Tree ring-based reconstruction of the long-term influence of wildfires on permafrost active layer dynamics in Central Siberia

Running title: Fire effects on permafrost active layer dynamics

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Abstract

Although it has been recognized that rising temperatures and shifts in the hydrological cycle affect the depth of the seasonally thawing upper permafrost stratum, it remains unclear to what extent the frequency and intensity of wildfires, and subsequent changes in vegetation cover, influence the soil active layer on different spatiotemporal scales. Here, we use ring width measurements of the subterranean stem part of 15 larch trees from a *Sphagnum* bog site in Central Siberia to reconstruct long-term changes in the thickness of the active layer since the last wildfire occurred in 1899. Our approach reveals a three-step feedback loop between above- and belowground ecosystem components. After all vegetation is burned, direct atmospheric heat penetration over the first ~20 years caused thawing of the upper permafrost stratum. The slow recovery of the insulating ground vegetation reverses the process and initiates a gradual decrease of the active layer depth. Due to the continuous spreading and thickening of the peat layer during the last decades, the upper permafrost horizon has increased by 0.52 cm/year. This study demonstrates the strength of annually resolved and absolutely dated tree-ring series to reconstruct the effects of historical wildfires on the functioning and productivity of boreal forest ecosystems at multi-decadal to centennial time-scale. In so doing, we show how complex interactions of above- and belowground components translate into successive changes in the active permafrost stratum. Our results are particularly relevant for improving long-term estimates of the global carbon cycle that strongly depends on the source and sink behavior of the boreal forest zone.

Keywords: Boreal forest, Ecological interaction, Ecosystem response, Seasonally thawing soil layer, *Sphagnum*, *Larix gmelinii*

1. Introduction

Comprising up to 24% of the Northern Hemisphere landmass (Zhang et al., 1999; 2000), the permafrost zone is a particularly important component of the circumpolar boreal forest. Both, soil-forming activities (Ershov 1994, 1995; Gubin and Lupachev, 2008), as well as water and nutrient supply for plants (Sugimoto et al., 2002; Saurer et al., 2016; Prokushkin et al., 2018), predominantly depend on the freeze-thaw processes of the upper permafrost stratum, the so-called active layer (Permafrost Subcommittee, 1988). Operating at large spatial and temporal scales, a multitude of effects, related to the current global climate change, have been reported as responsible for changes in the behavior of different components of the permafrost-sphere (Grosse et al., 2016); and these influences are expected to increase under predicted future warming (IPCC, 2013). In this regard, far reaching ecological consequences are expected well-beyond the widespread permafrost body itself (Chadburn et al., 2017; Gasser et al., 2018; Lawrence and Slater, 2005; Nelson et al., 2001; Schuur et al., 2015; Tei et al., 2017). A key example of indirect effects of warmer temperatures on permafrost thawing is a change in the hydrological and biogeochemical fluxes that are characteristic of high northern latitudes (McGuire et al., 2002; Pokrovsky et al., 2005).

Trees of genus *Larix* dominate over 20% of boreal forests and are the most wide-spread in the permafrost zone of Eurasia (Abaimov et al., 1997). Being well adapted to harsh environments, larch trees are resistant to extremely low winter temperatures and the effects of late spring and early autumn frosts. One of the genus' main protective adaptations to low soil temperatures, and a particularly shallow active layer, is production of adventitious roots (Cooper, 1911; Sukachev, 1912). Adventitious rooting is also observed in other species in the boreal forests, e.g. black spruce (*Picea mariana* (Mill.) BSP), balsam fir (*Abies balsamea* (L.) Mill.), Scots pine (*Pinus sylvestris* L.), Siberian fir (*Abies sibirica* Ledeb) and Siberian pine (*Pinus sibirica* Du Tour). Tree-rings studies of roots help in understanding the adaptive strategy of trees on permafrost. Studies on the timing of root initiation of conifers in Canada (Fayle,1968; Krause and Morin, 2005) and Siberia (Kajimoto, 2010) suggest a process of renewal of the adventitious roots due to reductions of deeper soil temperature and decrease of active layer thickness with stand maturation. However, despite the importance of roots for tree stabilization, as well as absorption and transport of water and minerals, investigations of tree roots in boreal and especially permafrost zones are relatively rare and mainly focused on root biomass estimations and above- to belowground carbon partitioning (Baret et al., 2015; Kurz et al., 1996; Mokany et al., 2006 and references therein). Most tree-ring studies of roots are devoted to specific questions, like understory competition (Zaitsev et al., 2018), effect of thinning (Krause et al., 2014; Lemay et al., 2017; Vincent et al., 2009; Ruel et al., 2003), species adaptation to local soil conditions (Kajimoto et al., 2003; Krause and Morin, 2005).

Wildfires are the major driver of forest structure and species composition in the boreal zone and their impact should be considered when assessing spatiotemporal changes in the energy exchange, biogeochemistry, hydrology and carbon storage of the boreal forest (Certini, 2005; Conard and Ivanova, 1997; Köster et al., 2017). Various ecosystem components including stand composition, ground vegetation, organic layer and soils, soil microbial community and zoobiota are heavily affected by wildfires (Bezkorovainaya et al., 2016; Gibson et al., 2018; Masyagina et al., 2016; Moore, 1996; Sorokin et al., 2000; Tiedemann et al., 1979; Viereck and Schandelmeier, 1980; Waldrop and Harden, 2008 and reference therein). The mean return interval of extensive fires in the larch dominated areas of the middle taiga, in the south of permafrost zone in Central Siberia, is 77±20 years. The frequency of wildfires decreases with latitude to 82±7 years in the northern taiga zone at ~64°N, and up to 320±50 years at the treeline ecotone ~71°N (Kharuk et al., 2011; Panyushkina and Arbatskaya, 1999; Vaganov and Arbatskaya, 1996). Although it has been argued that the frequency and intensity of wildfires will increase under warmer temperatures (Kharuk et al., 2013), little is known how fires will, directly and/or indirectly, contribute to changes in the seasonally thawing active layer. Considering most of northern Eurasia's permafrost area is covered by larch forests (Abaimov et al., 1997), and the importance of wildfires in boreal zone, it is worthwhile to assess possible fire effects on permafrost active layer dynamics in larch dominated ecosystems. The impact of wildfire on forest ecosystems in the permafrost zone has been intensively studied in Siberia (Sofronov and Volokitina, 2010 and references therein). However, our knowledge of the long-term effect of fire on active soil layer is still limited. Though it is well-known that seasonal thaw depth increases after wildfire (e.g. Mackay, 1970; Pozdnyakov, 1986; Yoshikawa et al., 2002), and decreases with subsequent re-vegetation (e.g. Fisher et al., 2016; Loranty et al., 2018; Mackay, 1995; Shiklomanov et al., 2010), the rates of these processes are unknown for Siberia. This pending task appears particularly relevant to current debates on the amount of carbon and methane that might be released from melting permafrost in a warmer future (Anisimov, 2007; Koven et al., 2011; Schaefer et al., 2011; Schuur et al., 2015).

Here, we present the first tree ring-based reconstruction of long-term changes in the depth of the seasonally thawing upper permafrost stratum that occurred after a massive wildfire burned most of a forest ecosystem in 1899. Conducted in an undisturbed, natural forest in Central Siberia, our study aims to test the hypothesis that fire-induced modifications of the active layer depth are directly related to the rate of change in the insulating vegetation cover, and thus may range from decades to centuries.

2. Material and Methods

This study was conducted in an undisturbed Gmelin larch (*Larix gmelinii* (Rupr.) Rupr.) dominated *Sphagnum* bog, in the Kochechum River valley, in Central Siberia (64°19'30''N, 100°14'53'E and 147 m a.s.l.) (Fig. 1a). Details on stand and soil characteristics are given in a recent study by Prokushkin et al. (2018). Located within the continuous permafrost zone, the region is characterized by a severe continental climate. Based on meteorological measurements from the nearby instrumental station in Tura, the mean annual temperature since 1929 is -8.9° C. The warmest (+16.6° C) and coldest (-35.9° C) monthly means are most often recorded in July and January, respectively. The average amount of annual precipitation is 357 mm, and the growing season is generally restricted to ~70–90 days between the end of May and the beginning of September (Bryukhanova et al., 2013; Shishov et al., 2016).

In this study we follow the approach proposed by Borggreve (1889), who suggested that tree seeds, which germinate on the surface of a *Sphagnum* bog, allow moss expansion to be estimated. This is based on the fact that *Sphagnum* grows vertically during succession, but a tree's root collar (hypocotil) remains at the same position at which its seed germinated. The upright developing *Sphagnum* mat thus buries the lower part of a tree stem which can, in the case of larch, produce adventitious roots (Cooper, 1911; Kajimoto et al., 2003; Sukachev, 1912). Assuming that seed germination occurred on the *Sphagnum* surface, tree age at the collar provides precise information of the annual rates of vertical moss growth (Borggreve, 1889; Dubakh, 1927; Schulze at al., 2002; Knorre et al., 2003; Prokushkin et al., 2006).

For larch growing on *Sphagnum*-dominated permafrost sites, it was found that tree-ring formation ceases at different positions along those portions of roots and stem that are buried in moss in different years (Fig. 2). Consequently, we use data on cambium cessation at different locations along the larch tap-roots and stems, below the current moss surface, to reconstruct changes in the active soil layer thickness.

Ten and five larch trees between 0.6-3.0 m high were sampled in late July 2002 and 2005, respectively. From each tree, a total of 3-11 discs were cut along the buried stem section from the current surface of the moss layer down to the level of the root collar (Fig. 1b). For each disc sample, ring widths were measured along the two longest, undisturbed and continuous radii using a LINTAB measuring system (RINNTECH e.K., Heidelberg, Germany). The disc-specific ring width series were visually cross-dated and then averaged with the TSAP-win software (Rinn, 2003). The resulting within-disc chronologies were further cross-dated between discs from different positions of the same tree. The cross-dated ring width chronologies were then used to define the calendar year of the first, oldest (innermost) and last, youngest (outermost) tree ring at each sample depth of the belowground stem section. The calendar year of the innermost ring at the root collar was considered the year of tree establishment, whereas the year of the outermost ring referred to the last year of cambium activity at this particular stem position. Due to heavily suppressed wood formation, the outermost rings in 3 out of 75 discs could not be accurately cross-dated and were therefore excluded from further analysis.

To test the hypothesis of a thermally-induced cessation of cambial activity within the belowground part of a tree, a set of waterproof sensors (S-TMB-M002; Onset Computer Corporation, Bourne, MA, USA) were installed to measure soil temperatures at 5, 10, 20 and 40 cm stem depth below the *Sphagnum* surface. All sensors were connected to a HOBO Micro Station Data Logger (H21-002; Onset Computer Corporation, Bourne, MA, USA), which recorded mean temperatures each hour at each depth from the end of the 2007 growing season until the end of the 2008 growing season. The hourly data were then averaged to produce a time series of daily temperature means at different soil/stem depths.

To date the wildfire at our site, fire-scars on two trees that survived the last fire, growing at the edge of the *Sphagnum* bog, were dendrochronologically analyzed. To estimate the spatial extent of this wildfire fire scars on trees at 8 sites, located up to 22 km away, were also dated. To reconstruct the active soil layer thickness during the first decades after fire, we complement our data with measurements of seasonal permafrost active layer depth at four sites affected by different wildfires in 2005, 1994, 1990 and 1981. These additional measurements were obtained between mid-July and mid-August 2005.

3. Results and Discussion

The tree-ring analysis of fire scars from trees in the region indicate that the last major wildfire at the study site occurred in 1899 AD and affected an area of at least 250 km^2. The vast spatial extent of the fire and low number of survived trees at the edge of the studied ecosystem suppose high severity of the wildfire at the site. This suggests the fire completely devastated the site, burning nearly all trees, as well as the understory vegetation, including the extensive moss layer and large parts of the organic upper soil horizon.

Tree-ring dating of wood samples from the root collar indicates that the regeneration rate of new larch trees was particularly high during the first decades after the wildfire (Fig. S1), which is due to favorable soil temperature regime and, most probably, a lack of competition for new seedlings since the ground vegetation had been completely removed by wildfire (Sofronov and Volokitina, 2010). About 50% of all of the trees germinated within the first 10 years after the fire, and all of the larch seedlings established between 1900 and 1932 AD. Therefore, the age of the individual larches that were sampled varies from 71–103 years, with a mean of 91 years (±9.4 standard deviation; STDEV). As a direct consequence of the post-fire reforestation that coincided with the spatial expansion and vertical rise of the *Sphagnum* mat, the root collars of the sampled trees are now buried under a 20–45 cm thick moss layer. The mean root collar depth is 32.5 cm (±6.5 STDEV).

Recovery of ground vegetation reduced the depth of the permafrost active layer. Sealing the roots and stems in permafrost leads to cessation of cambial activity. Since the outermost tree ring of each disc refers to the year in which cambial activity stopped, we found a positive relationship between cessation and moss-peat layer thickness, with the upper levels of the buried stem dying later (Fig. 2, S1). The average difference, in calendar years, of the formation of the last (outermost) tree-rings in the uppermost discs collected at the current moss-layer surface, and the lowermost root collar disks was 35.6 years (±13.1 STDEV), and ranged from

6–58 years for trees established in between 1900 and 1932. In general, belowground stem parts at positions closest to the current moss surface, on average, live longer than deeper stem layers (Fig. 2, S1). The duration of cambial activity for buried stems, at around 30–45 cm depth, ranged between 24 and 69 years, compared to 61–97 years of cambial activity at the moss surface. At our study site, the cessation of cambial activity in larch stems started in 1946 (Fig. 3). Using the information of cessation dates and *Sphagnum* layer thickness for all the trees at our site (as an example shown to Fig. 2 for tree N5), we find a significant linear relationship ($R=0.81$, $p<0.001$) between these two variables (Fig. 3). Consequently, the most recent cases of cambial termination are observed at a depth of 10–15 cm below the moss surface.

Seasonal measurements of temperature at different moss depths confirm the importance of low temperatures on belowground stem growth at depths of 10–40 cm (Fig. 4). At a depth of 10 cm, the 5°C level, that is widely accepted as the lower temperature limit for xylogenesis (Rossi et al., 2007, 2008; Körner 2012), is reached by the middle of June, and never reached at a depth of 20 cm. Though the temperatures at a depth of 15 cm were not measured, we theorize that a suitable period for tree-ring formation below 15 cm is too short and arrives, if ever, late in the season (Bryukhanova et al., 2013).

The combination of tree-rings in buried stems, active layer thickness at sites affected by wildfire in different years, as well as features of *Sphagnum* growth (Prokushkin et al., 2006), permit the reconstruction of changes in the seasonal thaw depth of the upper permafrost layer over the last century (Fig. 5). The forest fire that occurred in 1899 and killed most of the larch trees also burned the insulating layer of ground vegetation. As a consequence of this removal, seasonal thawing of permafrost started earlier in spring. In 1-2 years after the fire the active layer is up to 1.5 m thick. Rain water, which is not intercepted by the ground vegetation, supplies additional heat from the atmosphere to the soil. These favorable conditions stimulate successful regeneration of larch (current density at the site is 5700 trees/ha) and formation of deep rooting systems. During the first years after wildfire seasonal tree growth extends from late May till early September. During this period the ground vegetation, is largely represented by patches of *Sphagnum* and other vegetation that extend mostly horizontally, and gradually occupy the area with time. Vertical growth of *Sphagnum* occurs primarily in slight depressions. According to our estimates (Prokushkin et al., 2006) the duration of this recovery period is approximately 20 years (Fig. 3). The decomposition rate of litter during this period is high due to optimal hydro-thermal conditions, and vertical growth rates of mosses are low.

Formation of a continuous ground vegetation layer insulates the soil. Vertical growth of *Sphagnum* leads to a delay in seasonal permafrost thawing in summer and a gradual decrease of active soil layer thickness from year to year. Our data suggest that the rising permafrost table leads to the progressive cessation of growth of the buried stem, as well as adventitious roots beneath the moss layer. Cambium cessation of buried stems started in the 1940s at the current depth of ~40 cm. If 20 years are necessary for *Sphagnum* to cover the surface (Prokushkin et al., 2006) (Fig. 5, stage i), then it would take 25-30 years for the moss to develop a 15 cm thick layer, assuming an annual rate of 0.5-0.6 cm/year (Prokushkin et al., 2006; Knorre et al., 2006), which is large enough to insulate the ground sufficiently for the permafrost to rise (Fig. 5, stage ii). As the peat layer continues to grow, the permafrost rises, and cessation of cambial activity occurs at higher and higher levels along the buried stems (Fig. 5 stage iii).

The data presented in Fig. 3 are used to estimate the rate of post-fire permafrost “rise”, i.e. reduction of the active layer post 1940s. The slope of the regression (0.52 cm/year) indicates the rate at which the height of cambial activity cessation, along the buried stem, rises following the active layer thinning. Our estimate for the rate of permafrost recovery (0.52 cm/year) is in line with the rate of vertical moss growth in the region (Prokushkin et al., 2006, Knorre et al., 2006). Some difference in the rate of permafrost rise between the trees (Fig. 3) could be related to the difference in thermo-hydrological conditions and various elements of micro-topography (mounds and troughs), and variations in density of the insulating moss cover.

In the forest ecology community, the general understanding of post-fire dynamics of vegetation and consequent changes in active soil layer thickness in the permafrost zone is that the seasonally thawing soil layer usually deepens quickly over the first post-fire years, and slowly recovers following re-vegetation (e.g. Brown et al., 2015; Pozdnyakov, 1986). These conclusions are supported by a number of multi-decadal observations of soil layer thickness in Canada and Alaska (Brown et al., 2000; Mackay, 1995; Viereck et al., 2008). Though these data provide unique information, their obtainment requires repeated measurements over several decades and are mostly devoted to particular habitats (Burn, 1998; Minsley et al., 2016). Our study case is also site-specific. The proposed technique was tested at only site which is characterized by high accumulation rates of insulating soil organic matter. To understand the spatial applicability of this methods, it needs to be verified at a variety of permafrost sites dominated by moss across the boreal forest, which occupy up to 55% of the studied region (Korets et al., 2016). Moreover, this new tree-ring based approach can provide annually resolved data from many sites within one field season, which is not possible with the direct observation methods.

4. Conclusions

Here we demonstrate a new technique for reconstructing the post-wildfire recovery of permafrost in Central Siberia based on dendrochronological dating of stems buried in the moss layer. Our case study is supported with direct measurements of active layer thickness at the chronosequence of forest ecosystems affected by fires over the past decades. The data indicate the proposed technique is successful in reconstructing the dynamics of ground cover recovery and soil active layer thickness changes with annual resolution, and shows that the effect of wildfire on active soil thickness persists for several decades. This implies long-term consequences for carbon, nutrient and water balance of the ecosystem, resulting in increased microbial and zoobiota activity in a deeper and warmer active soil layer (Fig. 5). Further investigations on root tree-rings in the permafrost zone are needed at more sites to quantify the effect of the current climate changes on the active soil layer thickness.

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Author contributions

AVK initiated the study. AAK, ASP and AVK collected the material, AAK measured the material and prepared the first draft of the manuscript. UB and PJK worked on the final version of the paper with comments from AVK and ASP. All authors provided critical discussion.

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Figure Captions

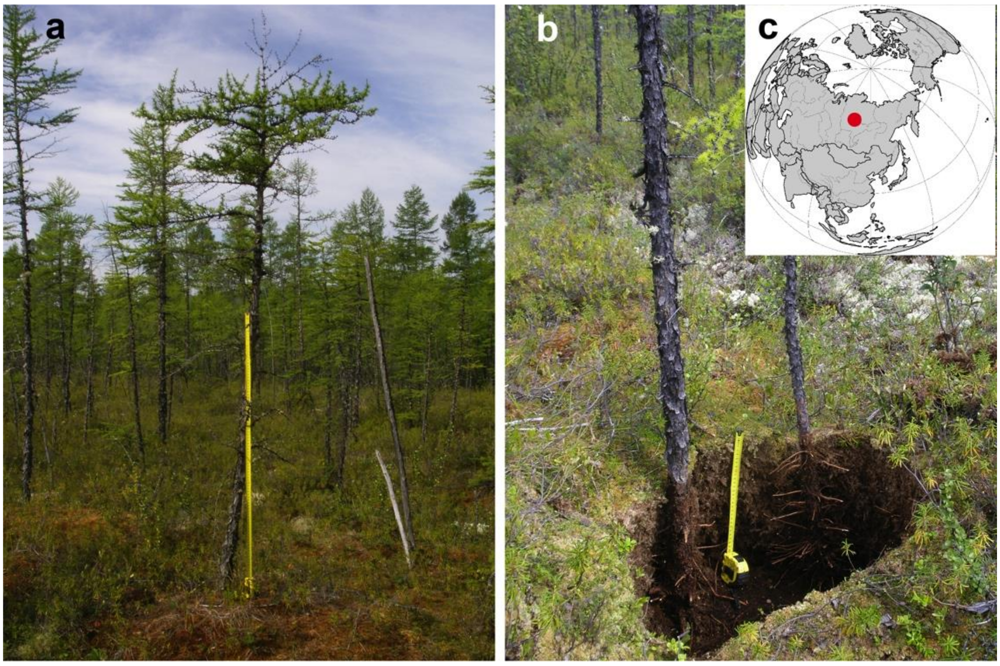
Figure 1. (a) Study site, (b) excavated larches with adventitious roots (cut), and (c) location of the sampling area within Central Siberia (red circle).

Figure 2. Averaged tree-ring width measurement series that represent different below-surface stem heights of tree N5.

Figure 3. Precise calendar dates of the outermost, last tree rings, formed at different stem depths below the upper *Sphagnum* surface before death (ranging from ~ 10 to ~ 50 cm). The linear function is a least square approximation of the permafrost rise rate, and the three-step feedback loop of: i) thawing of the upper permafrost stratum, ii) decreasing active layer depth, and iii) increasing of the upper permafrost horizon by 0.52 cm/year is shown at the bottom of the figure.

Figure 4. Temperature dynamics at four depths (5, 10, 20 and 40 cm) of a moss-peat layer at the studied site. The temperature sensors were installed in late summer 2007. The dashed horizontal line indicates the physiological minimum threshold for root growth of frost-tolerant species 2.3°C (Schenker et al., 2014), and the solid line corresponds to 5°C, a widely accepted low temperature limit for xylogenesis (Rossi et al., 2007, 2008; Körner 2012).

Figure 5. Schematic representation of the post-wildfire development of a forested *Sphagnum* bog ecosystem in the continuous permafrost zone in Central Siberia together with the main features of our sampling design and data recording.



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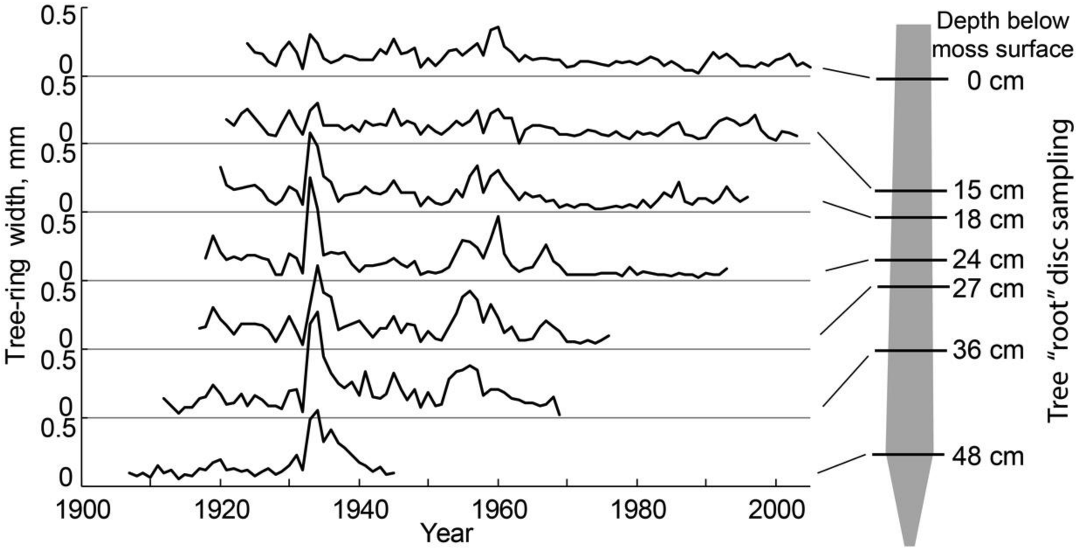

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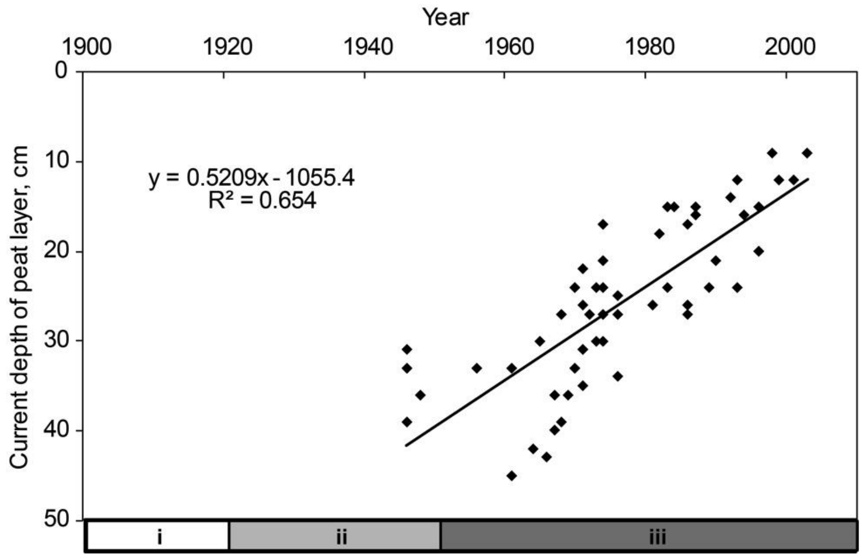

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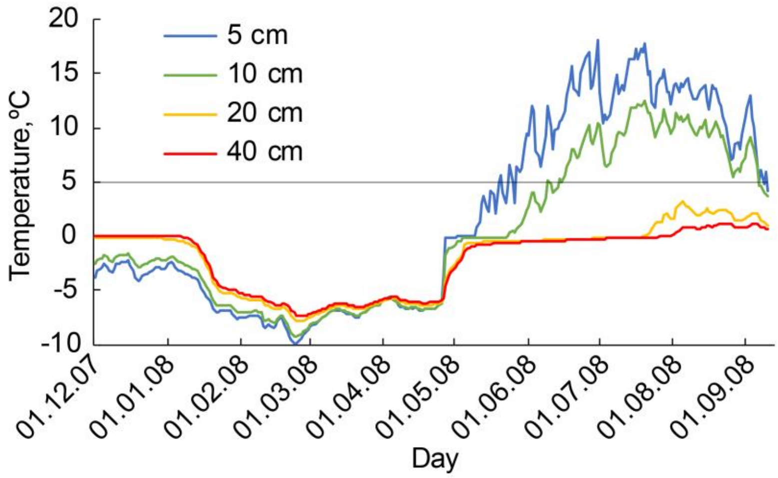

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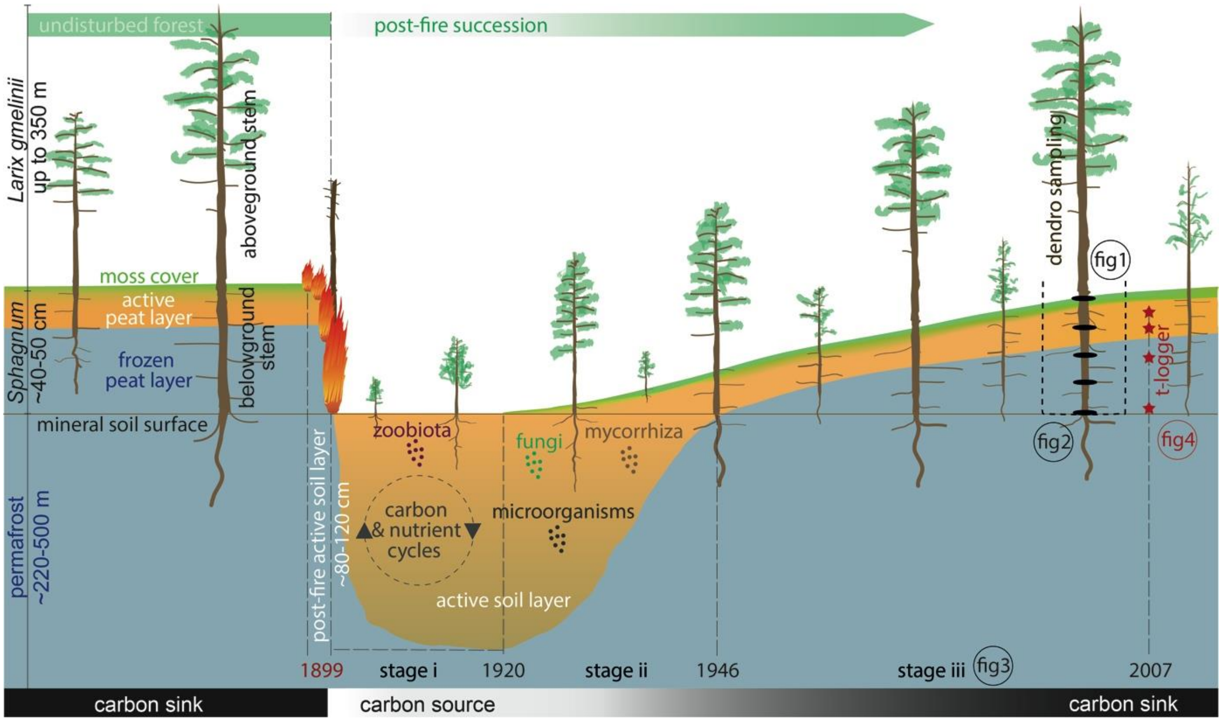

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