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Impacts of increased soil burn severity on larch forest regeneration on permafrost soils of far northeastern Siberia

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ABSTRACT

Fire severity is increasing across the boreal forest biome as climate warms, and initial post-fire changes in tree demographic processes could be important determinants of long-term forest structure and carbon dynamics. To examine soil burn severity impacts on tree regeneration, we conducted experimental burns in summer 2012 that created a gradient of residual post-fire soil organic layer (SOL) depth within a mature, sparse-canopy Cajander larch (*Larix cajanderi* Mayr.) forest in the Eastern Siberian Arctic. Each fall from 2012 to 2016, we added larch seeds to plots along the burn severity gradient. We tracked density of new larch germinants and established seedlings (alive ≥ 1 year) during subsequent growing seasons, along with changes in seedbed conditions (permafrost thaw depth, moisture, and temperature). Over the study, a cumulative total of 17 and 18 new germinants m^{-2} occurred in high and moderate severity treatments, respectively, while germinants were rare in unburned and low severity treatments (< 0.5 germinants m^{-2}). Most seedlings ($> 50\%$) germinated in summer 2017, following a mast event in fall 2016, suggesting safe sites for germination were not fully occupied in previous years despite seed additions. By 2017, established seedling density was ~5 times higher on moderate and high severity treatments compared to other treatments. Cumulative total density of new germinants and established seedlings increased linearly with decreasing residual SOL depth, as did thaw depth, soil moisture, and soil temperature. Our findings suggest that increased soil burn severity could improve seedbed conditions and increase larch recruitment, assuming seed sources are available. If these demographic changes persist as stands mature, a climate-driven increase in soil burn severity could shift forest structure from sparse-canopy stands, which dominate this region of the Siberian Arctic, to high density stands, with potential implications for carbon, energy, and water cycling.

1. Introduction

In recent decades, fire frequency, extent, and severity have increased across much of the boreal forest biome in conjunction with climate warming (Kasischke et al., 2010; Ponomarev et al., 2016; Soja et al., 2007). Because boreal forests contain a large proportion of global terrestrial carbon (C) stocks (Pan et al., 2011), there has been great interest in understanding the effects of an altered fire regime on these ecosystems and potential feedbacks to climate warming (Beck et al., 2011; Bond-Lamberty et al., 2007; Johnstone et al., 2010; Randerson et al., 2006). Directly, increased fire activity can combust C stored in vegetation and organic soils and increase atmospheric CO_2 emissions, creating a positive feedback to climate warming (Bond-Lamberty et al., 2007; Harden et al., 2000). However, fires can also initiate an array of indirect effects on forest regrowth and permafrost stability that can magnify or offset direct fire effects by influencing net ecosystem carbon balance (NECB; (Chapin et al., 2006)).

An important way that intensifying fire activity can impact boreal forest stand dynamics and C pools is by altering demographic processes during early succession, thereby initiating a post-fire successional

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trajectory that results in a mature stand with a different structure than that of the pre-fire stand. Across the boreal forest, post-fire recruitment of trees and large shrubs is strongly influenced by the depth of the soil organic layer (SOL) (Greene et al., 1999, 2007; Greene and Johnson, 2000; Johnstone and Chapin III, 2006), a thick layer of undecomposed dead mosses, lichens, leaf litter, and fine roots (Dyrness, 1982) that accumulates in cold, moist conditions. In mature forests, the SOL is typically thick and porous, so seedlings experience strong fluctuations in moisture and temperature (Johnstone and Chapin III, 2006) and often desiccate before roots reach the stable moisture environment provided by underlying mineral soils (Brown and Johnstone, 2012; Hollingsworth et al., 2013; Johnstone and Chapin III, 2006). Boreal fires are largely fueled by combustion of the SOL, and the proportion of SOL consumed by fire is a major determinant of fire severity (i.e., amount of organic material consumed by fire; (Rowe, 1983), referred to as soil burn severity (Johnstone and Chapin III, 2006). Increased soil burn severity often correlates with decreased SOL depth and increased mineral soil exposure (Johnstone and Kasischke, 2005; Turetsky et al., 2011), which improves seedbed conditions for many boreal plants (Johnstone and Chapin III, 2006; Tautenhahn et al., 2016). For example, recruitment of boreal trees in North America and Scandinavia increased when fire reduced the SOL to < 2.5 cm (Johnstone and Chapin III, 2006). As long as seed sources are available, high soil burn severity can improve post-fire tree recruitment for decades until the understory and SOL reestablish (Nilsson and Wardle, 2005). Given that soil burn severity is predicted to increase with increased climate warming (Schaphoff et al., 2016; Turetsky et al., 2011), this change in the seedbed could have long-lasting implications for future stand dynamics across the boreal region.

Fire-driven changes in SOL depth also influence permafrost stability due to the SOL's insulating properties (Abaimov et al., 2002a,b), which in turn, can impact tree regeneration through impacts on soil growing conditions and germination microsites. The SOL acts as a thermal insulator and decouples air temperatures from those of the mineral soil (Sofronov and Volokitina, 2010). As such, a post-fire reduction in SOL depth can increase soil temperature, deepen the active layer (Kasischke and Johnstone, 2005; Yoshikawa et al., 2002), and increase unfrozen soil volume, allowing roots to access water and nutrients in deeper soils (Kajimoto et al., 2003). Increased soil temperatures may also speed up decomposition rates and increase soil nutrient availability (Biasi et al., 2008; Schimel et al., 2004). In addition, fire removal of the SOL may promote soil subsidence and thermokarst formation (Brown, 1983; Kharuk et al., 2005; Viereck, 1973), which could expose mineral seedbeds and increase favorable microsites for germination. Conversely, if permafrost is ice-rich, deepening of the active layer and thermokarsting could waterlog soils, thereby reducing seedling establishment. Thus, changes in exploitable space and resources within permafrost soils due to increased fire severity and a shallower SOL depth could further influence the rate and magnitude of forest regrowth post-fire.

Over the post-fire successional interval, fire removal of the SOL and subsequent changes in forest regrowth may impact long-term successional trajectories of forest stands because of the tendency for initial post-fire recruitment patterns to predict future stand dynamics (Johnstone et al., 2004, 2010). Different successional trajectories may, in turn, lead to variability in C storage because of differences in forest stand structure, productivity, longevity, litter availability, and flammability. For example, in boreal Alaska, high severity fires that reduce SOL depth and expose mineral soils can shift forest successional trajectories away from black spruce (*Picea mariana*), an evergreen conifer, to pathways with greater deciduous dominance (Johnstone et al., 2011; Johnstone and Chapin III, 2006; Johnstone and Kasischke, 2005). This shift leads to greater aboveground C storage because deciduous stands accumulate more C in live and dead trees than black spruce stands (Alexander et al., 2012a; Alexander and Mack, 2016). Ultimately, forest recruitment patterns can determine whether C lost during fire is re-accumulated during the post-fire successional interval.

The primary objective of this research is to increase our understanding of post-fire forest successional dynamics by investigating if increased soil burn severity could alter patterns of tree regeneration (i.e., germination and seedling establishment for at least 1 year) on permafrost soils within Cajander larch (*Larix cajanderi* Mayr.) forests of the Siberian Arctic when seed sources were available. To address our objective, we conducted experimental burns of varying soil burn severity in a mature, sparse-canopy larch stand, representative of a 'typical' forest in this region having low-density and aboveground biomass (Alexander et al., 2012b; Berner et al., 2012). Each fall from 2012 to 2016, we added larch seeds and monitored larch regeneration and seedbed conditions (permafrost thaw depth, soil moisture, and soil temperature) for five subsequent growing seasons. We focused on Siberian larch forests because they comprise 20% of the world's boreal forests (Osawa et al., 2010), grow on top of C- and ice-rich, loess-like sediments called Yedoma permafrost or Ice Complex in Russia (Schirrmeister et al., 2013; Sher, 1971; Zimov et al., 2006), and contain a quarter of the C in high latitude permafrost soils (Loranty et al., 2016). These forests span much of Arctic treeline in Siberia (Zyryanova et al., 2007), and the ability of larch to recruit in both the presence or absence of fire will be a primary determinant of whether boreal forests respond to climate warming via treeline migration or retrogression (MacDonald et al., 2008). Further, despite the global importance of larch forests and the potential for an altered fire regime to modify regeneration patterns and future forest cover, larch forests of Eurasia remain largely understudied compared to boreal forests of North America. This study aims to fill this knowledge gap by providing experimental data of how variable soil burn severity impacts larch forest recruitment and successional pathways.

2. Methods

2.1. Study area

Research was conducted near the Northeast Science Station (NESS) in Cherskiy, Sakha Republic, Russia in far northeastern Siberia (68.74° N, 161.40° E), which is located on the Kolyma River, ~250 km north of the Arctic Circle and ~130 km south of the Arctic Ocean. Climate is continental, with warm summers (July average = 12 °C), cold winters (January average = −33 °C), and average annual temperature of −11.6 °C. Annual precipitation is low (230 mm yr^{-1}, with ~ half falling during summer (Cherskiy Meteorological Station, https://rp5.ru/Weather_archive_in_Cherskiy). Forests in this region of the Russian Far East are typically open-canopy, sparse stands dominated by Cajander larch (Alexander et al., 2012b; Berner et al., 2012; Loranty et al., 2016), a deciduous needleleaf conifer, which is adapted to growth on continuous permafrost and a short, cool growing season (Abaimov, 2010). Trees in this region rarely exceed 10 m tall, and stands tend to have relatively low aboveground biomass ($< 1{,}200\ \text{g m}^{-2}$) (Berner et al., 2012). Seeds are produced annually, with heavy mast events every 2–3 yr and seed dissemination beginning in early autumn (Abaimov, 2010). Ground vegetation consists of deciduous shrubs (*Betula nana* L. ssp. *exilis* (Sukaczev) Hultén, *B. divaricata* Ledeb., *Salix* spp.), evergreen shrubs (*Vaccinium vitis-idaea* L., *V. uligosium* L., *Empetrum nigrum* L., *Ledum subarcticum* (Ait.) Lodd. ex Steud., herbs (*Artemisia tilesii* Ledeb., *Chamerion angustifolium* (L.) Scop., *Equisetum scirpoides* Michx., *Luzula multiflora* (Ehrh.) Lej., *Pedicularis lapponica* L.), grasses (*Calamagrostis neglecta* (Timm.) *Koeler*), mosses (e.g., *Aulacomnium turgidum* (Wahlenb.) Schwägr. (which is dominant)), *Dicranum* spp., *Polytrichum* spp.), and lichens (e.g., *Cetraria cuculata* (Bellardi) Ach., *Cladonia rangiferina* (L.) Nyl., *Peltigera* spp.).

Current fire return interval in the Russian Far East is 80–200 years (Ponomarev et al., 2016), with an annual burned area of ~2.0 Mha yr^{-1} (Rogers et al., 2015), but fire frequency and extent are increasing across the region (Ponomarev et al., 2016). Most fires are