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Article

Vulnerability of larch forests to forest fires along a latitudinal gradient in eastern Siberia

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Abstract

The predicted increase in frequency and intensity of boreal forest fires is considered a significant source of carbon dioxide emissions and linked with the degradation of permafrost covering more than half of Russia. Here we analyzed the stand structure and growth of East Siberian larch forests in response to fire severity. We measured 23 sites in the southern part of eastern Siberia along a latitudinal transect with a length of more than 1500 km. Live tree volume differed significantly across geographical regions ($p < 0.05$), decreasing from south to north (76–250 $m^3 \cdot ha^{-1}$), with higher values in forests burnt with low severity. Similarly, volume of coarse woody debris decreased from south to north. The volume of dead standing trees, on the other hand, increased from south to north. The distribution of trees by diameter class in some areas showed clear evidence of fires, with small trees being absent to rare in forests burnt at high severity. The impact of severe fires on stand volume was negligible at the southern sites, potentially associated with rapid regeneration of birch. Birch is an important component of larch forests near the southern boundary of the permafrost, which may contribute to larch forests in the southern part of the study transect being less vulnerable to wildfires compared to northern larch forests.

Key words: *Larix gmelinii*, wildfire, mortality, carbon emissions, coarse woody debris, permafrost, Yakutia, *Pinus sylvestris*, *Pinus pumila*, *Picea obovata*, *Betula platyphylla*

Résumé

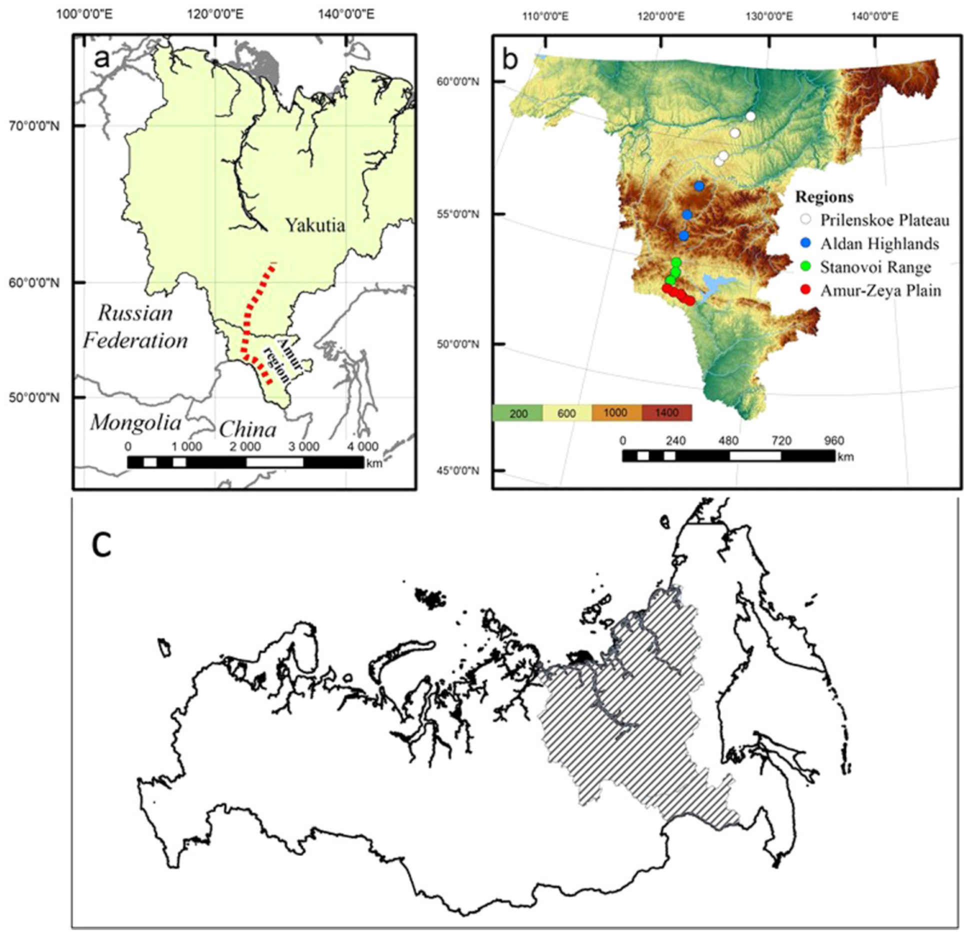
L'augmentation prévue de la fréquence et de l'intensité des incendies de forêt boréale est considérée comme une source importante d'émissions de dioxyde de carbone et est liée à la dégradation du pergélisol couvrant plus de la moitié de la Russie. Nous avons analysé ici la structure et la croissance des peuplements de mélèzes de Sibérie orientale en fonction de la gravité des incendies. Nous avons mesuré 23 sites dans la partie sud de la Sibérie orientale le long d'un transect latitudinal de plus de 1500 km de long. Le volume des arbres vivants différait significativement entre les régions géographiques (p < 0,05), diminuant du sud au nord (76–250 $m^3 \cdot ha^{-1}$), avec des valeurs plus élevées dans les forêts brûlées avec une faible sévérité. De même, le volume des débris ligneux grossiers a diminué du sud au nord. Le volume des arbres morts sur pied, en revanche, a augmenté du sud au nord. La distribution des arbres par classe de diamètre dans certaines zones a montré des signes évidents d'incendies, les petits arbres étant absents ou rares dans les forêts brûlées avec une sévérité élevée. L'impact des incendies graves sur le volume des peuplements était négligeable sur les sites du sud, ce qui pourrait être associé à une régénération rapide du bouleau. Le bouleau est une composante importante des forêts de mélèzes près de la limite sud du pergélisol, ce qui pourrait contribuer à rendre les forêts de mélèzes de la partie sud du transect étudié moins vulnérables aux incendies que les forêts de mélèzes du nord. [Traduit par la Rédaction]

Mots-clés : *Larix gmelinii*, feu de forêt, mortalité, émissions de carbone, débris ligneux grossiers, pergélisol, Yakoutie, *Pinus sylvestris*, *Pinus pumila*, *Picea obovata*, *Betula platyphylla*

Introduction

In the 21st century, the crucial role of forest ecosystems in maintaining and regulating the processes and structures of the biosphere has been recognized at the level of policy decisions, now aimed at preventing forest loss and forest degradation and restoring degraded forests (Kindler 2016; Duc et al. 2020; Cao et al. 2020; Lee et al. 2020). A significant proportion of the boreal forest grows on permafrost (i.e., perennially

Fig. 1. Overview of study region (shaded) and location of transect shown as dashed line (*a*), a detailed elevation map showing the locations of the sample sites (*b*) and location of the study region in Russia (*c*). DATA: (*a*, *c*) from shapefile ESRI: World Countries (Esri 2022); (*b*) from SRTM (Jarvis et al. 2008). Borders of countries and Yakutia obtained from ESRI open access layer "World Administrative Divisions" https://www.arcgis.com/home/item.html?id=f0ceb8af000a4ffbae75d742538c548b. Track and points were obtained from GPS. Elevation map based on SRTM open data https://srtm.csi.cgiar.org/. [Colour online]



frozen soil), making these ecosystems particularly vulnerable to warming and disturbances. Wildfires are the most extensive and damaging disturbance in much of the boreal forest. These fires vary in frequency, intensity, and severity and are critical for the global carbon and energy cycles, plant regeneration, and vegetation structure in boreal forests (Taylor and Skinner 2003; Alexander et al. 2018; Loranty et al. 2018; Paulson et al. 2021). While many remote-sensing and modelling studies have been conducted on the temporal and spatial variability of forests in the permafrost zone (DeLuca and Boisvenue 2012; Schaphoff et al. 2016; Talucci et al. 2020), studies using field sample sites for assessing the impacts of forest fires remain scarce, in particular in the permafrost region of eastern Russia (Utkin 1965; Bondarev 1997; Abaimov 2005; Kajimoto et al. 2010; Prokushkin et al. 2011).

Russian permafrost-affected forests are mostly (70%) dominated by larch (*Larix* spp.). In these communities, forest growth is limited by moisture and not limited by radiation, as in non-permafrost forests (Abaimov 2005; Kharuk et al. 2016). We have only a few field studies aimed at studying the stand structure of larch-dominated forest stands in Siberia and the Far East. Studies of larch mixing with other species, differentiation of trees by size, and allocation of age generations are specific to different parts of the range and are very important for understanding the functioning of these ecosystems under current conditions and in the future. In Siberia, forest fires commonly have a natural origin and are started by lightning for latitude higher than 65°N, while the proportion of fires with the anthropogenic origin increasing southward (Kajimoto et al. 2010; Kharuk et al. 2016). In boreal forests, fire severity and area burnt annually vary significantly from year to year, which results in mixed-age structures, species composition, and regeneration stages on a landscape scale (Utkin 1965; Young et al. 2017). Thus, fire in boreal forests, particularly permafrost regions, can increase beta diversity (ecosystem diversity) (Krivobokov et al. 2015). The frequency and severity of future forest disturbances are projected to increase both in Russia and worldwide (Kajimoto et al. 2010; Young et al. 2017; Aaltonen et al. 2019). The Amur Region and Yakutia form a vast territory in the Asian part of Russia, extending from the southern to the northern border of the country (Fig. 1). Most of the forests in the study area are managed. However, the spread of forest fires is difficult to control due to the large area, limited access, and fire-fighting abilities, so fire suppression in eastern Siberia is much lower compared to European Russia. The objectives of this study were to (1) collate data on stand structure along a latitudinal transect, from the Amur basin to the Yakutian basin of the Lena River (50°–62°N), and (2) quantify the impact of fire severity on live tree volume, volume of standing dead trees, and coarse woody debris (CWD). We were interested in how vulnerable and resilient the forest communities in the study region are to disturbances due to differing site conditions, topography, and location. Improved knowledge of the fire response of forests in eastern Siberia provides a basis for more effective adaptation measures and forest management practices.

Materials and methods

Study region

The study region is located in the Russian Federation in the basins of the Amur and Lena rivers along a transect of 1500 km length at the latitude range between 50° and 62°N (Fig. 1). This is an area with complex macro- and microrelief and pronounced latitudinal–altitudinal climate gradients. An analysis of the condition of larch forests in this region, taking into account the natural features of the area and the history of disturbance, will provide new data for understanding the structure, dynamics, and vulnerability of these ecosystems. The Stanovoi Range is the main watershed of the Amur and the Lena basins and separates the two catchments. Within the study area, there are four topographical regions: the Amur-Zeya Plain (AZ), the northern slope of the Stanovoi Range (SR) in the Amur basin, the Aldan Highlands (AH), and the Prilenskoe Plateau (PP) in the Lena basin. The study region is characterized by regular accidental fires, which are often impossible to suppress and extinguish. Most fires usually occur in June and July, with reduced fire activity in August and early September. These fires have predominantly anthropogenic origin, with some caused by thunderstorms (Kharuk et al. 2016). The average annual area burned in the East Siberian taiga estimate at ~6 million hectares (Talucci et al. 2022). We estimated the time since fire in this region to be 4–40 years (e.g., for site PP6 time since fire 7 years, 4 years for SR4, and 35 years for AZ5) using satellite data analysis. Roads and railroads are protected from forest fires by ditches and strips kept unvegetated. Anthropogenic activities in the study region are mostly road construction, forest management, geological exploration, and mining. The larch forests studied here are a typical, native forest formation. In the second half of the Holocene, the role of humans in shaping the vegetation in the study area greatly increased (Utkin 1965). Historically, fires have been the key factor in the dynamics of larch forests. The harvested area is commonly smaller than the annually burnt area (Zamolodchikov et al. 2019). The effects of fires on the forests include thinning, reduced diversity and age, reduced resistance of trees towards pathogens, as well as a general decreased productivity of stands (Utkin 1965).

Fig. 2. Two typical examples of larch stands affected by fire of different severity. Site PP5 (top) was subject to low severity fire and site PP6 (bottom) affected by high fire intensity about 10 years ago. [Colour online]

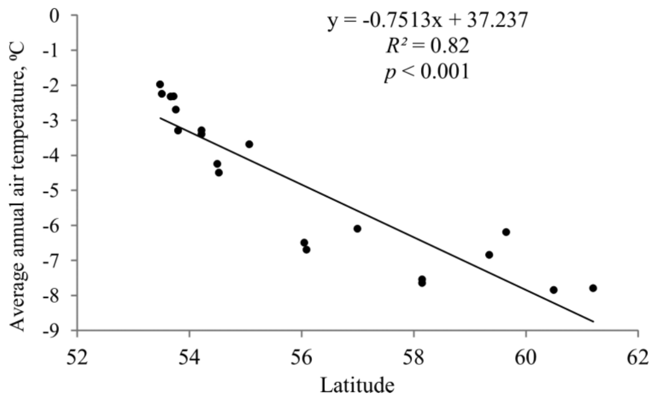
The degree of fire severity was assessed by the presence of charred bark on old trees, presence/absence of young forest generation, composition of flora of herbaceous plants, general appearance of the stand, and the number of dead standing trees. Typical examples for the two fire severities are shown in Fig. 2. All forests in the study region have been affected by fires in the past. Thus we were not able to find unburnt reference stands. In each of the four regions, six sample sites were established, of which three were intensively disturbed by fire, and three were weakly disturbed (Fig. 1). In total, we established 23 sites (only two intensively disturbed sites were sampled in AH region). Our sample sites were selected to represent growing conditions and forest types typical of the study region. We used soil maps and a digital elevation model to ensure that plots were matched in relation to soil type, elevation, and aspect within each of the four regions (Supplementary Fig. S3). Within the four regions, the dominant soil type varies little (Table 1). In the central mountainous part of the transect, podzols are most common. In the flat parts of the transect, forests mainly grow on brown soils and leptosols. The average annual temperature in the study region for the years 1979–2013 varied from −1.5 to −9.3 °C, annual precipitation ranging from 200 to 800 mm and the altitude above sea level between 200 and 1000 m.

Table 1. Locations, elevation, and stand characteristics of the used sample sites.

Zone	Site	Latitude (°)	Longitude (°)	Elevation (m)	Fire severity	Stand volume ($m^3 \cdot ha^{-1}$)	Basal area ($m^2 \cdot ha^{-1}$)	Stem density (ha^{-1})	Age (years)	Species composition	Type of soil
PP	PP2	59.5001	127.042	340	High	114	14	796	114	60%L, 30%Pss, 10%Pi	Leptosols
	PP4	60.4685	127.764	497	High	24	3	224	121	100%L	Leptosols
	PP6	61.2138	128.924	235	High	3	1	16	140	100%L	Fluvisols
	PP1	59.255	126.748	556	Low	195	33	2333	127	90%L, 10%Pi	Leptosols
	PP3	60.4683	127.762	496	Low	162	20	1616	95	90%L, 10%Pi	Leptosols
	PP5	61.2126	128.925	233	Low	76	10	540	115	100%L	Fluvisols
AH	AH1	56.0753	124.834	985	High	19	2	76	75	100%L	Podzols
	AH5	58.1664	125.447	945	High	65	9	620	75	50%L, 40%Pi, 10%Ps	Podzols
	AH2	56.0782	124.827	976	Low	98	13	920	59	100%L	Podzols
	AH3	56.939	124.863	820	Low	152	18	700	160	100%L	Podzols
	AH4	58.1647	125.448	926	Low	115	14	528	220	70%L, 30%Pi	Podzols
SR	SR2	54.1921	124.378	574	High	132	17	1556	40	80%L, 20%B	Podzols
	SR4	54.5811	124.636	747	High	46	6	335	66	100%L	Rock outcrop
	SR6	54.9624	124.573	602	High	53	7	904	100	100%L	Podzols
	SR1	54.1897	124.367	555	Low	224	22	1300	72	100%L	Podzols
	SR3	54.5054	124.637	708	Low	250	22	608	124	100%L	Podzols
	SR5	54.5814	124.639	780	Low	74	10	688	49	100%L	Rock outcrop
AZ	AZ1	53.4981	125.925	381	High	229	31	2188	60	80%B, 10%L, 10%P	Cambisols
	AZ4	53.7119	125.191	432	High	162	17	508	107	100%L	Cambisols
	AZ5	53.7572	124.691	471	High	158	9	533	72	90%L, 10%B	Histosols
	AZ2	53.5718	125.462	435	Low	246	24	1150	80	80%L, 20%B	Histosols
	AZ3	53.6756	125.275	445	Low	150	19	1724	28	70%L, 30%B	Cambisols
	AZ6	53.8677	124.229	585	Low	272	28	1136	120	90%L, 10%B	Cambisols

Note: From south to north: AZ, the Amur-Zeya Plain; SR, the Stanovoi Range; AH, the Aldan Highlands; and PP Prilenskoe Plateau. Age was estimated using increment cores. For species composition, only tree species with share greater than 5% were shown. L, *Larix gmelinii* (Rupr.) Kuzen.; B, *Betula platyphylla* Sukaczev; P, *Populus tremula* L.; Pi, *Picea obovata* Ledeb.; Ps, *Pinus sibirica* Du Tour; Pss,*Pinus sylvestris* L.

Fig. 3. The relationship between latitude and average annual temperature of study sites along the transect from Amur to Yakutia.



Average annual air temperature changes strongly across the transect with latitude and there is negative trend of 0.7 °C per degree of latitude (Fig. 3). One of the most common species in the study region is *Larix gmelinii* (Rupr.) Kuzen., which grows in monospecific stands and occasionally mixed with *Betula platyphylla* Sukaczev and *Pinus sylvestris* L. At elevation higher than 600 m, *Pinus pumila* (Pall.) Regel becomes more frequent, occasionally forming continuous closed stands. The permafrost in SR region occurs in isolated regions and has its most southern occurrence in AZ region. In contrast, continuous permafrost prevails in northern regions (AH and PP).

The sample sites were placed in larch-cowberry forests, the most common community type in this region. In this community, cowberry (*Vaccinium vitis-idaea* L.) has a projected foliage cover of 70%–100% and is replaced by marsh tea (*Ledum palustre* L.) in wetter habitats. In forests burnt with high fire severity, the dominance of herbaceous species increased, especially *Carex globularis* L. and *Chamaenerion angustifolium* (L.) Scop.

Volume of live and dead standing trees

Stand structure was quantified using quadratic sample sites with 50 m × 50 m size. In some cases, we had to make a rectangular-shaped site (50 m × 40 m or 50 m × 30 m) to have the same growing conditions at the site. The diameter of breast height (DBH at 1.3 m) was measured for each tree above 6 cm of DBH. We recorded each tree species and condition (living or dead). On each plot, tree height was measured for 10–12 trees of each species to obtain a DBH–tree height relationship for each species (Supplementary Fig. S1). We calculated stem volumes of both living and dead trees using regional yield tables, then stand volumes were estimated in surveyed plots (Table 1). The distribution of tree number by size is shown in Supplementary Fig. S2, and stem density and basal area were estimated.

Coarse woody debris

The CWD volume on the forest floor was measured using the line transect method (Van Wagner 1968; Woldendorp et al. 2004; Grabovsky and Zamolodchikov 2012). We measured four 50 m length transects along the perimeter of the 50 m × 50 m plot or along the perimeter of the rectangle for sites with other dimensions. For each CWD fragment with a diameter larger than 4 cm crossing a transect, we measured species, maximum and minimum diameter (measured crosswise), length, and stage of decomposition. CWD classes were distinguished visually according to the method developed for coniferous tree species: (1) thin branches are preserved, no rot; (2) the bark is preserved, thin branches are lost, and the trunk may by covered by mosses and lichens; (3) the bark is preserved as fragments, only first- and second-order branches remain on the trunk, and heart rot is possible; (4) the bark is almost completely lost, first-order branches shorter than trunk diameter; (5) the initial shape and structural integrity are lost (Ivanov et al. 2018). Calculations were done using the software "Debris," publicly available from the Center for Forest Ecology and Productivity, Russian Academy of Sciences (http://cepl.rssi.ru/r-and-d-8/).

Statistical analysis

All data were checked for normality and homogeneity of variances using the Shapiro and Levene tests. We used a pairwise *t* test to detect significant differences between plots by fire severity in one region. For multiple comparisons between regions, we used ANOVA followed by Tukey post hoc test. All statistical analysis and visualization were done in R studio (R Core Team 2020).

Results

Stand structure across a latitudinal transect of Larch forests on permafrost

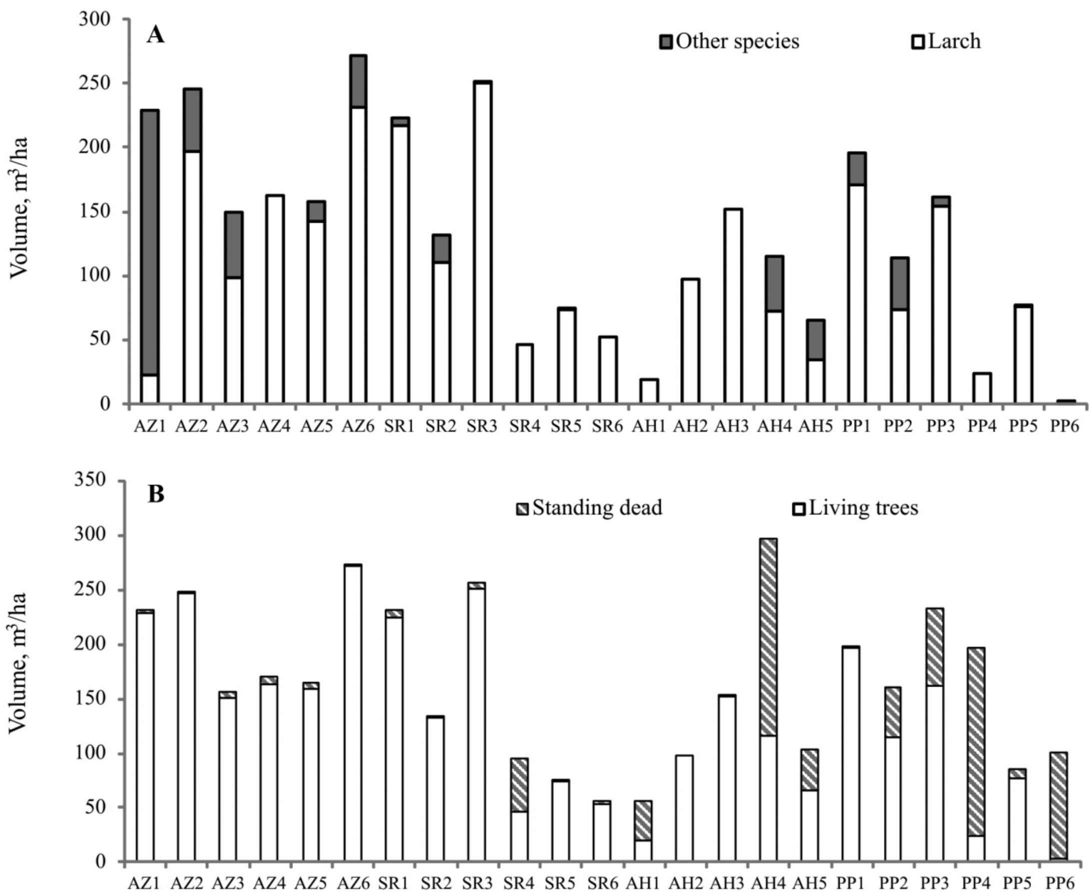
Most sample sites were dominated by *Larix gmelinii*. *Betula platyphylla* was a frequent secondary species in the southern sites, while *Picea obovata* and *Pinus sibirica* were common in the northern sites. Volume of living trees ranged from 3 to 272 $m^3 \cdot ha^{-1}$. Basal area and stem density were also highly variable (Table 1).

The average stand age ranged from 28 to 160 years, with on average lower stand age in the southern Amur–Zeya region (AZ) with 78 years. The stand age reported in Table 1 provides evidence for the infrequent nature of stand-replacing fires in this region, but gives no information on the frequency of less severe surface fires.

All studied stands (except AZ1) were dominated by living larch trees (Fig. 4). In the southern part of the transect (AZ region), larch was replaced by *Betula platyphylla* following forest fires. In the AH and PP regions, larch often grows associated with *Pinus sylvestris*, *Pinus sibirica*, and (or) *Picea obovata* (Table 1).

The proportion of dead standing trees increases with latitude (Fig. 4B). In the AH and PP regions, the volume of dead standing trees is on average eight times higher than in the AZ region. A similar pattern can be observed when grouping live and dead volume by sampling regions (Figs. 5 and 6).

Fig. 4. Forest volumes at all study sites for larch and other species (*a*), and for alive trees and standing dead trees of all species (*b*).



Effect of the region and fire intensity on stand volume and CWD

Despite the small sample size ($n = 3$ per region and severity), our data reveal significant differences in the amount of live wood in intensively and weakly disturbed forests in the northern part of the study area (regions AH and PP, $p < 0.01$) (Fig. 5). Here the stock in weakly disturbed forests is more than two times higher than in intensively disturbed ones. In the southern part (AZ and SR), however, the differences in average volumes were not significant. Live tree volumes were higher in stands affected by fires of low severity. The volume of CWD was larger in the north, however, highly variable and not significantly different by fire severity (Fig. 6A). Higher proportion of CWD in early stages of decomposition at severely disturbed sites, suggesting more recent mortality and input of CWD associated with severe fires (Fig. 6B).

Discussion

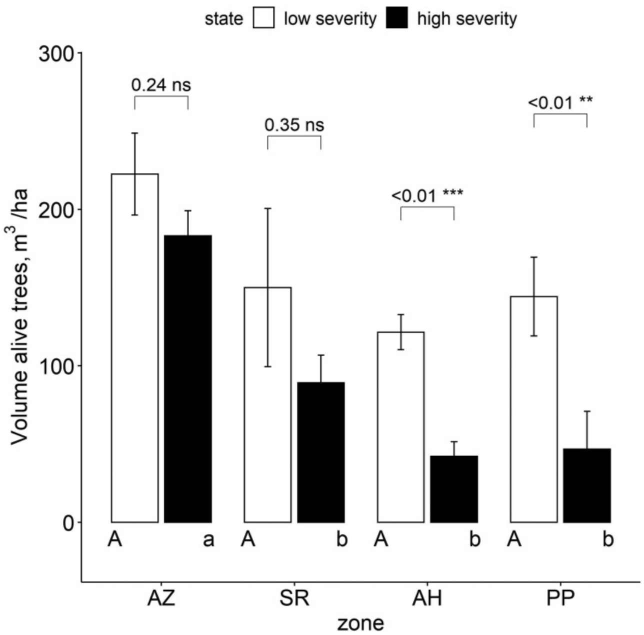
Our study is, to our knowledge, the first attempt to analyze the effects of fire severity on stand structure on larch permafrost forest in Central Yakutia. Sampling 23 sites along a 1500 km latitudinal transect (53°–61°N) provides insight into how forests change with increasing latitude and colder conditions. Our results indicate large spatial variability of forest structure due to historic fire intensity and fire severity, presumably caused by differences in fire weather, vegetation, and soil conditions.

Our observations of live tree volume agree with data from official forest statistics and estimates derived from remote-sensing. According to the materials of the state accounting of the forest fund, the average growing sock volume in the forests of Yakutia and the Amur region are 62 and 110 $m^3 \cdot ha^{-1}$, respectively, and the average reserve of mature and over-mature forests in the Amur region is 129 $m^3 \cdot ha^{-1}$ (amurobl.ru; deples.sakha.gov.ru). Similar values obtained in the sampling areas are 101 and 176 $m^3 \cdot ha^{-1}$ for Yakutia and the Amur region, respectively (Table 1). The differences in volume can be explained by the local geography of the study. Our sampling areas describe the stand conditions in southern Yakutia (while the statistics are given for the whole of Yakutia). In the Amur region, the underestimation of tree volume in official statistics is likely due to a history of more intensive forest exploitation According to some studies, the average timber reserves in the region's forests are estimated at 50–100 $m^3 \cdot ha^{-1}$, which is consistent with our data. (Gaveau et al. 2003; Zyryanova et al. 2005; Kukavskaya et al. 2013; Prokushkin et al. 2014).

Effects of fires on Siberian larch forests

We found that forest fires did not affect forest stands equally within the four geographic regions. Larch stands in

Fig. 5. Stand volume of the alive trees grouped by four geographical regions and fire severity. For each group, the number of observations is 3 (except AH intense with $n = 2$). Uppercase letters represent differences for forests subject to low fire severity and small letters for high fire severity, based on the Tukey post hoc test. The p values of pairwise t tests are shown across top.



the mountainous part of southern Yakutia (AH region) were apparently most vulnerable to fire impacts. In the lowland areas, such as the Amur and Lena valleys, differences in fire severity were not linked to differences in the stand structure. The southern larch stands were commonly mixed with other species (Cai et al. 2018; Kang and Park 2019). Thus, our results support the ecological rule that "the more diverse the ecosystem, the more resilient it is" (Isbell et al. 2011).

Diversity is often also correlated with productivity (Liang et al. 2016). Our study confirms that productivity is linked with diversity in Siberian larch forests. Under more favourable growth conditions in the south and high fire severity, larch forests are often replaced by birch-dominated forests after the fire. This is facilitated by the easily wind-dispersed birch seeds and birch being a common mixed species in the studied ecosystems. Under such conditions, the growth is fast and by the age of 50 years, the total stand volume commonly reaches or exceeds 200 $m^3 \cdot ha^{-1}$. In this case, the effects of forest fires are partly mitigated by changes in species composition. Fire severity effects in southern regions may be more viable. Several studies have shown significant variability of forest fires in Siberian larch forests by location, climate and radiation, as well as species composition, productivity, causes of fires, and mean fire return interval (Utkin 1965; Kharuk et al. 2016; Young et al. 2017; Narita et al. 2021; Burrell et al. 2022). Features of recovery and growth of Siberian larch forests are similar to those of Alaskan forests (Mack et al. 2021). In agreement with the Alaskan study, we found that immediate regeneration of the burnt forest and the rapid formation of the secondary forest is critical for offsetting carbon losses. We note the few number of observations per region and fire severity ($n = 3$) and that a larger sample size may result in different relations as reported here.

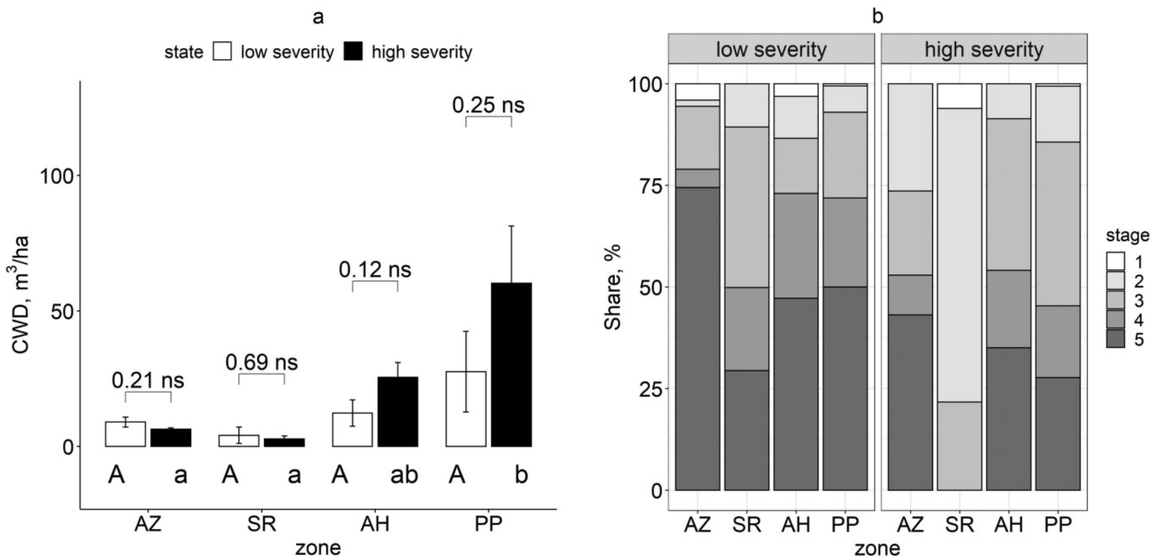
Biomass is an important carbon storage across boreal forests (Pan et al. 2011). Forest fires in the mountainous and colder parts of our transect apparently reduced the forest carbon sequestration more than in the warmer and lower regions. Presumably, a combination of topography and cold climates is important for forest growth and permafrost melt, as evident in a study of larch forests in the Da Hinggan Mountains (Li et al. 2021). Our study suggests the following patterns: higher elevations are associated with lower mean annual temperatures and greater precipitation, which leads to greater permafrost, lower forest productivity, and an increased vulnerability to fires (see also Brown et al. 2002). However, in the northern part of the larch range (Kolyma River basin), the topography did not strongly influence the effects of fire on stand structure (Berner et al. 2012).

We can assume that the high proportion of standing deadwood in the second half of the transect (sites SR4 to PP6, Fig. 5) is associated with harsher growing conditions, namely low precipitation. Here, weakened trees are less likely to survive than in the southern part of the transect. Therefore, an increase in the share of dead standing trees in the stand can be considered as an additional factor of increased forest vulnerability. When logging forests in the study region, it is necessary to remove dead trees from logging sites as a matter of priority, where possible. Not all forest fires completely destroy forest stands or lead to the combustion of the entire organic matter. Considerable volumes of dead standing trees and CWD in our study indicate that low severity surface fires predominate in eastern Siberia. Our results suggest that small-sized trees (until about 12 cm DBH) are killed and burned completely, while larger-sized trees with thicker bark usually survive fires and continue to grow.

Coarse woody debris

The increase in CWD stocks from south to north was an unexpected result and may indicate that southern parts of the study area experience more severe or more frequent fires (Kharuk et al. 2016). Another reason for the increasing CWD volume by latitude could be slower decomposition associated with decreasing temperature and decreasing annual precipitation. This result is supported by investigations showing that annual average temperature is the major predictor of CWD decomposition (Berg 2000; Bradford et al. 2016; Neumann et al. 2021). In western Siberian forests, the decomposition rate of deadwood is two times slower than in the southern taiga due to differences in temperature (Mukhin and Voronin 2007). Climate change can be expected to have two contrasting effects on CWD accumulation in Siberian forests. Increasing temperature by one degree will increase the rate of decomposition and in turn, loss of CWD by 12% in Siberian forests (Mukhin et al. 2010). On the other hand, warmer conditions will increase productivity and fire intensity (Utkin 1965), and both will most likely increase the inputs of CWD.

Fig. 6. Coarse woody debris (CWD) grouped by regions and fire severity (*a*) and the decay stages of the CWD (*b*). Stages of decomposition vary from 1, fresh CWD, to 5, well-decomposed CWD. For details see Fig. 5.



The CWD volume in forests burnt at high severity is almost two times greater than forests burnt at low severity. We also observed pronounced differences in the decay stages, with the well-decomposed decay stages 4–5 representing 50%–80% of CWD in weakly disturbed forests. In intensively disturbed forests, decay stages 1–3 account for 50%–100% of total CWD. Our results suggest that fire severity, in addition to quantity, also changes the quality of deadwood. The proportion of fresh CWD increases in forests that have been heavily fire-prone. This pattern is fairly consistent across studied regions, suggesting that fire intensity is an important driver for CWD input. Combustion of dead wood is always an instantaneous release of large amounts of carbon into the atmosphere. The climate-regulating function of such forests is significantly reduced. Forest fires, destroying CWD stocks, can change the carbon stock of forests, turning them into carbon sources (Mitchell et al. 2009).

Stand density

The tree diameter–density distributions of our 23 sample sites suggest striking differences between intensively disturbed forests (e.g., AZ4) and weakly disturbed forests (e.g., SR1). An early study on the effect of fire on larch stand structure showed that the most frequent stem size in undisturbed forests is small-sized trees (Utkin 1965). Trees with DBH of 8–12 cm have thin bark and may die following brief exposure to fire, even of low intensity. The bark thickness of larch trees with DBH > 25 cm is about 4–5 cm, and such bark thickness seems to be an adaptive trait to survive under fire disturbances (Vines 1968; Lawes et al. 2011). Bark is important for moderating heat transfer, insulation, and tree survival (Gill and Ashton 1968; Schwilk et al. 2013; Wesolowski et al. 2014)

Conclusion

The forests in our study region have a pyrogenic origin and need fire for stand regeneration. However, the increase in fire frequency (in particular fires caused by humans), global climate change, and infrastructure development disrupt the natural balance of biogeochemical cycles and reduce carbon stocks in the aboveground part of forests. This study contributes to our understanding of the functioning of forest ecosystems growing on permafrost and can be used to develop and calibrate suitable growth and forecasting models. Due to the underdeveloped infrastructure and low population density in the study region, the available resources to undertake forest management are scarce and large areas are unmanaged. Forest management can modify stand structures and forest resilience towards fires. New technologies to monitor, contain and extinguish forest fires can also have considerable effects on permafrost forests. We expect that the impact of management might be strong for forests affected by permafrost, as tree growth increases due to soil thawing and changes in vegetation cover.

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Data availability

All the data in this study are available from https://figshare.com/s/08c88140597310603ccf.

Code availability

Code is available on request from the corresponding author.

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Competing interests

The authors declare that they have no conflict of interest.

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Supplementary material

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References

Aaltonen, H., Palviainen, M., Zhou, X., Köster, E., Berninger, F., Pumpanen, J., and Köster, K. 2019. Temperature sensitivity of soil organic matter decomposition after forest fire in Canadian permafrost region. J. Environ. Manage. **241**(April): 637–644. doi:10.1016/j.jenvman.2019.02.130. PMID: 30962006.

Abaimov, A. 2005. Peculiarities and main directions of forest and sparse forest dynamics in the permafrost zone of Siberia. Contemp. Probl. Ecol. **4**: 663–675.

Alexander, H.D., Natali, S.M., Loranty, M.M., Ludwig, S.M., Spektor, V.V., Davydov, S., et al. 2018. Impacts of increased soil burn severity on larch forest regeneration on permafrost soils of far northeastern Siberia. For. Ecol. Manage. **417**(January): 144–153. doi:10.1016/j.foreco.2018.03.008.

Berg, B. 2000. Litter decomposition and organic matter turnover in northern forest soils. For. Ecol. Manage. **133**(1–2): 13–22. doi:10.1016/S0378-1127(99)00294-7.

Berner, L.T., Beck, P.S.A., Loranty, M.M., Alexander, H.D., MacK, M.C., and Goetz, S.J. 2012. Cajander larch (*Larix cajanderi*) biomass distribution, fire regime and post-fire recovery in northeastern Siberia. Biogeosciences, **9**(10): 3943–3959. doi:10.5194/bg-9-3943-2012.

Bondarev, A. 1997. Age distribution patterns in open boreal Dahurican larch forests of Central Siberia. For. Ecol. Manage. **93**(3): 205–214. doi:10.1016/S0378-1127(96)03952-7.

Bradford, M.A., Berg, B., Maynard, D.S., Wieder, W.R., and Wood, S.A. 2016. Understanding the dominant controls on litter decomposition. J. Ecol. **104**(1): 229–238. doi:10.1111/1365-2745.12507.

Brown, J., Ferrians, J.O., Heginbottom, J. A., and Melnikov, E. 2002. Circum-Arctic map of permafrost and ground-ice conditions. Version 2. NSIDC: National Snow and Ice Data Center, Boulder, Colorado USA, pp. 1–11.

Burrell, A.L., Sun, Q., Baxter, R., Kukavskaya, E.A., Zhila, S., Shestakova, T., et al. 2022. Climate change, fire return intervals and the growing risk of permanent forest loss in boreal Eurasia. Sci. Total Environ. **831**: 154885. doi:10.1016/j.scitotenv.2022.154885. PMID: 35358519.

Cai, W.H., Liu, Z., Yang, Y.Z., and Yang, J. 2018. Does environment filtering or seed limitation determine post-fire forest recovery patterns in boreal larch forests? Front. Plant Sci. **9**(September): 1–12. doi:10.3389/fpls.2018.01318. PMID: 29410674.

Cao, S., Suo, X., Xia, C., Yu, Z., and Feng, F. 2020. Net value of forest ecosystem services in China. Ecol. Eng. **142**(580): 105645. doi:10.1016/j.ecoleng.2019.105645.

DeLuca, T.H., and Boisvenue, C. 2012. Boreal forest soil carbon: distribution, function and modelling. Forestry, **85**(2): 161–184. doi:10.1093/forestry/cps003.

Duc, M., Ancev, T., and Randall, A. 2020. Forest governance and economic values of forest ecosystem services in Vietnam. Land Use Policy, **97**: 103297. doi:10.1016/j.landusepol.2018.03.028.

Esri. ArcGIS Content Team. 2022. World countries. Available from https://services.arcgis.com/P3ePLMYs2RVChkJx/arcgis/rest/services/World_Countries/FeatureServer [accessed October 2021].

Gaveau, D.L.A., Balzter, H., and Plummer, S. 2003. Forest woody biomass classification with satellite-based radar coherence over 900 000 km^2 in Central Siberia. For. Ecol. Manage. **174**(1–3): 65–75. doi:10.1016/S0378-1127(02)00028-2.

Gill, A.M., and Ashton, D.H. 1968. The role of bark type in relative tolerance to fire of three central Victorian Eucalyptus. Aust. J. Bot. **16**: 491–498.

Grabovsky, V., and Zamolodchikov, D. 2012. Models of estimating slash reserves according to data obtained on transects. Russ. J. For. Sci. **2**: 66–73.

Isbell, F., Calcagno, V., Hector, A., Connolly, J., Harpole, W.S. Reich, P.B., et al. 2011. High plant diversity is needed to maintain ecosystem services. Nature, **477**(7363): 199–202. doi:10.1038/nature10282. PMID: 21832994.

Ivanov, A.V., Braun, M., Zamolodchikov, D.G., Loshakov, S.Y., and Pototskii, O.V. 2018. Carbon emission from the surface of coarse woody debris in Korean pine forests of southern Primorye. Russ. J. Ecol. **49**(4): 306–311. doi:10.1134/S1067413618040070.

Jarvis, A., Reuter, H.I., Nelson, A., and Guevara, E. 2008. Hole-filled seamless SRTM data V4. International Centre for Tropical Agriculture (CIAT). Available from http://srtm.csi.cgiar.org [accessed 15 November 2011].

Kajimoto, T., Osawa, A., Usoltsev, V.A., and Abaimov, A.P. 2010. Biomass and productivity of Siberian larch forest ecosystems. et al. Permafrost Ecosystems. Ecological Studies, vol. 209. *Edited by* A. Osawa, O. Zyryanova, Y. Matsuura, T. Kajimoto and R. Wein. Springer, Dordrecht. doi: 10.1007/978-1-4020-9693-8_6.

Kang, J.W., and Park, Y.D. 2019. Effects of deforestation on microbial diversity in a Siberian larch (*Larix sibirica*) stand in Mongolia. J. For. Res. **30**(5): 1885–1893. doi:10.1007/s11676-018-0689-3.

Kharuk, V.I., Dvinskaya, M.L., Petrov, I.A., Im, S.T., and Ranson, K.J. 2016. Larch forests of middle Siberia: long-term trends in fire return intervals. Reg. Environ. Chang. **16**(8): 2389–2397. doi:10.1007/s10113-016-0964-9.

Kindler, E. 2016. A comparison of the concepts: ecosystem services and forest functions to improve interdisciplinary exchange. For. Policy Econ. **67**: 52–59. doi:10.1016/j.forpol.2016.03.011.

Krivobokov, L. V., Zverev, A.A., and Mukhortova, L. 2015. Floristic characteristics, types and ecology of larch forests of the middle Siberia of northern boreal subzone. Ecol. Saf. **9**(February 2017): 1–8.

Kukavskaya, E.A., Buryak, L. V., Ivanova, G.A., Conard, S.G., Kalenskaya, O.P., Zhila, S.V., and McRae, D.J. 2013. Influence of logging on the effects of wildfire in Siberia. Environ. Res. Lett. **8**(4): 1–11. doi:10.1088/1748-9326/8/4/045034.

Lawes, M.J., Richards, A., Dathe, J., and Midgley, J.J. 2011. Bark thickness determines fire resistance of selected tree species from fire-prone tropical savanna in North Australia. Plant Ecol. **212**(12): 2057–2069. doi:10.1007/s11258-011-9954-7.

Lee, J., Kim, H., Song, C., Sun, G., Lee, W., and Son, Y. 2020. Determining economically viable forest management option with consideration of ecosystem services in Korea: a strategy after successful national forestation. Ecosyst. Serv. **41**(September 2019): 101053. doi: 10.1016/j.ecoser.2019.101053.

Li, Y., Liu, H., Zhu, X., Yue, Y., Xue, J., and Shi, L. 2021. How permafrost degradation threatens boreal forest growth on its southern margin? Sci. Total Environ. **762**:143154. doi: 10.1016/j.scitotenv.2020.143154. PMID: 33131839.

Liang, J., Crowther, T.W., Picard, N., Wiser, S., Zhou, M., Alberti, G., et al. 2016. Positive biodiversity–productivity relationship predominant in global forests. Science, **354**(6309). doi:10.1126/science.aaf8957.

Loranty, M.M., Davydov, S.P., Kropp, H., Alexander, H.D., Mack, M.C., Natali, S.M., and Zimov, N.S. 2018. Vegetation indices do not capture forest cover variation in upland Siberian larch forests. Remote Sens. **10**(11): 1686. doi:10.3390/rs10111686.

Mack, M.C., Walker, X.J., Johnstone, J.F., Alexander, H.D., Melvin, A.M., Jean, M., and Miller, S.N. 2021. Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees. Science, **372**(April): 280–283. doi:10.1126/science.abf3903.

Mitchell, S.R., Harmon, M.E., and O'Connell, K.E.B. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecol. Appl. **19**(3): 643–655. doi:10.1890/08-0501.1. PMID: 19425428.

Mukhin, V., and Voronin, P. 2007. Mycogenic decomposition of wood and carbon emission in forest ecosystems. Russian J. Ecol. **38**: 22–26.

Mukhin, V., Voronin, P., Kuznetsov, V., and Sukhareva, A. 2010. Wood decomposition by fungi in the boreal-humid forest zone under the conditions of climate warming. Dokl. Biol. Sci. **431**: 423–425. doi:10.1134/S0012496610020110.

Narita, D., Gavrilyeva, T., and Isaev, A. 2021. Impacts and management of forest fires in the Republic of Sakha, Russia: a local perspective for a global problem. Polar Sci. **27**(October 2019): 100573. doi:10.1016/j.polar.2020.100573.

Neumann, M., Turner, J., Lewis, T., McCaw, L., Cook, G., and Adams, M.A. 2021. Dynamics of necromass in woody Australian ecosystems. Ecosphere, **12**(8): e03693. doi:10.1002/ecs2.3693.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E. Kurz, W.A., et al. 2011. A large and persistent carbon sink in the world's forests. Science, **333**(6045): 988–993. doi:10.1126/science.1201609.

Paulson, A.K., Peña, H., Alexander, H.D., Davydov, S.P., Loranty, M.M., Mack, M.C., and Natali, S.M. 2021. Understory plant diversity and composition across a postfire tree density gradient in a Siberian Arctic boreal forest. Can. J. For. Res. **51**(5): 720–731. doi:10.1139/cjfr-2020-0483.

Prokushkin, S.G., Bogdanov, V.V., Prokushkin, A.S., and Tokareva, I.V. 2011. Post-fire restoration of organic substance in the ground cover of the larch forests in permafrost zone of Central Evenkia. Biol. Bull. **38**(2): 183–190. doi:10.1134/S1062359011020129.

Prokushkin, S.G., Prokushkin, A.S., and Sorokin, N.D. 2014. The intensity of phytodetrite decomposition in larch forest of the permafrost zone in Central Siberia. Biol. Bull. **41**(1): 89–97. doi:10.1134/S1062359014010075.

R Core Team. 2020. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Schaphoff, S., Reyer, C.P.O., Schepaschenko, D., Gerten, D., and Shvidenko, A. 2016. Tamm review: observed and projected climate change impacts on Russia's forests and its carbon balance. For. Ecol. Manage. **361**: 432–444. doi:10.1016/j.foreco.2015.11.043.

Schwilk, D.W., Gaetani, M.S., and Poulos, H.M. 2013. Oak bark allometry and fire survival strategies in the Chihuahuan Desert Sky Islands, Texas, USA. PLoS ONE, **8**(11): e79285. doi:10.1371/journal.pone.0079285.

Talucci, A.C., Forbath, E., Kropp, H., Alexander, H.D., DeMarco, J. Paulson, A.K., et al. 2020. Evaluating post-fire vegetation recovery in cajander larch forests in northeastern Siberia using UAV derived vegetation indices. Remote Sens. **12**(18): 2970. doi:10.3390/RS12182970.

Talucci, A.C., Loranty, M.M., and Alexander, H.D. 2022. Siberian taiga and tundra fire regimes from 2001–2020. Environ. Res. Lett. **17**(2). doi:10.1088/1748-9326/ac3f07.

Taylor, A.H., and Skinner, C.N. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecol. Appl. **13**(3): 704–719. Available from https://www.fs.usda.gov/treesearch/pubs/36548.

Utkin, A. 1965. Forets of Central Yakutia. Nauka, Moscow.

Van Wagner, C.E. 1968. The line intersect method in forest fuel sampling. For. Sci. **14**(1): 20–26.

Vines, R.G. 1968. Heat transfer through bark, and the resistance of trees to fire. Aust. J. Bot. **16**(3): 499–514. doi:10.1071/BT9680499.

Wesolowski, A., Adams, M.A., and Pfautsch, S. 2014. Insulation capacity of three bark types of temperate Eucalyptus species. For. Ecol. Manage. **313**(2014): 224–232. doi:10.1016/j.foreco.2013.11.015.

Woldendorp, G., Keenan, R.J., Barry, S., and Spencer, R.D. 2004. Analysis of sampling methods for coarse woody debris. For. Ecol. Manage. **198**(1–3): 133–148. doi:10.1016/j.foreco.2004.03.042.

Young, A.M., Higuera, P.E., Duffy, P.A., and Hu, F.S. 2017. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. Ecography (Cop.), **40**(5): 606–617. doi:10.1111/ecog.02205.

Zamolodchikov, D.G., Grabowsky, V.I., and Chestnykh, O.V. 2019. Dynamic pattern of carbon balance in the forests of federal districts of the Russian Federation. For. Sci. issues, **2**(2): 1–19. doi:10.31509/2658-607x-2019-2-2-1-19.

Zyryanova, O.A., Takayoshi, K.O., Kaichiro, S.A.S.A., and Minoru, T.E. 2005. Problems in the maintenance and sustainable use of forest resources in Priamurye in the Russian far east. Eurasian J. For. Res. **8**(1): 53–64.