those values were corrected for the lag between dates of stand-replacing fire and establishment of regeneration. That lag was calculated as the difference between post-fire cohort natality and the date of wildfire, which induced cohort establishment. The lag value (12 ± 2) was estimated based on wildfires which were marked by both fire scar and cohort natality (see Results section: sites 2, 5, 6; Fig. 3). FRI were determined as the number of tree rings between (1) consecutive fire scars and (2) consecutive fire scars and "origin-to-scar" intervals. We used site composites and report a single value for each site and the average for all sites combined.

In addition, "growth release" data were considered as a possible indicator of fire events. "Growth release" of surviving trees, i.e., an abrupt increase in growth ring increment, may be induced by post-fire decrease in tree competition for light, soil enrichment with nutrients, increases of permafrost thawing depth and drainage. The growth accelerations are visible on the tree ring records and are considered to be an indirect indicator of fires in some systems (Nowacki and Abrams 1997). However, growth release (especially at northern latitudes) could be also climate-driven. Following the method of Lombardo et al. (2009), we visually identified "growth accelerations" on disks radii. Then the mean tree rings width for 10 years before and after acceleration was calculated. If that ratio (mean tree ring width after/before growth release) was > 2.0, the "growth acceleration" was considered as significant.

Results

Dendrochronology

Dendrochronology data are given in Table 1. Interseries correlation provided by COFECHA was 0.573; mean sensitivity for master-chronology and individual series were satisfactory (i.e., 0.205 and 0.323, respectively). The analysis showed that 20 disks out of the total 102 samples contained missing rings due to fire damage. Average number of missing rings for these samples was about 1.6 (with mean tree age about 260 yr). In addition, each tree natality date has to be adjusted to the "stump age", i.e., the difference of real and measured tree age at the stump height. Even if a tree was cut at the root collar level, this difference can be 2–5 years. For adjustment we used the more conservative estimate (5 years).

FRI values

The mean FRI were estimated based on (1) fire scars and (2) fire scars plus natality date. The resulting FRI values were 112 ± 49 and 106 ± 36, respectively (Table 2). Tree ring growth releases coincided with fire scars within all cohorts with precision of ±3 years (Fig. 3). Since no additional fire events were discovered based on growth releases, these data were not used in the final fire chronology.

Wildfires and climate changes

Wildfires chronologies for each test site were reconstructed based on fire scars and tree natality dates and are shown in Figure 3 along with dates for all fires. During the post Little Ice Age (LIA) period (1850–2010 wildfire frequency nearly doubled from 7 (1700–1849) to 13 (1850–2000) years. The comparison was based on trees with Age>300 years (N=19).

FRI along northward transect

Combining the data from this study with previously published data (Kharuk et al. 2008, 2011, 2013; Fig. 1) allowed consideration of the FRI dependence on latitude along a south to north transect. Vegetation type is similar within all I–IV sites (see Fig. 5 for site locations). These areas are larch-dominant northern taiga underlain by permafrost. The dominant species is *L. gmelinii* Rupr., which forms sparse stands (mean crown closure ≤0.3) with admixture of *Betula pendula* Roth. Ground cover is composed mostly of lichen and moss (Kharuk et al. 2008, 2011, 2013). Within all sites fires are predominantly caused by lightning strikes rather than human activity. Within the study areas, as well as within the majority of larch-dominated forests, fires are not suppressed (Forest Fund of Russia 2003).

Earlier, it was found that FRI were 82 ± 7 years at 64° N (site II), 200 ± 51 years near the Arctic Circle (66°N+; site III), and 295 ± 57 yr. at 71° +N (site IV). To be consistent with previous studies, for site I we used FRI calculated based on fire scars and tree natality dates (106 ± 36 years). Data presented in Fig. 5 showed that along a south-north transect FRI increased with latitude increase, and decreased with insolation.

Discussion

FRI

Wildfires were not "full-synchronous" over all study area, although synchrony was observed within some sites (ca. 1890; 1958; Fig. 3). Stand-replacing fires occurred at the end of the 17^{th} – beginning of 18^{th} centuries on the majority of sites. Low wildfire synchrony was attributed to rugged topography with a dense river network, including Embenchime River, a large firebreak. Topographic gradients have an important role in the occurrence, frequency and extent of wildfire (Rollins et al. 2002), although within areas with intensive anthropogenic impact the role of landscapes may become secondary (Drobyshev et al. 2008). Topography is likely to play a larger role in northern larch stands, since the probability for ground fires to cross a river or creek is lower than for crown fires within southerly forest lands.

Mean fire return intervals within the study (106 years) area were within the range of FRI similar to the reported for conifer forests in North America (60–150 years; Payette 1992; Larsen 1997) , and slightly higher than found by Sofronov et al. (1998; 80–90 yr.), Vaganov and Arbatskaya (1996; 82 yr.) southward (about two degrees longitude). Very long FRI (about 300 yr.) were found for larch forests near the northern limit of tree growth (Kharuk et al. 2013). Within other forest types (southward Scots pine stands grown on well drained sandy soils) FRI were shorter (50-60 yr.; Swetnam 1996). It should also be pointed out that those pine stands were within zone relatively high human activity. Within larch stands southeast of our study area FRI were found to be about 164 years in the

20^{th} century (Wallenius et al. 2011). The longer FRI should be attributable to fire suppression since the 1930s. For fire-protected forests in Europe and North America very long FRIs (up to 300 years) were reported (Weir et al. 2000; Heyerdahl et al. 2001; Bergeron et al. 2004; Buechling and Baker 2004)

Fire-induced even-age tree cohorts

Within the study area there were few stand-replacing fires, with a maximum of only 3 fires observed in the tree ring record across the study sites. To account for this, we use the time period from tree natality to the first fire scar as a fire free interval in calculating FRI. Stephens et al. (2010) stated that this interval is extremely conservative and will almost certainly overestimate the FRI for each site. However, in our case both approaches (based on fire scars and "fire scar plus natality" dates) provided the same (within error) results: 112±49 and 106±36, respectively. We attribute this to the significant difference in the forest types studied. Stephens et al. (2010) and Brown et al. (2008) studied pine stands within arid areas, whereas we focused on northern larch communities. As Stephens wrote, "the degree of underestimation of [fire frequency] depends on the density of woody debris and rates of fuel accumulation". In the case of sparse larch forests the main source of fuel is not the trees themselves, but the available moss and lichen fuel matrix (estimated fuel load was up to 8 kg m^{-2}). For more arid forests, many assume ground fires to be of low severity, but the available fuel in larch stands is quite different and therefore surface fires can and do burn with high intensity, forming an even-age stand mosaic. Moreover, larch regenerates very poorly over a moss and lichen ground floor (where it is difficult for sapling roots to reach the soil surface), and extremely well on post-fire mineralized soil. Thus, larch is a "pyrophytic" species and fires are necessary for larch forest regeneration (Sofronov et al. 1999). Fires also increase soil drainage by increasing permafrost thawing depth, which is very important to larch growth. With time, an increase in the thermal insulator layer composed of moss and lichen ground cover causes 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, promote tree growth because larch is an extremely shade-intolerant species (Koropachinsky and Vstovskaya 2002).

It is of interest to compare the survival strategy of *Larix gmelinii* vs *L. sibirica*. In southern larch communities dominated by *L. sibirica* ground fires have generally less intensity (in comparison with northern areas) due to less moss and lichen fuel availability and deeper (up to >2.0 m) rooting zone. Thus, ground fires regularly do not have a strong impact on the *L. sibirica* root system (with the exception of shallow rocky soils). Additionally, and the *L. sibirica* cambium is protected by thick bark (up to 20 % weight of trunk). In comparison, the bark of *L. gmelinii* bark is thinner, and protects trees from surface fires only. The main damage, as was mentioned earlier, is caused by overheating the root system compressed within the shallow active soil layer (Sofronov et al. 1999, Kharuk et al. 2011). Meanwhile even killed trees may disseminate seeds over fire-mineralized soil with consequent regeneration up to $5–7\times10^5$ saplings ha^{-1} (Kharuk et al. 2008; see also inset on Fig, 1).

Along with the above mentioned two mechanisms, we also checked a "growth release" approach for wildfire dating. Tree ring growth releases were synchronized with fire scars on the trees within the same cohort (Fig. 3). However, the growth release method of wildfire dating should be applied carefully, since tree ring width increases can be also be climate-induced. The latter would take more time, whereas fire-related growth surges are rapid and not sustained.

FRI and climate change

The observed fire history allows estimation of fire frequency back to the Little Ice Age (LIA) period. LIA within Siberia began in the 14^{th} century and ended in 1850, approximately (Fig. 4). Comparison of the number of fires during LIA (1700–1849) and a similar post-LIA period (1850–2000) showed an approximate doubling of fire frequency in the post-LIA period (7 vs 13 fires). A similar result (doubling of fire frequency in the post-LIA warming) was obtained earlier for sites III and IV (Fig. 1) (Kharuk et al. 2008, 2013). These data support the hypothesis that modern climatic warming will increase fire frequency (e.g., Girardin et al. 2009).

Even during LIA some trees had wide ring widths (Fig. 5), which we attributed to fire-caused melioration, i.e., soil enrichment with nutrients, decreased competition, and increased permafrost thawing depth and soil drainage. Trees that survived wildfire showed an approximately twofold increase in radial increment (up to ten times in extreme cases) in comparison with the background measurements (Kharuk et al. 2011).

Since the 1990s a significant increase of June temperature and drought index were observed, that is likely to lead to an increase of wildfire danger and fire frequency. This observation coincides with predicted climate-change induced increases of drought frequency and severity (IPCC 2014). Earlier (Kharuk et al. 2008) it was shown FRI reduction from about 100 years in the 19^{th} century to 65 years in the 20^{th} century (site II, Fig. 1). Meanwhile for the area (about 61°N, 106°E) Wallenius et al. (2011) reported that minimal FRI occurred in the 18^{th} century (52 years) and lengthened into 164 years in the 20^{th} century. That phenomenon should be attributed (1) to increased settlement and (2) gold rush within that period. FRI increase in 20^{th} century should be attributed, as was mention above, to fire suppression since 1930s.

Remote sensing based observations over Siberia also have shown an increase in wildfire frequency and burned area (Ponomarev and Kharuk 2016). Similarly, Gillett et al. (2004) showed increase of the area burned by forest fires in Canada over the last four decades of the 20^{th} century and that climate change had a detectable influence on the area burned by forest fires in Canada over recent decades.

An increase in fire frequency is likely to be favorable for larch, because this species successfully regenerates within burned areas (Fig 1, inset). An increase in fire frequency will preserve larch dominance by suppression of climate-induced migration of species that are not tolerant of fire (such as Siberian pine and fir). Meanwhile climate-induced migration of “dark needle conifers” (i.e., *Pinus sibirica*, *Picea obovata*, and *Abies sibirica*) into traditionally larch-dominated areas was described earlier for areas below 65°N (Kharuk et al. 2005). Within the sites reported herein (Fig. 1), larch dominates on burned areas, with birch and alder (*Duschekia fruticosa*) also present. Birch regeneration on burns originates from both seeds and sprouts, suggesting that birch is a possible future competitor of larch.

FRI changes along northward meridian

The data obtained for this study add information on the fire regime in the remote and poorly explored area of northern Siberia and allow, and together with previously obtained data, track the changes in FRI from south to north. The initial point (site II) is actually nearby the southern boundary of larch dominance in Central Siberia, whereas the northern point was actually within the northern boundary of closed larch stands (site IV). Thus, FRI increased from about 80 years at 64° N (Kharuk et al. 2008) to about 110 yr within study site (65°N+), increasing to 200 years at about Arctic Circle (66°N+; Kharuk et al. 2011) and reaching ~300 years at the northern limit of closed larch stands (~71°N+; Kharuk et al. 2013; Fig. 5). Fires in the study area (including all sites) are caused primarily by lightning (e.g., Kharuk et al. 2008). With increasing latitude incoming solar radiation decreases. At high latitudes low insolation is hardly sufficient to dry moss and lichen cover, thus shortening the fire-danger period and decreasing the fire hazard. In addition, the latitudinal insolation decrease results in a lower frequency of lightning, the dominant cause of forest fires at high latitudes. Thus, within northern larch stands FRI is controlled by the major climatic factor, i.e., solar incoming irradiation. Observed and predicted increases in air temperature and drought frequency and severity will likely modify FRI values, including increase in fire activity even in northern areas, but are not expected to cause a general trend of FRI increase in a northward direction.

Conclusion

Wildfire history within the northern larch forests growing on permafrost in Central Siberia (latitude range 64N–71N+) was studied. The study area is remote and fires within this area were predominantly caused by lightning strikes rather than human activity. FRI increased with an increase in latitude and was observed to be about 80 years at 64°N, about 200 years near the Arctic Circle, and about 300 years nearby the northern limit of closed larch stands (~71°N+). Northward FRI increase was correlated with incoming solar radiation (r=0.95). Post Little Ice Age warming caused approximately a doubling of fire events. An increase in fire frequency is likely to be favorable for larch, since this species successfully regenerates within burned areas. An increase in fire frequency (reduced FRI) would preserve larch dominance by suppression of climate-induced migration of species that are not tolerant of fire (such as Siberian pine and fir).

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References

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

Brown PM, Wienk CL, Symstad AJ (2008) Fire and forest history at Mount Rushmore. Ecological Applications 18:1984–1999

Buechling A, 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

Cook ER, Kairiukstis LA (1990) Methods of Dendrochronology: Applications in the Environmental Sciences. Springer Science & Business Media, Boston.

Goldammer JG (2013) Vegetation fires and global change. Challenges for concerted international action: A white paper directed to the United Nations and international organizations. Remagen-Oberwinter: Kessel Publishing House.

Drobyshev I, Goebel PC, Hix DM, Corace III RG, Semko-Duncan ME (2008) Pre- and post-European settlement fire history of red pine dominated forest ecosystems of Seney National Wildlife Refuge, Upper Michigan. Canadian Journal of Forest Research 38:2497–2514

Forest Fund of Russia (2003) A handbook. Roslesinforg Publishing House, Moscow. In Russian

Fritts HC (1991) Reconstruction Large-scale Climatic Patterns from Tree-Ring Data: A Diagnostic Analysis. University of Arizona Press, Tucson

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. Geophysical Research Letters 31. doi:10.1029/2004GL020876

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

Heyerdahl EK, Beubaker LB. Agee JK (2001) Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology 82:660–678

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43:69–78

IPCC (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. IPCC Working Group II Contribution to AR5. Yokohama, Japan.

Kharuk VI, Dvinskaya ML, Ranson KJ, Im ST (2005) Expansion of Evergreen Conifers to the Larch-Dominated Zone and Climatic Trends. Russian Journal of Ecology 36:164–170

Kharuk VI, Ranson KJ, Dvinskaya ML (2008) Wildfires dynamic in the larch dominance zone. Geophysical Research Letters. 35. doi:10.1029/2007GL032291

Kharuk VI, Ranson KJ, Dvinskaya ML, Im ST (2011) Wildfires in northern Siberian larch dominated communities. Environmental Research Letters 6. doi:10.1088/1748-9326/6/4/045208

Kharuk VI, Dvinskaya ML, Ranson KJ (2013) Fire return intervals within the northern boundary of the larch forest in Central Siberia. International Journal of Wildland Fire 22:207–211

Koropachinsky IYu., Vstovskaya TN (2002) Tree species of Asian Russia. Novosibirsk, Nauka Publishing House. Novosibirsk, Russia. In Russian

Korovin G N (1996) Analysis of the distribution of forest fires in Russia Fire in Ecosystems of Boreal Eurasia SE-18 Forestry Sciences. Eds JG Goldammer and VV Furyaev. Springer, Dordrecht. pp 112–28

Krylov A, McCarty JL, Potapov P, Loboda T, Tyukavina A, Turubanova S, Hansen MC (2014) Remote sensing estimates of stand-replacement fires in Russia, 2002-2011. Environmental Research Letters. 9: 105007

Kukavskaya EA, Soja AJ, Petkov AP, Ponomarev EI, Ivanova GA, Conard SG 2013) Fire emissions estimates in Siberia: Evaluation of uncertainties in area burned, land cover, and fuel consumption. Canadian journal of forest research. 43(5):493–506

Larsen CPS (1997) Spatial and temporal variations in boreal forest fire frequency in northern Alberta. Journal of Biogeography 24:663–673

Lombardo KJ, Swetnam TW, Baisan CH, Borchert MI (2009) Using bigcone Douglas-fir fire scars and tree rings to reconstruct interior chaparral fire history. Fire Ecology 5:32–53

Nowacki GJ, Abrams MD (1997) Radial-growth averaging criteria for reconstructing disturbance histories from presettlement-origin oaks. Ecological Monographs 67:225–249

Payette S (1992) Fire as a controlling process in the North American boreal forest. In: Shugart HH, Leemans R and

Bonan GB (eds). A systems analysis of the boreal forest. Cambridge University Press: Cambridge. pp 144–169

Ponomarev EI, Kharuk VI (2016) Wildfires in Altai-Sayan Region in context of observed climate change. Contemporary Problems of Ecology 9(1): 29–36

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

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

Sofronov MA, Volokitina AV, Shvidenko AZ (1998) Wildland fires in the north of Central Siberia. Commonwealth Forestry Rev 77:211–218

Sofronov MA, Volokitina AV, Kajimoto T (1999) Ecology of wildland fires and permafrost: their interdependence in the northern part of Siberia. In: Proc. 8th Symposium on the Joint Siberian Permafrost Studies Between Japan and Russia in 1999. pp. 211–218

Stephens SL, Fry DL, Collins BM, Skinner CN, Franco-Vizcaíno E, Freed TJ (2010) Fire-scar formation in Jeffrey pine-mixed conifer forests in the Sierra San Pedro Mártir, Mexico. Canadian Journal of Forest Research 40:1497–1505

Swetnam TW (1996) Fire and climate history in the central Yenisey Region, Siberia. In: JG Goldammer and VV Furyaev (eds) Fire in ecosystems of boreal Eurasia. Kluwer Academic Publisher: Dordrecht, Boston, London. pp. 90–104.

Shvidenko A, Schepaschenko D (2013) Climate change and wildfires in Russia. Contemporary Problems of Ecology 6(7):683–692

Vaganov EA, Arbatskaya MK (1996) The climate history and wildfire frequency in the Mid of Krasnoyarsky Kray. I. Growing seasons climatic conditions and seasonal wild fire-distribution. Siberian Journal of Ecology 3:9–18

Vicente-Serrano SM, Beguería S, López-Moreno I (2010) A Multiscalar Drought Index Sensitive to Global Warming. The Standardized Precipitation Evapotranspiration Index. J Climate 23:1696–1718. doi: 10.1175/2009JCLI2909.1

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

Weir JMH, Johnson EA, 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

Figure 1

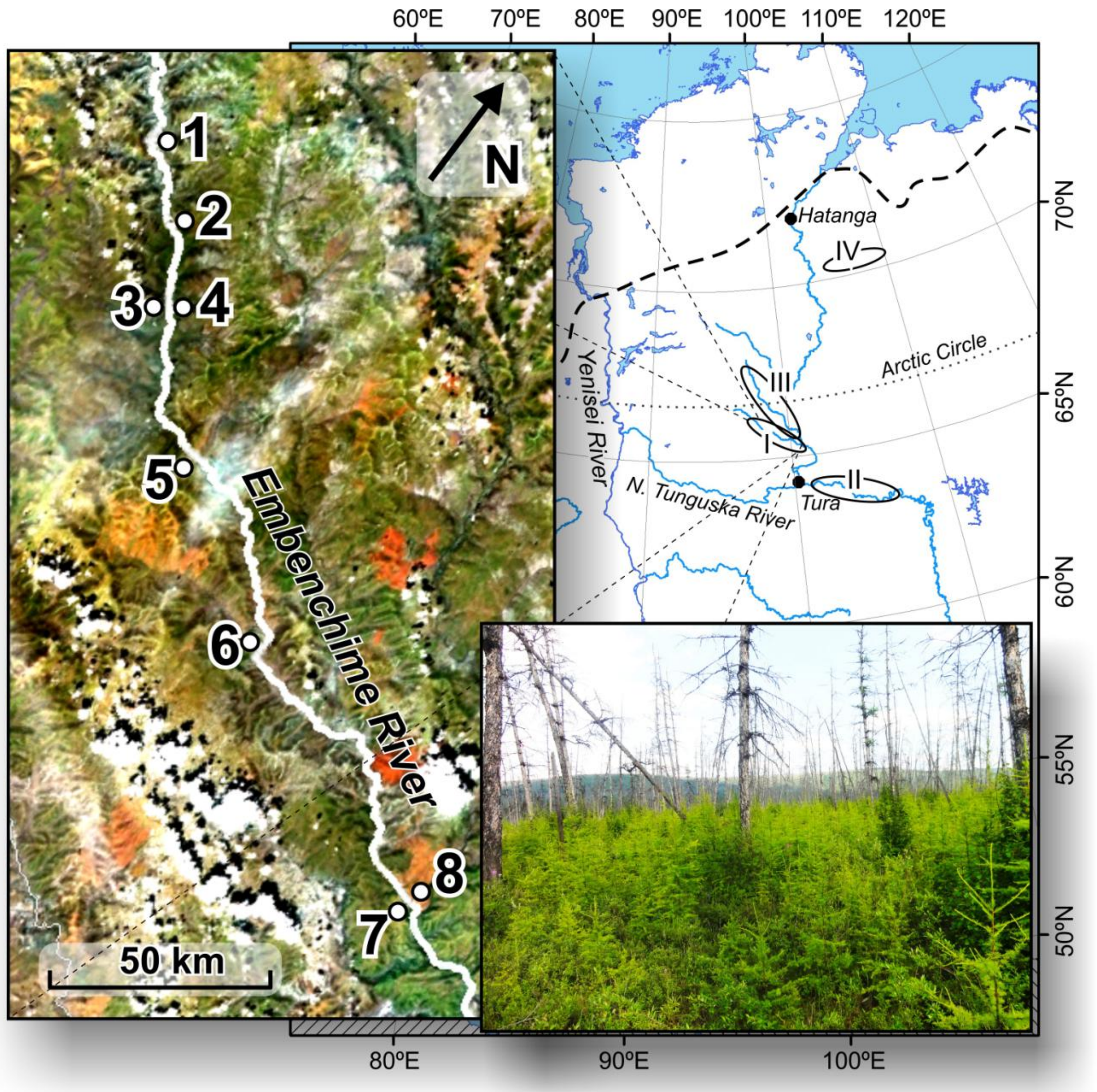

Figure 2

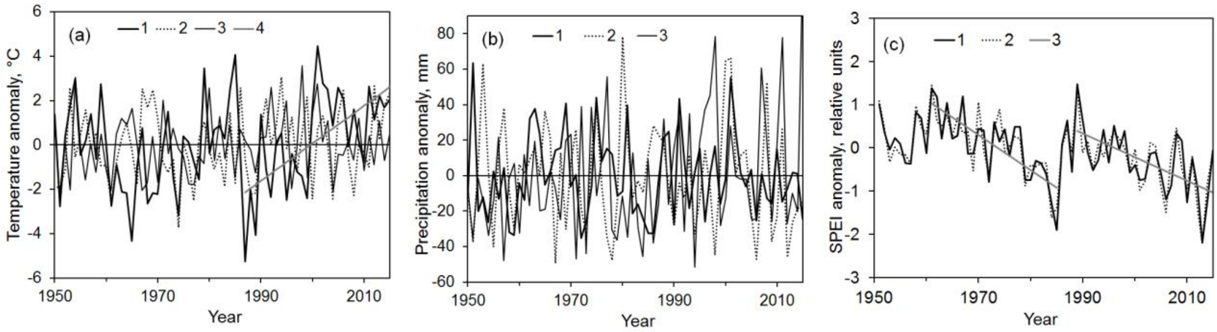

Figure 3

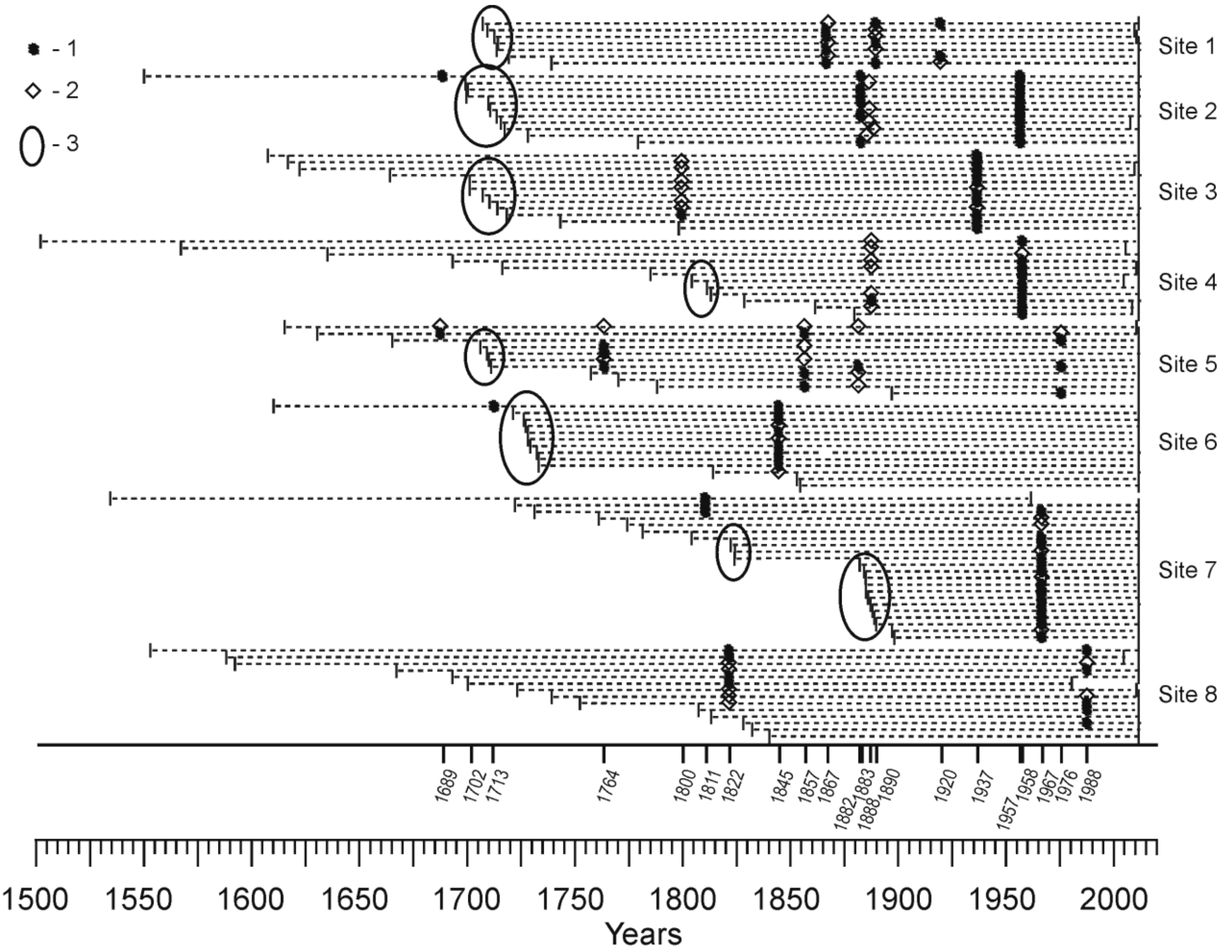

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Figure 4

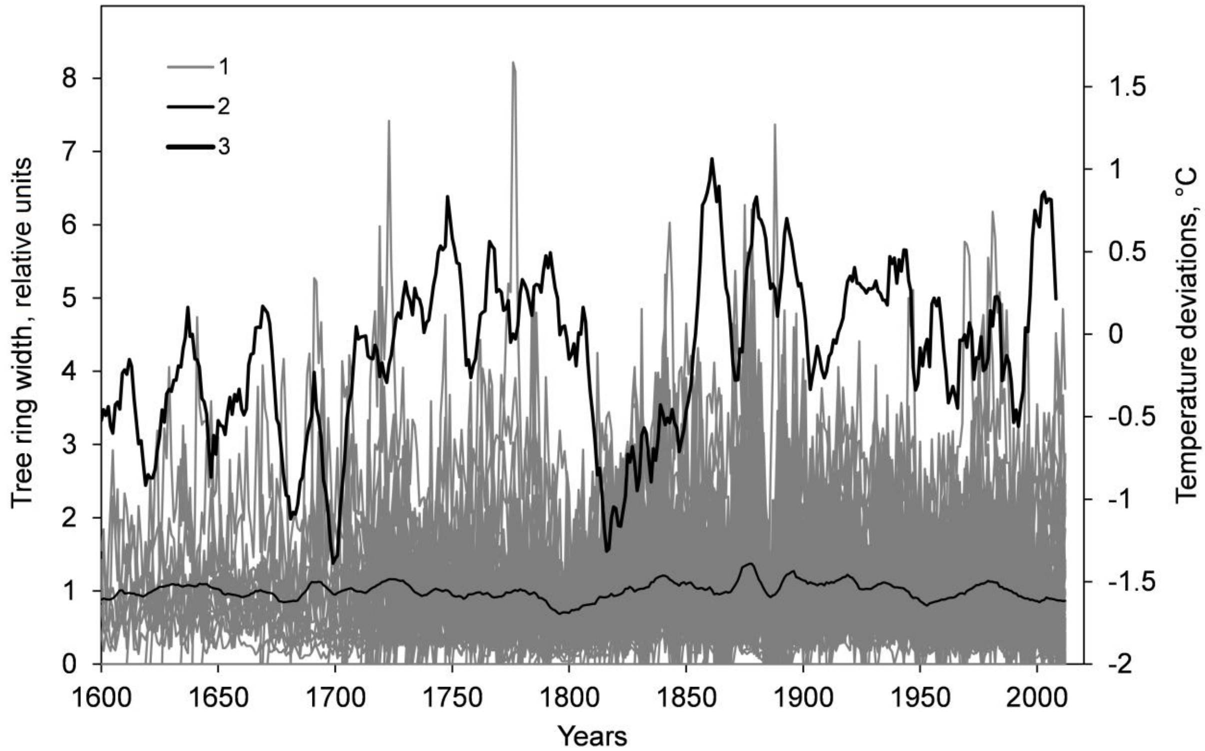

Figure 5