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SIBERIAN ENVIRONMENTAL CHANGE

Wildfires in the Siberian taiga

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Abstract The majority of area burned by wildfire are located in Siberia. Mainly low-intensity surface fires occur in larch forests, whereas in evergreen forests both surface and crown fires are observed. Warming has led to an increase in the frequency and area of wildfires that have reached the Arctic Ocean shore. However, wildfires are the most important factor in taiga dynamics; larch and Scots pine have evolved under conditions of periodic forest fires, thereby gaining a competitive advantage over non-fire adapted species; in the permafrost zone, periodic fires are a prerequisite for the dominance of larch. Wildfires support ecosystem health, biodiversity, and conservation; periodic wildfires decrease the danger of catastrophic wildfires. With an amplified rate of increase in fires, it is necessary to focus fire suppression on areas of high social, natural, and economic value, while allowing a greater number of wildfires to burn in the vast Siberian forest landscapes.

Keywords Forest fires · Siberian wildfire · Wildfire dynamics · Wildfire impacts in Siberia · Wildfire in permafrost zone

INTRODUCTION

Siberia in a broad sense spreads from the Ural Mountains to the Pacific Ocean. Here we focused on the Siberian territory without the Russian Far East that has noticeable differences due to the prevalence of the monsoon climate. The study territory coincided with official socio-economic boundaries of Siberia (Fig. 1). It encompasses ~ 9.7 × 10^6 km^2, which is similar in area to Canada. The forested territory of Siberia is estimated at 600 × 10^6 ha. Russian forests as a whole contain > 20% of the world's forested area, with the majority (~ 70%, including sparse stands) located in Siberia. The major Siberian forest types are formed by larch (*Larix sibirica, L. gmelinii,* and *L. cajanderi*), Scots pine (*Pinus sylvestris*), "dark-needled conifers" (DNC: Siberian pine, *Pinus sibirica*; fir, *Abies sibirica*; spruce, *Picea obovata*), birch (*Betula* spp.) and aspen (*Populus tremula*) species (Fig. 1). Larch-dominant communities make up the largest area of Siberian forests (~ 3 000 000 km^2, including sparse stands). Because of this, larch, as well as birch, may deserve to be considered the National Trees of Russia. The DNC, or "black taiga", encompasses ~ 760 000 km^2 of Siberian forest. Scots pine stands, which provide the best source of wood for both the domestic and export market, occupy ~ 860 000 km^2. Broadleaf birch and aspen cover ~ 670 000 km^2 and ~ 120 000 km^2, respectively (based on http://pro-vega.ru/maps/).

Periodic wildfires are a permanent, natural process of Siberian forests. More than 70% of fires, and up to 90% of the total area burned, in Russia occurred in Siberia (Shvidenko and Schepaschenko 2013; Kharuk and Ponomarev 2017). In recent decades, elevated air temperatures in Siberia have led to an increase in wildfire frequency, burned area, and carbon emissions, while fire return interval has decreased (Kharuk et al. 2005a, 2008, 2013a; Bartalev et al. 2015; Kukavskaya et al. 2016; Ponomarev and Kharuk 2016; Ponomarev et al. 2018a; Bondur et al. 2020). Alongside elevated air temperature, climate change in Siberia has led to an increased frequency of acute droughts and heat waves. For example, in June 2020 a new record temperature (38 °C) north of the Arctic Circle was recorded in Verkhoyansk, Yakutia, during a prolonged heat wave that stimulated wildfires in the area. However, it is

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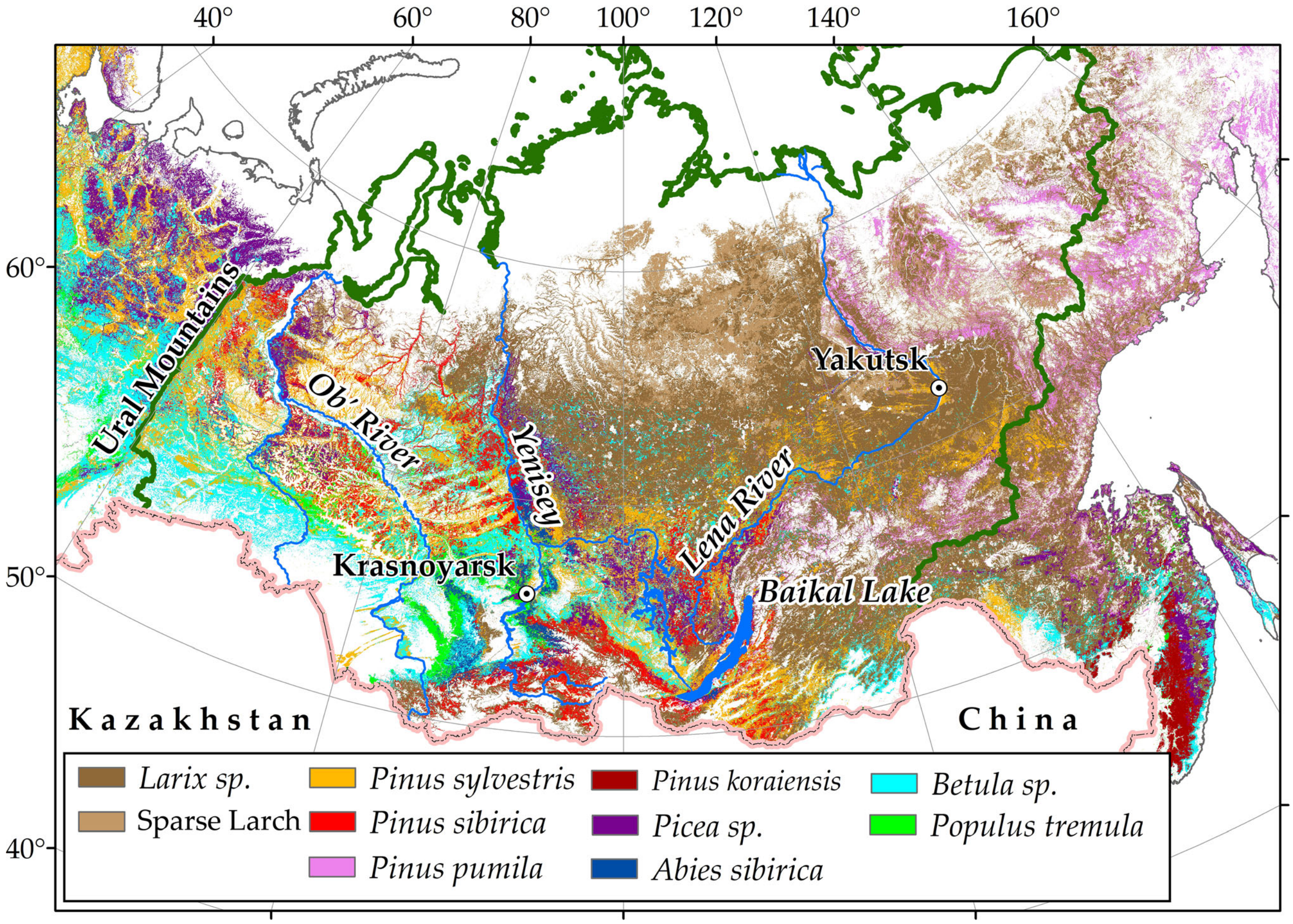

Fig. 1 Main Siberian forest types (based on http://pro-vega.ru/maps/). Forest types included "sparse" (crown closure ≤ 20%) and "closed" (cc > 80%; Bartalev et al. 2015). The boundary of the Siberian territory considered in this review marked in green

important to note that wildfires themselves are an important ecological process. For example, wildfires are essential for supporting the dominance of pyrophytic species (i.e., larch and Scots pine) within their range. Furthermore, wildfires are an important natural factor for supporting biodiversity within the vast Siberian taiga.

In recent decades, DNC mortality has increased because of periodic acute droughts and accompanied insect attacks, which have led to increased fuel accumulation. For example, a recent Siberian moth (*Dendrolimus sibiricus*) outbreak damaged over one million DNC trees in Western Siberia (Kharuk et al. 2020). A warming-driven bark-beetle (*Polygraphus proximus*) outbreak in 2003–2018, in combination with acute droughts, led to a loss of ~ 5% of fir-dominant stands mostly in southern Siberia (Kharuk et al. 2018a, 2019). Fire activity within dead stands has increased by approximately one order of magnitude (Kharuk and Antamoshkina 2017). With warming the ranges of insect outbreaks have spread to higher elevations and latitudes. For instance, since the mid-twentieth century the observed upper-elevation range of the Siberian moth has shifted upwards by ~ 350 m, while the potential northern outbreak boundary has moved ~ 300 km northward (Kharuk et al. 2020).

In the future, regional climate models project an increase in the fire danger period and fire occurrence in Siberia (Flannigan et al. 2009; de Groot et al. 2013b; Shvidenko and Schepaschenko 2013); thus, the Siberian taiga is expected to become more prone to forest fires (Malevsky-Malevich et al. 2008; Mokhov and Chernokulsky 2010). This will result in an increase in both fire rate and carbon emissions, and may potentially convert Siberian taiga into a source, rather than a sink, of greenhouse gases in years with extreme wildfires. However, positive gross primary productivity (GPP) trends across considerable parts of Siberia's forests, as well as growth increment increases in the main tree species, suggest an increase in carbon sequestration (Kharuk et al. 2015a, 2018b; Kharuk and Ponomarev 2020). Climate warming in Siberia has also promoted an increase in forested area due to shrub and tree species expansion along elevation and latitudinal gradients (Kharuk et al. 2005b, 2006, 2007a, 2013a, 2018a).

Furthermore, increases in stand density have raised the potential fuel availability for forest fires (Kharuk et al. 2010a, b, 2013b, 2018a; Im et al. 2020). There has also been an increase in Siberian pine and fir mortality at low elevations within the southern ranges of these species resulting in a subsequent increase in fire danger (Kharuk et al. 2018a).

Wildfires have caused economic losses and have impacted human health both within and outside of the boreal biome. Smoke plumes, which almost annually cover Siberian cities, can reach as far as European Russia and the Arctic during years with catastrophic fires resulting in harmful impacts on human health. Similarly, smoke from wildfires in western North America (e.g., British Columbia, Alaska, and California) have wafted across large swaths of land to impact air quality in far-away urban centers, such as Vancouver, Edmonton, Toronto, Montreal, and New York City (Flannigan 2019; https://www.cbc.ca/1.5135539). Thus, the impacts of wildfires can spread far beyond where they occur and are an international issue.

Climate change is also anticipated to present significant challenges to future fire suppression in Siberia, North America, and other regions around the globe (Podur and Wotton 2010; de Groot et al. 2013b). In light of both predicted and observed increases in fire frequency and area burned, it is likely that fire management agencies will be unable to suppress all wildfires in the future. Thus, it is inevitable that necessary and adequate modifications to wildfire suppression strategies are developed to face the challenges of more active current and future fire regimes.

In this paper, we review the available literature and data related to wildfires in Siberia. Specifically, we discuss characteristics of Siberian fire regimes and forest types, wildfire dynamics, wildfire impacts, and wildfire suppression. Finally, we offer our conclusions and recommendations for wildfire management. In addition, throughout the paper we compare aspects of Siberian fire regimes with those in the North American boreal forest (i.e., Canada and Alaska). This paper contributes to a range of studies dedicated to Siberian Environmental Change (Callaghan et al. 2021).

WILDFIRES IN SIBERIA

Wildfire numbers and areas

From 1999 to 2019, the total number of fires in Siberia (in forest, forest-steppe, and agricultural areas) was ~ 325 000 resulting in ~ 200×10^6 ha of area burned. The majority of fires (65%) occurred in the steppes, forest-steppe zones, and agricultural land—as is typical, these fires were recorded in the springtime in the southern regions of Siberia. Forest fire occurrence and area burned were 35% and 60% of the total, respectively. Approximately 50% of the total burned area was caused by extremely large fires (> 2000 ha), although they accounted for only 3% of fire occurrences. Large-scale forest fires (area > 200 ha) made up ~ 30% of total occurrences and ~ 90% of total burned area. Similar proportions for high-intensity fires (i.e., outside two SD of the mean) in the total forest fires statistics were 8% (by number) and about 10% (by area) (Ponomarev et al. 2018b). A study by de Groot et al. (2013a) reported that fire size distributions and area burned were similar between Siberian and Canadian study areas, although large fire frequency was higher and average large fire size was smaller in Canada.

Wildfire types

A quick glance of the map of fire-caused disturbances (Figs. 2, S1) might give the impression that half of the Siberian taiga has burned during the past decade. However, it is necessary to distinguish between forest stands that have been affected by fire versus stands that were killed by fire, because the consequences of a fire depend on its type and intensity, and on the forest type.

There are three types of fires: surface, crown, and peat fires. The majority of forest fires in Siberia (> 90%) are surface fires which spread along the forest floor, burning vegetation litter and lower tiers of vegetation. Surface fires are further divided into runaway and sustained fires based on their speed and combustion characteristics. Runaway fires are common in early spring when only the upper layers of litter and dead grass reach fire maturity (i.e., low moisture contents conducive to burning). Usually trees are not damaged by such fires, although the majority of seedlings and saplings are usually damaged or killed (Fig. S2a). However, in the case of young coniferous stands, surface fires can turn into crown fires. Sustained surface fires, which primarily occur in the summer and autumn, can cause ground cover and undergrowth mortality. Sustained surface fires can also damage the roots and trunks of trees with consequent mortality of some proportion of the forest stands. Within the permafrost zone, sustained surface fires are the main cause of forest stand mortality due to the shallow root habitat zone. Within peatland soils, surface fires can turn into peat fires. In the permafrost zone, where larch dominates, low-intensity surface fires prevail. Crown fires are the most intense type of fire which spreads from the surface to burn along the entire length of trees, including the top, and take over the entire forest canopy. The transition of a surface fire into a crown fire is promoted by woody debris and dense coniferous regeneration and undergrowth. For instance, the dense, long branches of some species (e.g., fir, spruce) often spread down to the

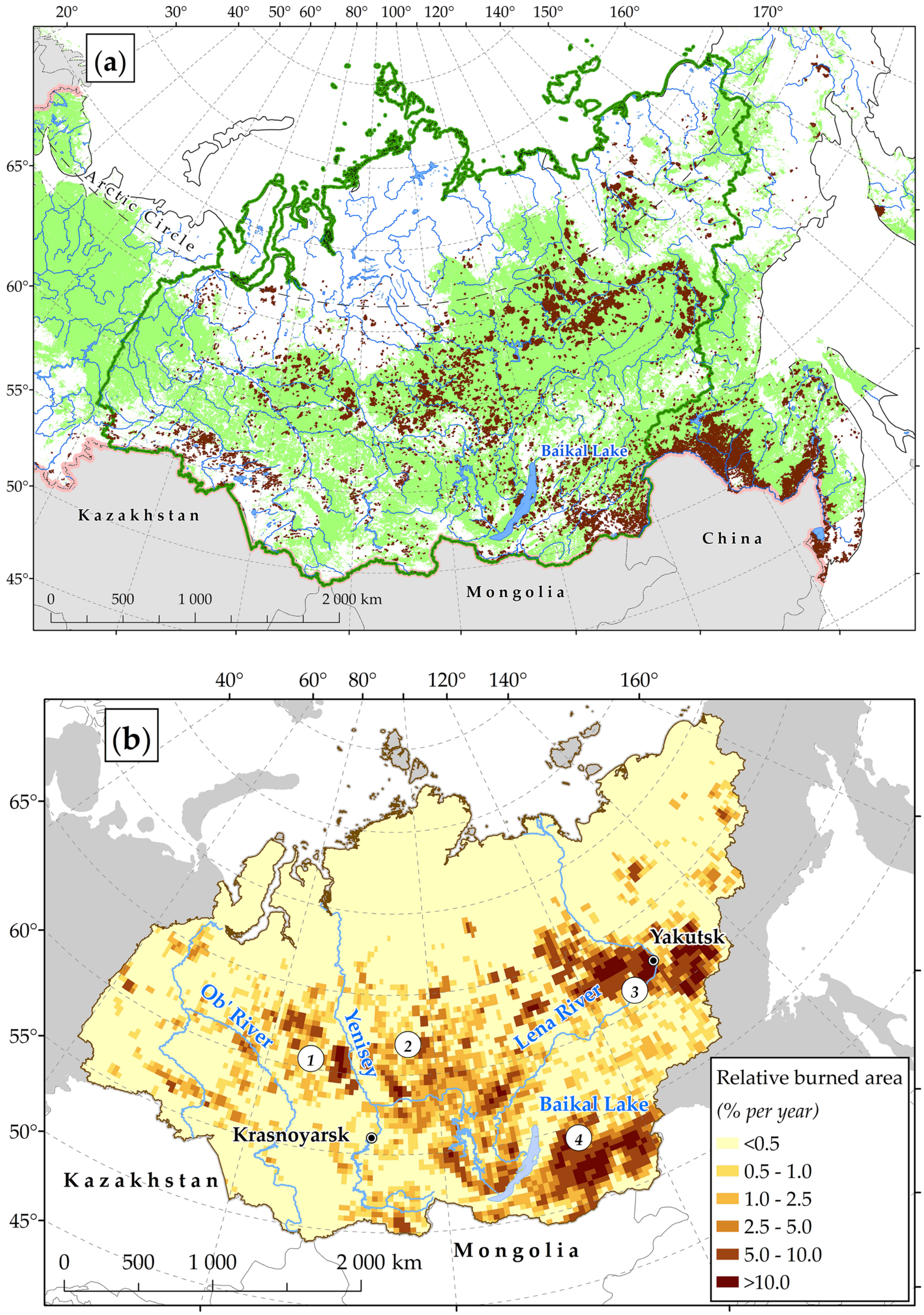

Fig. 2 A map of fire occurrences from 2012 to 2019 (**a**). Closed-forest areas are shaded light green. The boundary of Siberia (without the Russian Far East) is delineated by the green line (Kharuk and Ponomarev 2020). **b** Patterns of annual burning rate in Siberia (1996–2016). The highest burning rate was observed in the Trans Baikal regions (4), followed by Central Yakutia (3), South Evenkia (2), and West Siberian plane (1). Burned areas were averaged by 30 × 20′ clusters (about 100 000 ha per cluster) (modified from Ponomarev et al. 2018c)

ground (i.e., "ladder fuels") and promote the transition of surface to crown fires. Crown fires spread very quickly, advancing by leaps with a speed of up to 100 m/min and more. High-intensity crown fires occur in closed-forest stands mostly in the middle and southern taiga (Figs. S2S, S3). In the case of crown fires, forest mortality is inevitable; this occurs in 8–10% of the total fire-affected area (Ponomarev et al. 2018a, b). However, low-intensity surface fires, which primarily burn surface litter and the forest floor, do not result in significant stand mortality, especially in pine and larch forests that are resistant to forest fires. In fact, up to half of the forests exposed to all fire types do not die (Krylov et al. 2014).

Wildfire causes

There is a "triad" of reasons for forest fire susceptibility: the available combustible materials (fuels), their maturity (fuel moisture content), and ignition source (lightning- or human-caused). Siberian taiga forests are rich in accumulated fuel. Although, in the case of larch forests on permafrost the main source of fuel is not the trees themselves but the moss and lichen fuel matrix (with an estimated fuel load of up to 8 kg m^{-2}; Sapozhnikov and Krechetov 1982). Fuel readiness for ignition depends on humidity and precipitation, air temperature, period of drying, forest type, and topographic gradients (e.g., elevation, slope steepness and aspect). For example, factors such as fuel load, lightning frequency, and precipitation depend on elevation. Aspect also affects fuel conditions, where fuel tends to dry faster on south-facing and steeper slopes. Moreover, the speed of wildfires tends to strongly increase as slope increases (Kharuk et al. 2007b).

Humans cause $>80\%$ of fires in southern Siberia, where most of the population lives. Likewise, while $\sim 50\%$ of fires across Canada are due to humans, most human-caused fires occur in southern Canada where the population density is higher and where there is more infrastructure (Johnston and Flannigan 2018; Hanes et al. 2019; Coogan et al. 2020). In Alaska, most human-caused fire ignitions also occur in populated areas that have the highest suppression priority (Chapin III et al. 2008). Similar to Canada and Alaska, there are strong observed correlations between fire activity in Siberia and proximity to roads and human settlements (Kovacs et al. 2004). The farther north, the lower the population density, which in northern Siberia is < 0.03 people/km^2. Consequently, there is a lower likelihood of human-caused fires at higher latitudes. Importantly, local people, especially Indigenous People and *old believers* (a religious sect which denied the Russian church reform in the seventeenth century), follow the "taiga laws" and protect forests from fires.

In high-latitude areas of Siberia, the main cause of fires (up to 90%) is lightning (Ivanov and Ivanova 2010). Likewise, lightning is responsible for the majority of fires in Alaska (Kasischke et al. 2010) and northern Canada (Coogan et al. 2020). Lightning-caused fires in Siberia occur especially often during rainless "dry thunderstorms" that are typical during anticyclonic periods. Within the permafrost zone lightning causes twice the amount of fires than in non-permafrost areas because lightning energy is released within the shallow boundary between the active layer and permafrost strata due to the sharp change of dielectric constant (Sapozhnikov and Krechetov 1982). Moreover, lightning events may cause fires at several sites due to multiple ignitions. Climate warming was predicted to lead to an increase in the frequency of lightning strikes by about 12% per 1 °C of warming (Romps et al. 2014), which will likely lead to an increase in fire frequency. Already in North American boreal forests lightning-caused fires have risen by 2% to 5% per year since 1975 (Veraverbeke et al. 2017). Thus, should a similar relationship also apply to Siberia, it is likely that there will be an increase in lightning and lightning-caused fires over the current century.

Wildfires vs latitudinal gradient

In addition to lower human population densities at northern latitudes, the decrease in wildfire activity from southern to northern Siberia can be related to differences in incoming solar radiation. When moving to higher latitudes the insolation, and, consequently, fire danger period decreases (Fig. 3a, b). Fuels in northern areas generally receive less heat over a shorter fire season; therefore, there is a lower probability of fuels being susceptible to ignition sources, such as lightning strikes or sparks from a campfire, than in southern areas. In addition, lightning frequency decreases in a northward direction, which further reduces the chance of ignition. As such, the number of fires in Siberia decreases in a northward direction, and, accordingly, the fire return interval increases, reaching up to 300 years at the northern boundary of larch stands (Fig. 3a, b; Kharuk et al. 2013a, 2015b).

Despite that, the *number* of fires in Siberia decreases with higher latitudes, the *mean* burned area increases up to the Arctic Circle (Fig. 3c). This can be attributed to the decrease in anthropogenic forest fragmentation and increased fuel loads (mainly in the form of the moss and lichen matrix, the main fuel source for surface fires

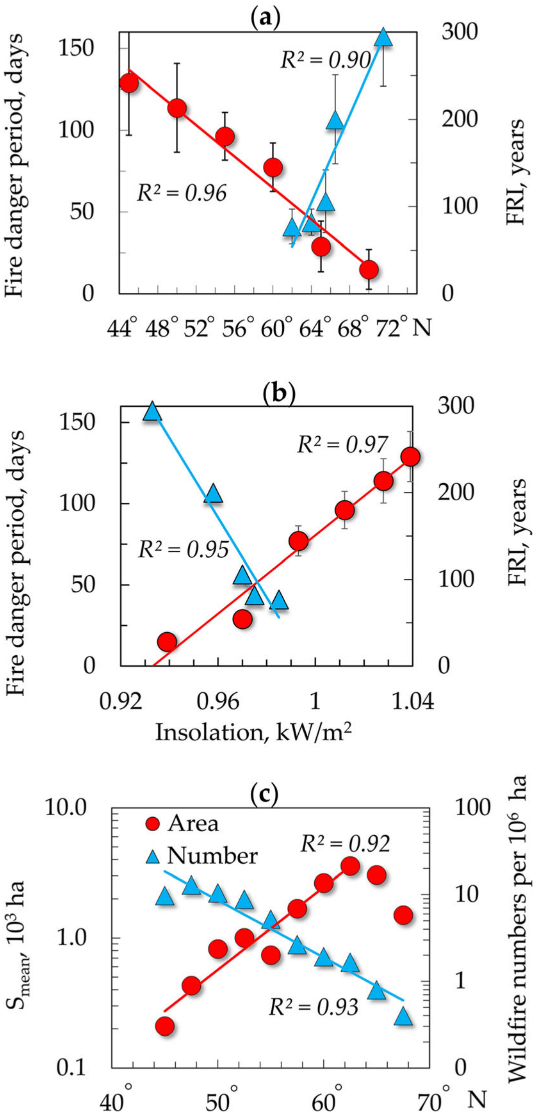

Fig. 3 (**a**) Fire danger period (red symbols) decreases in Siberia as latitude increases, whereas the fire return intervals (FRI; blue symbols) increase with latitude. (**b**) The fire danger period increases with solar insolation, while the FRI decreases (modified from Kharuk and Ponomarev 2017). **c** The number of fires in Siberia decreases with latitude. However, the mean fire area (S_{meanarea}) increases with latitude up to the Arctic Circle (modified from Kharuk and Ponomarev 2020)

dominant at higher latitudes). In addition, at higher latitudes wildfires are only monitored and usually not suppressed with the exception of those that may threaten people.

Large-scale and catastrophic fires (> 50 000 ha) mostly occur in high-latitude permafrost zones (i.e., ≥ 58°N; Fig. 3c). This area is limited to satellite monitoring only and these fires are not suppressed (Fig. S4). Major fires at high latitudes, as a general rule, occur in mid-summer and can continue until the beginning of autumn when incoming cyclones bring precipitation.

WILDFIRE INFLUENCE ON THE MAJOR SIBERIAN FOREST TYPES

Wildfires are the most important and permanent driver of forest dynamics in Siberia, but their impacts vary between different forest types. Maximal burning rates are observed within larch-dominated and Scots pine stands, while the lowest rates occur in DNC stands (Table 1).

Wildfires in larch-dominated areas

Larch stands (both open and closed) cover ~ 45% of the forested territory of Russia. Being an extremely cold-tolerant species, larch occupy ~ 80% of the forests within the permafrost zone. This forest type is the largest within the boreal biome. The majority of Siberian wildfires (> 40% in number and > 65% in area) occur within these forests (Table 1). The majority of larch habitat is located within a zone of frequent droughts and low precipitation (often < 300 mm/year). During summer anticyclones, no precipitation may be observed for decades which facilitates a high fire hazard. Due to the harsh environment and shallow root system, larch forests on permafrost have mostly low canopy closure and sparse trees (Figs. 4a, S5, S6). Therefore, surface fires prevail (> 90%). Early-summer surface ("runaway") fires, when fuel materials have dried to depths < 10 cm, typically do not cause stand mortality (Sofronov et al. 1999). However, sustained surface fires kill trees by thermal damage to the roots that are located within a shallow seasonal thaw layer (the active layer). Such fires result in an (semi) even-age stand mosaic.

Foresters call larch a pyrophytic or "fire-loving" species, because fires contribute to the dominance of larch, especially in the permafrost zone. The most important consequence of fires are the improved environmental conditions for larch regeneration on burned areas. Larch is an extremely shade-intolerant photophilic species that grows and regenerates poorly under a closed canopy. Within mid- and southern-Siberian mixed forests, the preservation of larch is due in part to its longevity: larches can reach an age of ~ 600 years, and up to a maximum of ~ 1000 years in the northern taiga. Other conifers have shorter lifespans: spruce 300–350 years; fir 200–250 years; and Scot pine and Siberian pine 400–500 years.

The survival strategy of *Larix gmelinii* and *L. sibirica* are different. In southern larch communities dominated by *L. sibirica*, ground fires are generally less intense (in comparison with northern areas) due to less moss and lichen fuel availability and a deeper (up to ~ 2.0 m or more) active root zone. Thus, ground fires regularly do not have a strong impact on the *L. sibirica* root system (with the exception of when they grow on shallow, rocky soils). Additionally, the cambium of *L. sibirica* is protected by

Table 1 Percentage of total fire occurrences, burned area, and relative burned area (RBA) by Siberian forest types from 1996 to 2019

Forest type	Fire number, % of total	Burned area, % of total	RBA* (%)
"Dark-needle coniferous" (*Pinus sibirica, Abies sibirica, Picea obovata*)	7.97	5.68	0.30
Larch (*Larix sibirica, L. gmelinii, L, cajanderi*)	41.12	65.15	1.13
Scots pine (*Pinus sylvestris*)	26.17	17.95	0.78
Deciduous (*Populus tremula* and *Betula spp.*)	22.26	10.15	0.50
Other types/Tundra	2.48	1.07	0.01

*RBA $= \frac{S_{\mathrm{burned}}}{S_{\mathrm{forest}}} \times 100\%/t$, where S_{burned}, S_{forest} are the burned and total areas of a given forest type, respectively and t is years (modified from Ponomarev et al. 2016)

thick bark (up to 20% of the trunk weight). In comparison, the bark of *L. gmelinii* is thinner and protects trees from low-intensity surface fires only (Fig. S7). *L. gmelinii* occurs mostly in the permafrost zone, where the main damage to the species is caused by overheating of the root system which is compressed within the shallow, seasonally thawed layer.

Fires contribute to the renewal of larch ecosystems. Trees that survive fires act as sources of seeds, although regeneration abundances are dependent on the fire severity (Cai and Yang 2016). Regular burns result in a mosaic of non-uniform forest structure due to relief features and refugia which allow trees to survive even severe stand-replacing fires. Even when stands are killed by fire, already ripe larch seeds in the dead mother canopy supply the burned area with seeds because the cones containing them regularly open in winter. Wind and meltwater spread the light, winged larch seeds into burned areas. The moss-free burn surface provides conditions for the abundant and rapid regeneration of up to 500 000 or more seedlings and saplings per ha (Fig. 5). Regeneration is facilitated by the enrichment of the soil with phosphorus, potassium, nitrogen, and other nutrients, as well as improved soil drainage and aeration, and an increase in the depth of seasonal thawing. The light regime dramatically improves by burning the upper canopy and ground cover, which is important for photophilic larch. In permafrost areas, burn out of ground cover leads to warmer surface temperatures for ~ 15 years with increased productivity (Kharuk et al. 2011; Kharuk and Ponomarev 2020; Ponomarev et al. 2020).

After a fire, larch growth on permafrost is strongly influenced by a decrease in the root habitat zone due to the growth of a moss "pillow" which serves as an excellent heat insulator (Figs. 6, S8). Therefore, the depth of the active layer decreases over time, and the root habitat zone gradually shrinks (up to 30 cm and less). The growth of the moss layer also leads to strong decreases in the number of seedlings because the moss traps the lightweight larch seeds and prevents them from reaching the soil surface. In addition, litter accumulates in the permafrost because decomposition rates are reduced by low summer temperatures.

As the active layer thickness decreases the availability of nutrients decreases, and so does the growth rate of the trees; larch trees "fall into a drowse", awaiting the next fire (Figs. S8, S9) which may be facilitated by the accumulation of fuel (e.g., mosses, lichens, and litter). Thus, wildfires reset the larch ecosystem, and larch forests on permafrost are a mosaic of (semi) even-age stands at different phases of post-fire succession.

Wildfires within Scots pine-dominated stands

Scots pine-dominated stands are second in area to larch forests in Siberia, covering ~ 860 000 km^2. Like larch, Scots pine is also a pyrophytic species and successfully regenerates regularly on burns (Fig. S10). In the absence of fires, competition by pine restricts other species, such as spruce, to poor soil habitats and boggy areas. Like larch, pine is photophilous and regenerates poorly when shaded by the forest canopy (Fig. 4b). Both of these species have evolved under conditions of periodic fires, adapting and deriving competitive advantages over other non-fire adapted species.

The majority of wildfires within pine stands are observed in the middle and southern taiga, which are the main pine habitat and pine harvesting zones. There are also many clearcuts with residual slash biomass that promote wildfires in this region (Kukavskaya et al. 2013). The majority of fires within the middle and northern taiga pine stands (~ 90%) are surface fires due to the usually low closure of the pine stands (Figs. 4b, S2a). Crown fires occur mainly within uneven age stands with well-developed understory and regeneration. There has been an increase in the severity and intensity of fires in Scots pine stands likely due to a warming climate (Ivanova et al. 2010).

Already in the first year after fires, regardless of their intensity, massive regeneration of Scots pine occurs in burned pine stands, particularly after crown fires (> 100

000 saplings/ha). Later in some areas, seedling frequency can decrease considerably (up to 90%) due to high surface temperatures within burns, moisture deficit, and consumption by wildlife (Tsvetkov 2005). Post-fire regeneration in southern and mid-taiga pine forests occurs regularly without species replacement. The fire return interval within pine stands ranges from 20 to 40 years, increasing in a northward direction (Swetnam and Baisan 1996).

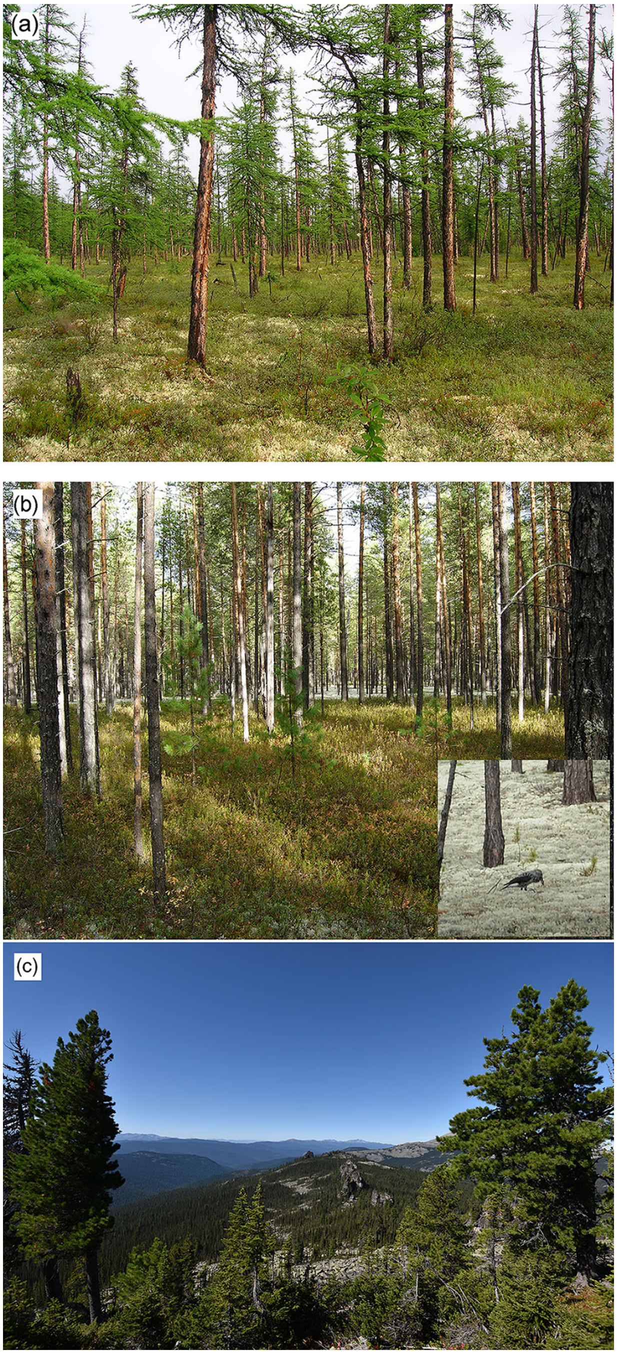

Fig. 4 **a** Larch (*Larix gmelinii*) stands within permafrost are sparse due to competition for moisture and mineral nutrition in the shallow root habitat zone. **b** A northern Siberian (~ 62°N) Scots pine stand. Note that Siberian pine are the only pine species regenerating because of dense ground cover. Siberian pine (a zoochoric species) regenerate due to the spotted nutcracker's (*Nucifraga caryocatactes*) "sowing" activity (inset). Surface fires are expected to eliminate the regeneration of Siberian pine in these stands. **c** Mixed Siberian pine and fir (*Abies sibirica*) "black taiga" stands in the West Sayan Mountains (~ 53°N)

Wildfires in "dark-needle conifer" (DNC) forests

DNC stands are less likely to burn because they grow in areas of relatively higher water supply. Siberian pine and fir (*Abies sibirica*) are called "trees of the fog" due to their moisture dependence (Fig. 4c). However, in dry years devastating crown fires do occur (Fig. S3). In drought years, the area of fires in DNC forests can reach millions of hectares, for example, on the West Siberian plain in 2012 when 1.4×10^6 ha burned. Unlike pine and larch, the DNC species are poorly protected by bark against surface fires. Furthermore, dense DNC crowns are saturated with terpenoids and often have branches that descend to the ground, thereby contributing to the transformation of surface fires into devastating crown fires.

Regeneration of burned areas in DNC forests usually involve species changes, with aspen and birch being the primary establishing trees; then, under their canopy, DNC species establish. Fir and spruce are able to tolerate dense shading, gradually making their way to the upper canopy. In contrast, birch and especially aspen are photophilous species that do not survive under a dense canopy of DNC. In addition, birch and aspen are short-lived species. For example, by the age of 80 aspen trunks are often affected by core rot. Thus, after 80–100 years the original DNC species usually return. However, grass and shrub communities, and hardwood species, can permanently capture part of the territory because the extensive and fast growth of grasses and shrubs facilitates surface fires that kill conifer seedlings. At the same time, birch and aspen resume their growth due to their ability to reproduce by root sprouts and a high seeds production rate. In such habitats, human assistance in restoring DNC forests is especially needed. However, the complete suppression of fires leads to the formation of overgrowth and weakened stands, which turn into a "breeding ground" for bark beetles and other phytopathogens that eventually kill the stands. Fuel accumulation within insect-affected stands eventually leads to wildfires with an area and frequency about one order of magnitude higher than those occurring in healthy stands (Kharuk and Antamoshkina 2017). It is expected that more

Fig. 5 Fires stimulate larch regeneration. The number of regenerating trees on a burn may exceed 500 000/ha. Photo was taken in the Lower Tunguska River watershed (65°40′N in 2016)

frequent and severe fires will promote substitution of the DNC within their southern range by broadleaf (birch and aspen) and drought-resistant larch and Scots pine species (Kharuk et al. 2018a). Similar substitution of "iconic" conifers for broadleaf species are expected in the southern Alaskan forests (Mekonnen et al. 2019).

Wildfire and Siberian versus North American forest types

While relatively few tree genera are found in the circumpolar boreal forest—including coniferous (*Abies*, fir; *Larix*, larch; *Picea*, spruce; *Pinus*, pine) and deciduous (*Betula*, birch; *Populus*, aspen) taxa—tree species within these common genera differ between continents (de Groot et al. 2013a; Rogers et al. 2015). These differences in boreal forest species composition between Siberia and North America are thought to be responsible for the distinct continental differences in fire regimes (Flannigan 2015; Rogers et al. 2015): the majority of wildfires in North American boreal forests are high-intensity crown fires, whereas most fires in Eurasia are documented as low-intensity surface fires (Wooster and Zhang 2004; de Groot et al. 2013a; Kharuk and Ponomarev 2017).

WILDFIRE DYNAMICS

Seasonality of wildfires

Wildfires begin in early March in southern Siberia (45–55°N; Fig. S11). The majority of spring (April–May) fires are recorded in 50–55°N latitudes. Farther north, the onset of the fire hazard season shifts to the early and middle of summer (at > 60°N), also a few fires occurred in spring. In the middle and southern taiga, seasonal fire patterns show a typical bi-modal shape with the main peak in the spring to early-summer period (Fig. S11). Typically during that period, low precipitation and increasing air temperatures make forest ground cover and grasses highly

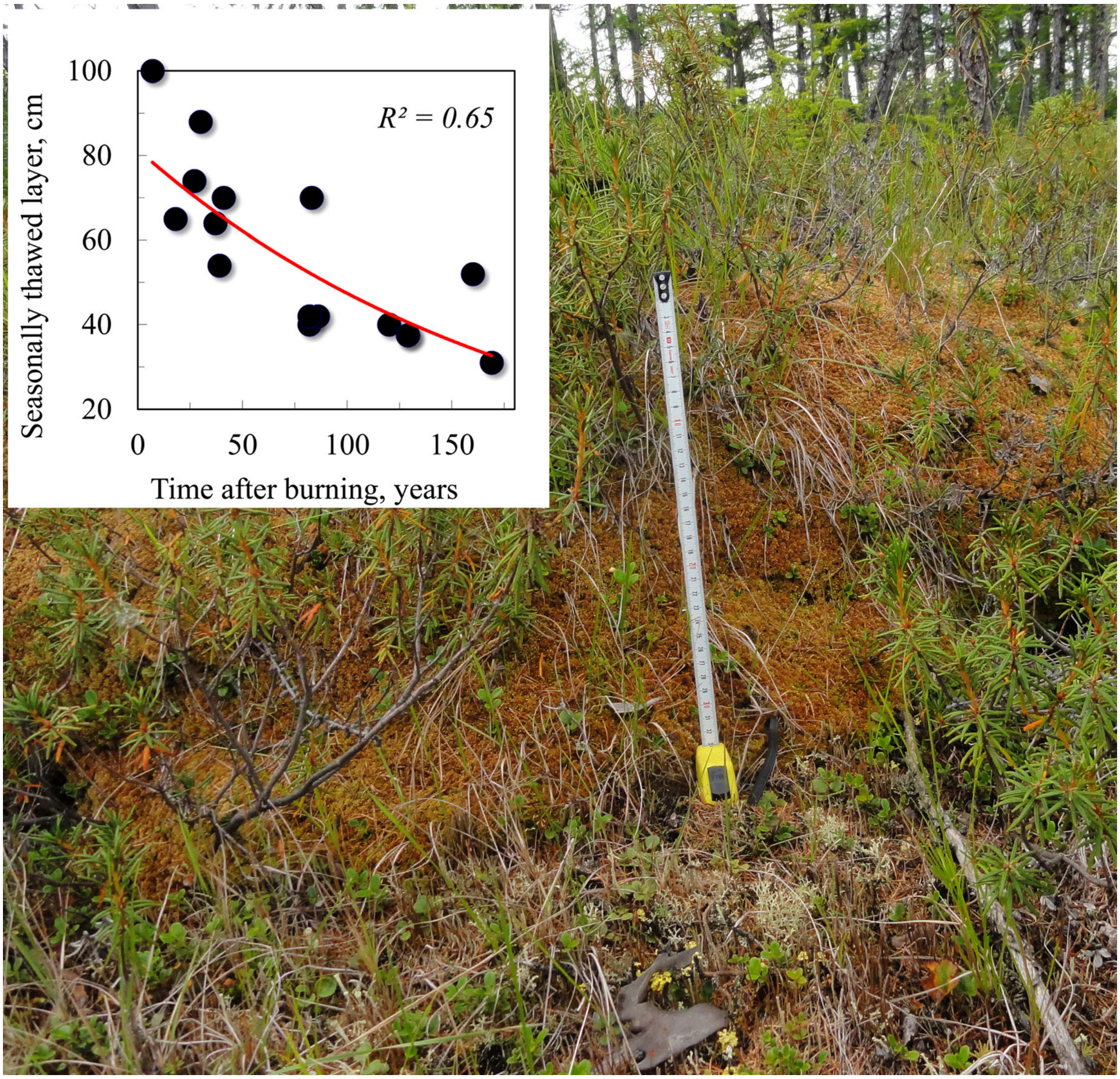

Fig. 6 High moss layer depths act as a thermal insulator, which leads to a decrease in the seasonally thawing soil layer. Inset: decreases in the depth of the seasonally thawed layer after burning. Modified from Kharuk et al. (2008)

susceptible to fire ignition, and the majority of fires occur as surface fires. A minor peak in fire activity in southern Siberia is observed in the late summer-early fall warm period which is similar to the "Indian summers" in North America. At higher latitudes, low incoming heat is hardly sufficient to dry the fuel load, thereby shortening the fire danger period and decreasing the fire hazard. This leads to a unimodal seasonal fire pattern (Fig. S11). The seasonality of wildfires in Canadian and Alaskan boreal forests is similar, with the majority of lightning-caused fires occurring during the summer (June and July) and the majority of human-caused fires occurring in the spring and to a lesser extent the autumn (Kasischke et al. 2010; Coogan et al. 2020).

Long-term trends

The chronologies of former fires can be inferred from burn marks on the trunks of surviving and dead trees (Figs. S12, S13). Based on dendrochronological analysis of tree rings between burn marks, fire history can be traced back for centuries. Longer chronologies can be constructed by other methods (e.g., by sediment analysis in water bodies).

The modern age of wildfire monitoring and research in Siberia began in the 1970s with NOAA/AVHRR satellite data applications. Satellite monitoring provided daily objective information about the number and area of forest fires within the vast Siberian landscape. Importantly, this satellite-derived objective information is now used in the official wildfire statistics. Throughout this paper, we used NOAA/AVHRR and Terra/Aqua/MODIS scenes analyzed at the Sukachev Institute of Forests.

Since the end of the twentieth century, Siberia has seen an increase in the frequency and area of forest fires (Fig. 7a, b). In extreme fire years, which coincided with years of anomalously high air temperatures (2002, 2003, 2012, 2019), the area burned by fire reached 10–12 × 10^6 ha (Fig. 7b). Catastrophic fires have also been observed in earlier times, but with much lower frequency. During the last decade the area burned increased by approximately two-fold and reached > 6.0 × 10^6 ha versus the previous decade's 3.0 × 10^6 ha (Fig. 7b). For comparison, in Canadian boreal forests an average of 2.5 × 10^6 ha burn annually, exceeding 7.0 × 10^6 ha in extreme years (Wotton et al. 2017). Likewise, trends in area burned and number of large fires (> 200 ha) have significantly increased in Canada since 1959 (Hanes et al. 2019). Alaska has also experienced increased burning rates over the past decades with the area burned reaching > 2.5 Mlha in 2004 (Calef et al. 2015). In 2019, extreme fires were observed throughout the world including the Amazon and Australia where > 6 × 10^6 ha of bushland burned. Climate warming has brought more tundra wildfire to Siberia, Alaska, and even Greenland in recent years (Mack et al. 2011; French et al. 2015; Kharuk and Dvinskaya 2020; Moskovchenko et al. 2020). In the Siberian Arctic, wildfires are increasing in number and are migrating northward (Fig. 8). The number of fires in the Siberian Arctic and the northern boundary of fires in Western Siberia are correlated with temperature anomalies (Fig. 8a, b). Maxima on the northern boundary are synchronized with air temperature extremes. Wildfires in Eastern Siberia have already reached the Arctic Ocean shore (Figs. 8, S14).

The increasing forest fire frequency and area burned in Siberia are related with air temperature anomalies, increasing climate aridity (indicated by the Standardized Precipitation-Evapotranspiration Index; SPEI), and drought events (Fig. S15; Kharuk and Ponomarev 2017).

The high burning rates observed during 2002, 2003, 2012, and 2019 (Fig. 7) were influenced by extreme weather events. Similar observations are referred to in ancient records. For instance, chronicles of the eleventh to fourteenth centuries described "a great swelter and drought and awful fires. Smoke was so dense that people bump each other and smoke-blind wild animals entered cities". In more recent records, we found that the catastrophic wildfires observed in Siberia in 1914–1916, when forests burned on average ~ 2.5 × 10^6 ha, coincided with extreme spring droughts and summer precipitation that was 30% below the statistical norm. Currently, satellite observations indicate an increasing trend in the number and area of extreme forest and non-forest (steppe and agricultural) fires in the twenty-first century (Fig. S16). For instance, heat waves in June 2020 led to a record high air temperature (38 °C) in Verkhoyansk City—located beyond the Arctic Circle and known as the Asian "cold pole" with a

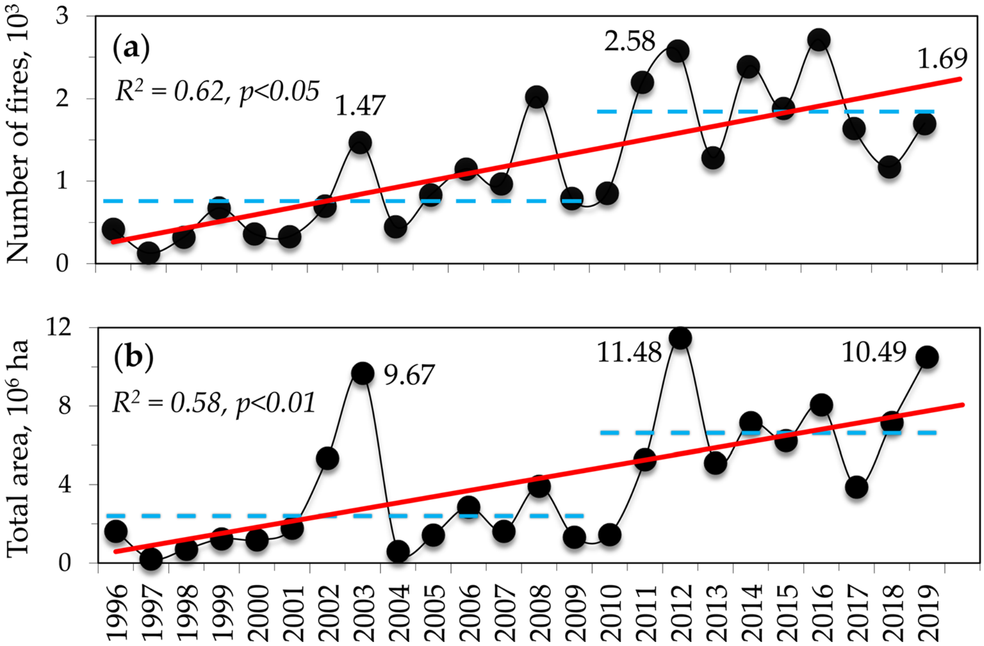

Fig. 7 The **a** number and **b** area of fires in Siberia show increasing trends from 1996–2019 based on NOAA/AVHRR and Terra /Aqua/ MODIS data analysis. The blue dashed lines show the average over the last decade versus background values. The number and area of extreme fire seasons in 2002, 2003, 2012, and 2019 coincided with extreme July air temperatures. Modified from Kharuk and Ponomarev (2020)

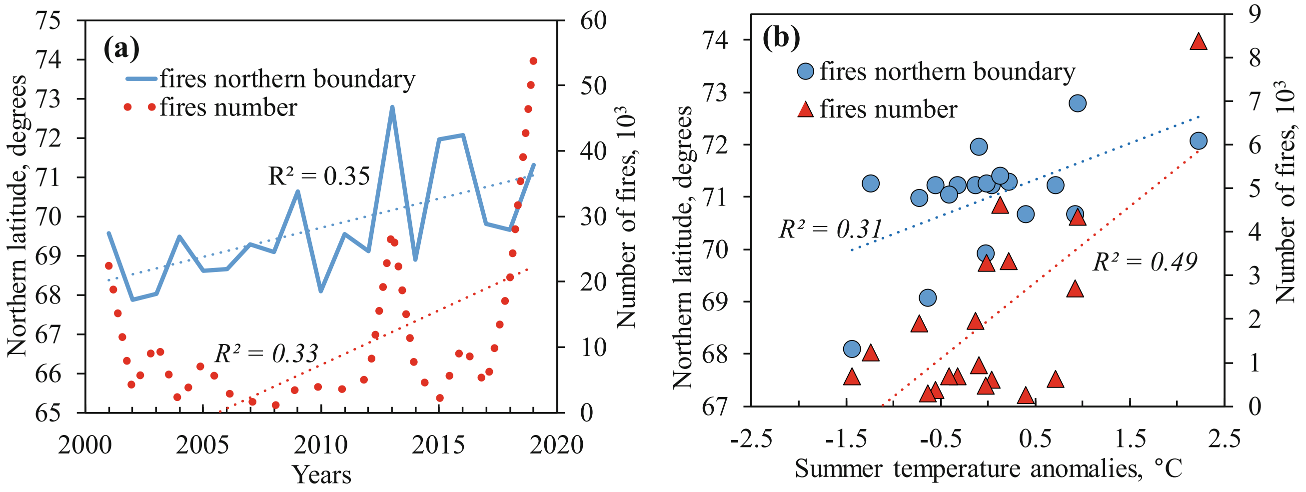

Fig. 8 The **a** number of fires and the northern fire boundary in Western Siberia are correlated and **b** with summer temperature anomalies. Modified from Kharuk and Dvinskaya (2020)

record low temperature of − 67.6 °C—with consequent fires within the area.

The mean annual rate of forest fire area burned is estimated at 1.3–2.6% for central Siberia and up to 5% for the forest-steppe zone (Fig. 2b; Ponomarev et al. 2016). This is lower than reported by Gauthier et al. (2015) who found that the mean annual fraction burned was similar between high-latitude areas in Canada and Siberia, ranging between 2 and 2.5% of the forested area.

Current trends in Siberian wildfire regimes are consistent with climate change projections, which predict an increase in fire severity, intensity, the spatial extent of fire danger, area burned, and stand-replacing fires, as well as lower fire return intervals (Flannigan et al. 2009; de Groot et al. 2013b; Kharuk et al. 2013a). The anticipated effects of climate change are similar for Canadian boreal forest fire regimes (Kitzberger et al. 2017; Coogan et al. 2019). Climate change is also predicted to increase fire activity in Alaska which will in turn have numerous effects on the region’s ecology and biota (Wolken et al. 2011; Yue et al. 2015).

WIDER CONSEQUENCES OF WILDFIRES

Wildfire impacts on human health and economics

Wildfire smoke regularly covers the main cities in Siberia (e.g., Novosibirsk, Krasnoyarsk, Yakutsk). In extreme years, smoke plumes have spread over thousands of kilometers to reach the European part of Russia, the Russian Far East, and the Arctic (Bondur et al. 2019). The aerosol concentration within these emissions may exceed 1000 times the background level, which can have negative impacts on human health (Kutsenogiy et al. 2003). While there is relatively little data regarding the impacts of wildfire smoke on public health in Siberia, the topic is beginning to gain attention globally, as longer and more active fire seasons, and smoke transport into cities, have brought the health-related issues of wildfire smoke into the public eye (Reisen et al. 2015).

Fortunately, forest fires in Siberia generally do not considerably impact people due to the low population density within the forested territory, and the efficient fire protection of human settlements. Most wildfire damage to humans and properties generally occurs in the steppe and forest-steppe regions in southern Siberia. For instance, the highest recorded damage was caused by steppe wildfires in the Khakassia Republic in April 2015, when multiple fires were ignited by routine seasonal dry grass burning. During that time, hot weather and strong wind (exceeding 30 m/s) promoted rapid fire spread over the forest-steppe part of the territory. These fires destroyed 1140 houses in 33 villages. Moreover, the fires and smoke affected ~ 1500 people, including causing serious health problems in 130 people as well as 27 fatalities[1].

Catastrophic forest and peat fires occurred in the European part of Russia in 2010. During this time, fires were ignited by extremely hot weather that was the highest on record for a period of 130 years. Fires and smoke spread over 17 Russian regions. The total number of fires recorded were 34 800 resulting in ~ 2×10^6 ha of burned area and > 60 fatalities[2].

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[1] https://tass.ru/sibir-news/2607517. Retrieved July 20, 2020.

[2] https://www.kommersant.ru/doc/1673040. Retrieved July 20, 2020.

The annual economic impact of wildfires, according to official Rosleskhoz (Russian Forest Service) information, is estimated to be within the US\$400 × 10^6 to \$10 × 10^9 range (see footnote 2; Rosleskhoz 2019).

Wildfire impacts on biodiversity and ecosystem services

Wildfires support the biodiversity of the Siberian taiga. The species that populate burns are often ones that were absent or poorly represented in the former phytocenosis. Pioneer tree species in former DNC stands are regularly birch and aspen, which are capable of regeneration by root sprouts. Anemophilous seeds of these species, light and abundant, spread over burns by wind and spring surface waters over distances of two and more km. In contrast, larch stands on permafrost and pine forests on sandy soils regularly regenerate without species changes. Nevertheless, birch and alder (*Duschekia fruticosa*) also regenerate as an admixture to larch. These less frost-resistant species can usually be found within relatively wind-protected areas (e.g., in river floodplains). On average, burn reforestation without species change occurs in one third of burns, mostly (65% of all forest areas) in forest stands formed by larch and pine (Krylov et al. 2014).

Along with tree species, fruit-bearing shrubs important to humans and wildlife, such as raspberry (*Rúbus idáeus*), cowberry *(Vaccínium vítis-idaéa),* blueberries *(Vaccínium myrtíllus, V. uliginósum*), honeysuckle (*Lonicera edulis)*, and currants (*Ríbes sp.)* populate burned areas. Herbs also regenerate on burned areas, such as fireweed (*Epilobium angustifolium*), which often grow in the same year post-fire.

Severe and frequent wildfires can negatively affect wildlife, often resulting in the loss of habitat; however, wildfire also provides benefits to wildlife. For example, bears (Ursidae) have been observed to migrate from areas during severe fire years, yet they also benefit from the early-seral vegetation and fruiting shrubs that repopulate burned areas. Wildfires are also beneficial to wildlife that forage on early-seral vegetation. Elk (*Cervus elaphus*) and moose (*Alces alces*), for example, feed on aspen and birch shoots, as well as on the grass communities in regenerating burned areas. Sables (*Martes zibellina*) are also attracted to regenerating burns due to increased populations of hares (Leporidae) and numerous mouse-like small mammals. Wildfire has differential effects on species, however, as some are more negatively impacted than others. On the Alaskan tundra, for instance, the winter range of caribou (*Rangifer tarandus granti*) is expected to decrease by ~ 30% by the mid-twenty-first century due to increasing wildfire activity, whereas the range of moose is expected to increase by up to 60% (Joly et al. 2012). In areas outside of the boreal zone (e.g., Amazonia and Australia), the increased occurrence of catastrophic fires has also strongly impacted biodiversity. During the 2019–2020 bushfire season in Australia, for example, fires burned in excess of 10 × 10^6 ha of area which resulted in the death of a billion animals (Cushman 2020).

Wildfire impacts on soil and water quality

Studies relating to wildfire impacts on soil and water quality are scarce in Siberia. For the recently burned watersheds in the Central Siberian Plateau, it was found that wildfires increased the concentrations of nitrate in water for a decade, while decreasing concentrations of dissolved organic carbon and nitrogen continued for five decades (Rodríguez-Cardona et al. 2020). Increased fire frequency in the region is likely to both decrease dissolved organic matter content and increase nitrate delivery to the Yenisei River, and ultimately the Arctic Ocean, in the coming decades. Meanwhile, there is no evidence of fire-caused water quality decreases in Siberian rivers, which can be explained by the vast amount of water resources.

Wildfire impacts on feedbacks to climate

Direct wildfire emissions affect air quality over vast territories. Indirect wildfire emissions, in contrast with direct ones, are observed years after the fire and are caused by the decomposition of post-fire dead wood. Indirect emissions are estimated to be as much as 50% of total emissions (Shvidenko and Schepaschenko 2013). The direct fire carbon emissions in Siberia range from 20 to 40 Tg C/year up to 250 Tg C/year in extreme years (Fig. S17; Ponomarev et al. 2018a). This is significantly lower than the previous extreme assessments for Siberian fires, from 116 Tg C/year in 1999 up to > 500 Tg C/year in 2002, obtained by Soja et al. (2004). The mean value of direct emissions in Siberia during the twenty-first century was 85 ± 20 Tg C/year on average (Ponomarev et al. 2018b). This value may more than double (up to 220 Tg C/year) by the end of the twenty-first century under a moderate RCP2.6 IPCC scenario. Interestingly, carbon emission rates were reported to be higher in the Canadian boreal forest than in Siberia in a comparative study, due to higher fuel loads and higher fuel consumption by crown fires; however, the Siberian study area had greater total carbon emissions due to greater annual burned area (de Groot et al. 2013a). Climate change is anticipated to increase the level of carbon emissions across the circumpolar boreal forest, with future emissions predicted to be higher in Siberia than Canada due to a greater total area burned (de Groot et al. 2013a).

The contributions of low-, moderate-, and high-intensity fires to the total Siberian carbon emission volumes are estimated as 33–37%, 47–49%, and 14–17% respectively. The corresponding specific values of these emissions are equal to 8.7, 12.0, and 15.4 t C/ha (Ponomarev et al. 2018a, b, 2019). Fire emissions predictions for mean and extreme fire years for the major Siberian forest types are given in Table 2.

Both direct and indirect wildfire emissions influence climate warming, and, subsequently, the burning rate in Siberia. A colloquialism regarding the boreal forests (but not tropical forests) is that they are the "Earth's lungs" and serve as a carbon sink. There is concern, however, that the increased burning rate in Siberia may transform the extensive larch-dominated area from a greenhouse gas sink to a source.

Alongside an increased burning rate, climate warming can lead to a lengthening of the growing season resulting in tree growth increment increases (Kharuk et al. 2018b). After the initial damage and greenhouse gas emissions from a fire, trees that survive significantly increase their growth index and burns typically regenerate quickly (Figs. 5, 9, S6, S10). Satellite-based observations show that the Enhanced Vegetation Index (EVI) which is related to vegetation vigor and productivity usually recover within about 15 years post-fire (Kharuk and Ponomarev 2020; Fig. S17). Warming also leads to positive trends in Gross Primary Productivity (GPP) within much of the larch habitat, and, despite increases in wildfires, the Siberian forests have remained a carbon sink from 2000 to 2019 (Kharuk and Ponomarev 2020; Fig. 18S).

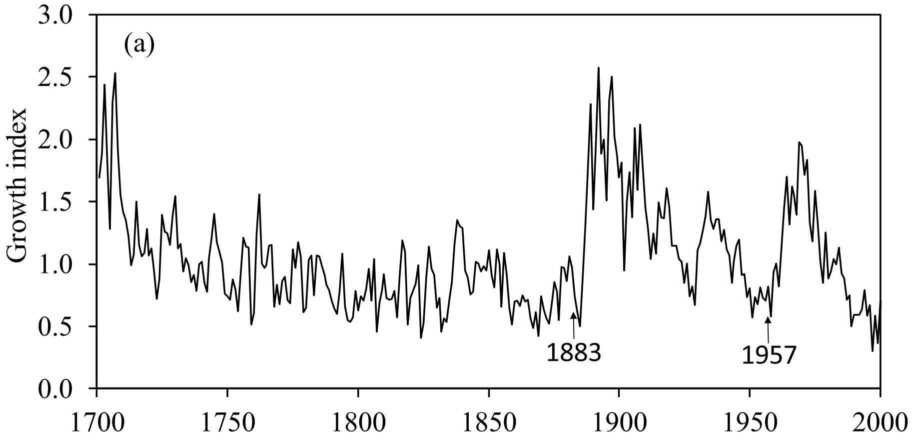
Wildfires also promote an invasion of more southern conifer (Siberian pine, pine, spruce, fir,) and hardwood species into larch-dominated areas (Kharuk et al. 2007a, b). Recent burns act as a starting place for invasions by southern species by providing improved thermal and soil conditions (Fig. 19S). Substitution of deciduous light-needle larch by evergreen dark-needle conifers will decrease albedo with consequent positive feedback to regional warming (Shuman et al. 2011). On the other hand, the increase in wildfire may slow down the southern species invasion into larch areas by eliminating the regeneration of Siberian pine, fir, and spruce (Kharuk et al. 2008). In addition, larch, Siberian pine, and fir, as well as birch and bushes, are migrating into the polar and alpine tundra, thereby increasing the forested area in these regions (Fig. 10; Kharuk et al. 2007a, 2010a, b, 2013b). It worthy note that increased seasonal thaw depth due to permafrost degradation (e.g., Vasiliev et al. 2020) might increase larch productivity 2–3 times by the end of twenty-first century (Sato et al. 2016). At present, the increasing water demands of trees experiencing warming are compensated in part by permafrost thaw (Euskirchen et al. 2017; Kharuk et al. 2018b). This suggests that warming may increase carbon storage within Siberian forests.

WILDFIRE SUPPRESSION

According to the pyrologist's truism, forests have been burning, are burning, and will be burning. The air temperature in Siberia, as well as in the boreal zone as a whole, has increased approximately twice as fast as the global average (Overland et al. 2017). Such warming is likely to lead to an increase in weather anomalies, as well as a lengthening of the fire season and an increase in the frequency, area, and intensity of fires. Fuel moisture, which is a critical factor in the ignition, spread, and intensity of wildfires, as well as the receptivity and availability of fuel, is also predicted to decrease with climate change—fuels are becoming drier with warming which is likely to intensify future wildfires (Wotton et al. 2017). In general, a more than two-fold increase in burning in the boreal zone is predicted for the coming decades (Flannigan 2019). Climate change is therefore anticipated to increase the challenges associated with fire suppression in Siberia and across the boreal forest as a whole (de Groot et al. 2013b; Kharuk and Ponomarev 2020). In Siberia, Alaska, and Canada, it has been suggested that fire management agencies may be overwhelmed by more active fire regimes in the future and the economic costs of fire suppression are expected to rise substantially (Flannigan et al. 2009; Podur

Table 2 Direct fire emission estimates in Siberia for average and extreme fire seasons by forest type

Stand type	Area burned, × 10^6 ha/year	Fire season type				% of emission (min–max)
		Average (moderate)		Extreme		
		T_g (C/year)	Ton (C/ha)	T_g (C/year)	Ton (C/ha)	
Larch	2.765	42.9	15.5	52.0	18.8	51.6–62.4
Pine	0.656	11.0	16.7	11.8	18.0	13.2–14.2
DNC	0.153	1.9	12.7	3.1	20.4	2.3–3.7
Deciduous/mixed	0.275	3.8	13.7	4.7	17.24	4.5–5.7



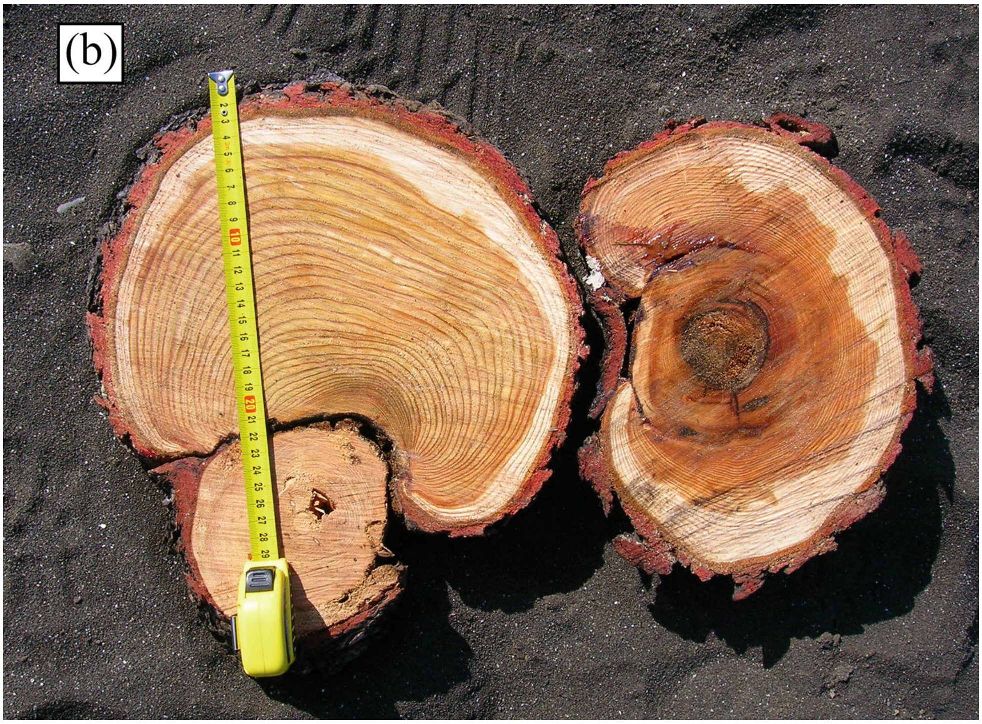


Fig. 9 **a** "Growth release" of larch trees ($N = 17$) that survived a fire; fire dates are indicated by arrows. **b** *Larix gmelinii* showed a strong post-fire growth increase even at Arctic Circle latitude

and Wotton 2010; de Groot et al. 2013b; Melvin et al. 2017; Kharuk and Ponomarev 2020). Given that > 80% of wildfires in southern Siberia are of anthropogenic origin, it is essential that people are educated about forest protection from fire hazards. In Russia, such education is organized at schools and colleges, annual "school forestry" conferences, and through lectures, posters, and mass media (Fedorov et al. 2003).

Systematic and developed firefighting in Siberia started in the 1930s, when the first airborne firefighting division was established in the Irkutsk region (near Lake Baikal). During the Soviet era, the fire suppression system was under continual development and reached a good level of efficiency. However, in the 1990s the forest firefighting system in Siberia, as well as across Russia as a whole, deteriorated. Since the 2000s, fire suppression in Siberia has been under redevelopment, although it has yet to reach its former level of efficiency.

The major features of Siberia include the vast area of fire-risk territory, low population density, and poor logistics and infrastructure. Consequently, geography has been a primary factor in the construction of the Russian fire protection system. In the current system, all Russian forests are classified into four monitoring zones (similar to the

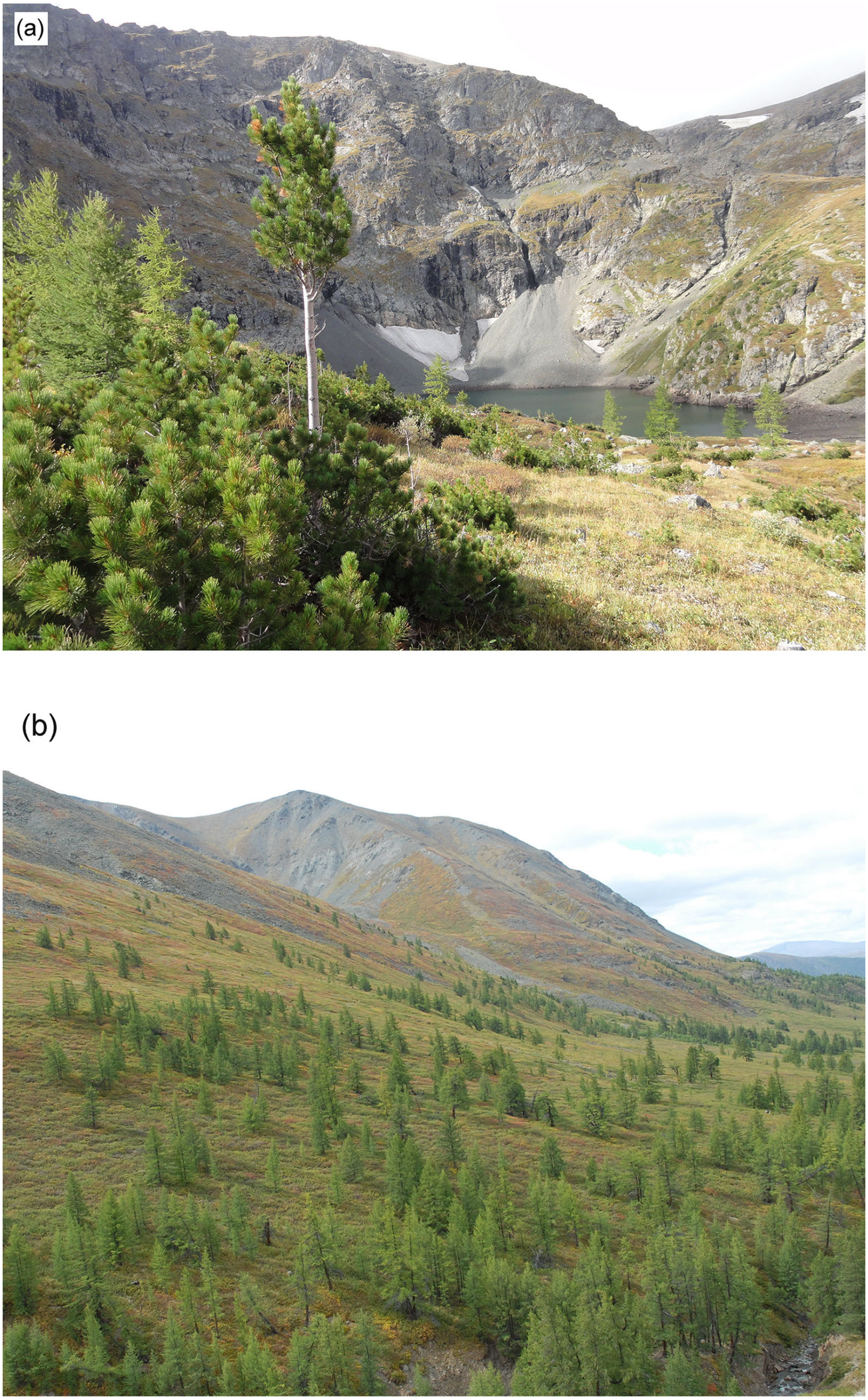


Fig. 10 **a** Siberian pine and larch (*L. sibirica*), **b** *L. sibirica* and **c** *L. gmelinii* migrations into treeline ecotones; **d** *L. gmelinii* seedlings and saplings near the northern treeline. It is predicted that larch will, over time, reach the Arctic Ocean. Locations: **a** 49°N, Altai Mountains; **b** south Siberia, Sangilen Ridge, 50°20′; **c** beyond Arctic Circle, Putorana Plateau; **d** Kheta River water basin (71°10′N)

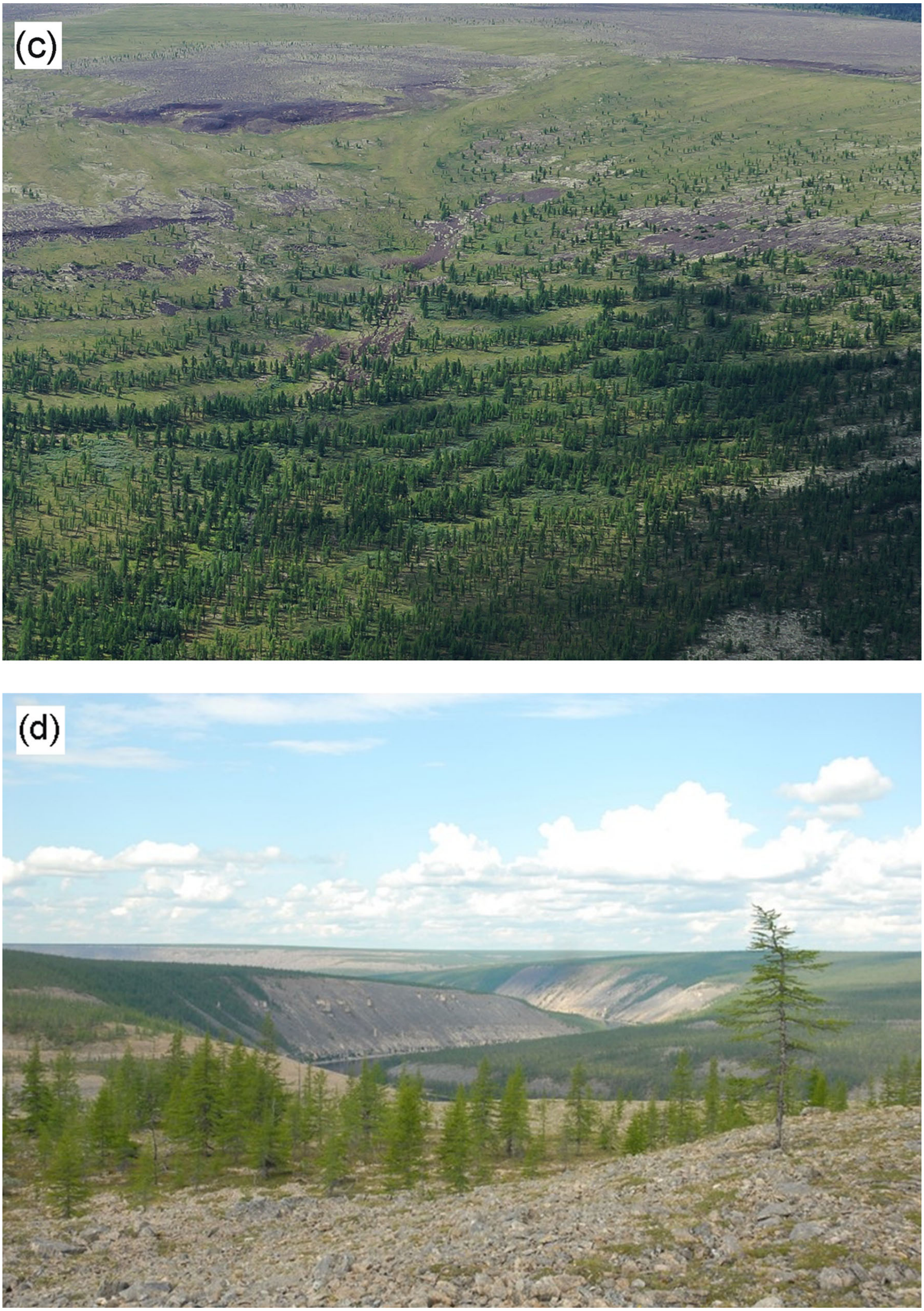


Fig. 10 continued

Alaskan fire management options; Melvin et al. 2017), which differ in the tactics, technology, and strategy of fire suppression (Fig. 4S):

1. The zone of on-ground monitoring, air survey, and satellite monitoring (~ 7% of the territory; total wildfire suppression).
2. The zone of combined air survey and satellite monitoring (~ 42% of forests; selective wildfires suppression).
3. The zone of satellite monitoring—level 1 (~ 20% of forests; selective wildfires suppression).
4. The zone of satellite monitoring—level 2 (~ 31% of forests; no wildfire suppression with the exception of settlements at risk).

As in Siberia, wildfires are typically not suppressed in northern Canada unless they threaten humans and assets at risk (Tymstra et al. 2020). However, increased fire activity necessitates modification of the Russian fire suppression strategy. It is known that the complete suppression of forest fires leads to fuel accumulation in some stands that can result in catastrophic fires. At the landscape level, natural fires are themselves a necessary tool in fire suppression, because other methods (e.g., prescribed fires, removal of fuel) are not readily applicable across the extensive ecosystems of northern fire-dependent forests (Kharuk and Ponomarev 2020; Tymstra et al. 2020). Thus, fires themselves are, paradoxically, part of the solution, as they reduce the likelihood of catastrophic fires and contribute to the conservation and restoration of boreal forest ecosystems.

We need to recognize that, under the conditions of increased forest burning, the impact of fires will increase while the possibility of complete fire suppression will decrease. Therefore, wildfire scientists and managers have suggested a paradigm change to allow more wildfires to burn across the landscape (Kharuk and Ponomarev 2020; Tymstra et al. 2020). Instead of total wildfire suppression, we suggest wildfire monitoring that allows fires to burn on the landscape under the right conditions, with fire suppression occurring when there is danger to people, industrial infrastructure, protected areas, and other assets at risk. Such an approach is already being adopted in parts of Canada, where the likely future constraints on fire suppression and the growing knowledge of the ecological importance of fire are increasingly acknowledged (Tymstra et al. 2020). Early policy in Alaska focused on the suppression and prevention of as many fires as possible despite limited resources (Todd and Jewkes 2006); however, given the infeasibility of suppressing all wildfires, a growing understanding of the ecological roles of fire, and changing US fire policy, Alaskan fire management agencies shifted from a strict suppression and prevention strategy to a wildfire management approach where fire is allowed on the landscape (where and when appropriate) thereby allowing for natural fire dynamics and ecological processes (Melvin et al. 2017). Likewise, we propose that fire suppression efforts in Siberia should focus on areas with high social, natural, and economic value. However, such an adaptive fire suppression approach in the face of more active fire regimes and their impacts is not well understood among politicians and the public, which further underscores the need for broad educational awareness of the role of wildfires in the Siberian province.

CONCLUSIONS AND RECOMMENDATION

1. In Siberia, fires are the major factor in climate–vegetation interactions and biogeochemical cycles. Within larch-dominant forests, fires are frequent and mainly low-intensity surface fires, whereas in evergreen forests dominated by Siberian pine, Scots pine, fir and spruce, both surface and high-intensity crown fires are observed.
2. Periodic wildfires are the most important natural ecological factor in taiga forest dynamics. Although the public and politicians are generally unaware, wildfires support the health and conservation of Siberian forests and they facilitate biodiversity support in forest ecosystems, providing opportunities for species migration northward.
3. Larch and Scots pine, the pyrophytic species, have evolved under conditions of periodic forest fires, adapting to them and gaining a competitive edge over non-fire adapted species in regenerating and growing in burned areas. In the permafrost zone, periodic fires are a prerequisite for the dominance of larch.
4. General warming, increased acute droughts, and heat waves have together led to an increase in the frequency and area of wildfires. Paradoxically, however, periodic wildfires themselves decrease the danger of catastrophic wildfires.
5. Wildfires in Siberia are migrating northward and have already reached the shore of the Arctic Ocean in Eastern Siberia.
6. The increased combustibility of the Siberian taiga due to climate warming has led to an increase in the smoke pollution of cities during the fire season.
7. We expect the area and number of wildfires to rise as climate warming continues to increase the number and severity of extreme fire-weather events.
8. With an amplified rate of warming and increase in fires in the Siberian taiga, we recommend that suppression focuses on areas that are of high social, natural, and economic value, while allowing a greater number of

wildfires to burn freely in the vast Siberian forest landscapes.

9. We recommend increased educational activities to help both the politicians and the public understand the role of wildfire in the boreal ecosystem and our proposed selective wildfire suppression strategy.

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