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Post-fire tree recruitment of a boreal larch forest in Northeast China

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ABSTRACT

Boreal larch forests in eastern Siberia contain about half of the carbon accumulated in Eurasian forest communities, and fire is an important disturbance in this area, contributing to changes in forest composition and breaking the original succession trajectory. Assessing burn severity and environmental controls on post-fire larch recruitment is critical for understanding long-term effects of fire disturbance on forest succession in this region. A mega-fire that burned 8700 ha in the year 2000 in the Great Xing' an Mountains provided an opportunity to study the effects of mixed-severity fire disturbance in larch forests. We sampled tree recruitment in 83 burned sites to address the question of how burn severity and site environment interact to influence the species composition and density of post-fire tree recruitment, and hence the successional trajectory of forest. We explored the hypothesis that the larch forest was more likely to replace itself rapidly ("self-replacement succession") in areas of low-severity burn, but was more likely to be replaced by an early-seral community of broadleaf trees ("relay succession") in areas of high-severity burn. Our analysis showed that post-fire conifer and broadleaf recruit densities were both negatively related to burn severity and understory cover. Environmental conditions (e.g. elevation, slope, aspect) had weaker influences than burn severity on post-fire tree densities, but played a stronger role in determining the relative proportion of conifer recruits. Broadleaf trees recruited abundantly in low-severity burns in upland areas, even though they were absent from most of the pre-fire sites. In contrast, coniferous trees recruited more abundantly in low-severity burns in valley bottom areas. The comparison of pre- and post-fire tree composition in the burned patches indicated that self-replacement succession was likely to occur in valley bottom areas that burned with low severity. Burned upland areas are more likely to experience an alternative, broadleaf-dominated trajectory of relay succession. The increase in the severity and frequency of fires due to climate warming may prompt shifts from a larch dominated forest to an increasingly birch dominated landscape, substantially altering landscape dynamics and ecosystem services.

1. Introduction

Fire is an important disturbance in boreal forests, which can change landscape dynamics (Johnson, 1996; Kurkowski et al., 2008). Because forest succession is a long-term process where initial conditions can be critically important, tree recruitment immediately (e.g., ⩽15 year) after fire provides a critical observational window to predict future canopy composition and stand dynamics (Johnstone et al., 2004). Characterizing patterns of post-fire recruitment is especially important in boreal forests where the return interval of stand-replacing fire is often shorter than the time required for the climax community to dominate (Johnstone et al., 2004). Post-fire tree recruitment has been frequently studied in North American boreal forests which are dominated by crown fires (Johnson, 1996; Johnson et al., 2001; Greene et al., 2007), but rarely in eastern Siberian larch forests which are dominated by surface fires (Conard and Ivanova, 1997; Ito, 2005). Although the variations in seed bed characteristics due to burn severity heterogeneity might be similar in North American and Eurasian boreal forests, the difference in characteristic fire behavior results in patterns of post-fire seed availability that can strongly differ between these two boreal forest ecosystems.

The boreal forests in Eurasia occupy more than 70% of the boreal forest biome globally (Goldammer and Furyaev, 1996), and about half of the carbon that has accumulated in Eurasian forest communities is contained in larch forests (Alexeyev et al., 1995). The larch boreal forests in Northeast China, which are located on the southern boundary of eastern Siberian larch forests, provide approximately 30% of the total timber production in China (Wang et al., 2001). Compared to black spruce (*Picea mariana*), the dominant conifer tree species in the boreal forest of North America,

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Gmelin's larch (*Larix gmelinii*) possesses different fire-adapted life history traits. Larch saplings are not fire-resistant, but mature trees are resistant to surface fires because of their thick bark near the bottom of the stem and self-pruning character (Ban et al., 1998; Makoto et al., 2007). Gmelin's larch is not a serotinous species and the effective distance of seed dispersal is only about 100 m (Xu, 1998), so the surviving seed trees are important for post-fire larch recruitment. If the seed availability is not the limitation, larch recruits well on exposed mineral soil or moss-covered mesic seed beds (Ban et al., 1998; Abaimov, 2010). The shallow distributed roots enable larch to grow in both well-drained and boggy sites, including in the wet valley bottom sites above the permafrost (Ban et al., 1998; Xu, 1998; Kajimoto et al., 2003). Compared with black spruce, the distinct life history traits of larch may result in different responses to fire disturbance. As a result, larch-dominated boreal forests in Eurasia may respond differently to fire than the well-studied, spruce-dominated boreal forests of North America.

Wildfires create biotic heterogeneities (e.g., seed tree abundance, interspecies competition) and abiotic heterogeneities (e.g., soil organic depth), which act as a filter for seed availability, seedling germination and establishment (Donato et al., 2009). Severely burned fires have the potential to kill seed trees and destroy aerial and soil seed banks over broad areas because of their high fuel consumption rate (Donato et al., 2009). Thus, for species with limited seed dispersal distance, seed availability may be the main limiting factor for recruitment in severely burned areas. Severely burned fires also alter seed bed characteristics, consuming much soil organic matter and reducing soil moisture content (Turner et al., 1997). Diverse seed availability and seed bed characteristics could consequently alter succession patterns compared with those resulting from mildly burned fires (Turner et al., 2003). Mixed-severity fire regimes have elements of surface, torching and crown fire behavior and therefore result in heterogeneous post-fire tree recruitment by leaving different seed availability and seed bed conditions in patches of various sizes. However, fire impacts on successional trajectories are likely to be contingent on a number of landscape factors, including environmental conditions (e.g., topography, landscape position) and pre-fire vegetation legacies (Pausas et al., 2004; Johnstone et al., 2010). Consequently, predicting the responses of forest recruitment and following successional trajectory to fire disturbance is a complex problem in heterogeneous landscapes (Goetz et al., 2007; Beck and Goetz, 2011).

Tree recruitment conditions result in two main forest successional pathways in boreal forest, being self-replacement and species-dominance relay succession (Kurkowski et al., 2008). In self-replacement succession, canopy-dominant tree species replace themselves as the post-fire dominants, implying a relatively unchanging forest composition through the time since last fire. In contrast, species-dominance relay succession is the simultaneous, post-fire establishment of multiple tree species which are not dominated by pre-fire canopy-dominant tree species, followed by later shifts in canopy dominance. These different successional pathways are important for the pattern of forest composition development, and largely influence the potential response of the boreal forests to future disturbance and climate change.

In this study, we examined how the landscape-scale variations in burn severity, environmental conditions and vegetation legacies affect patterns of post-fire tree recruitment in a mature larch forest located in Northeast China. We addressed the question of how burn severity and site environment interact to influence the species composition and density of post-fire tree recruitment, and hence the direction and rate of forest stand development. Given the important role of biological legacies (e.g. surviving trees after fire) for forest stand development following disturbance (Franklin et al., 2002), we hypothesized that the larch forest was more likely to replace itself rapidly ("replacement succession") in areas of low-severity burn, but was more likely to be replaced by an early-seral community of broadleaf trees ("relay succession") in areas of high-severity burn.

2. Methods

2.1. Study area

Our study area, the Huzhong National Natural Reserve (Fig. 1), is located in the Great Xing' an Mountains of Northeastern China (51°56′31″N 122°42′14″E to 51°17′42″N 123°18′05″E) with a total area of 167,213 ha. The study area is in the transition zone between boreal and temperate biomes, which is sensitive to climate change and susceptible to vegetation invasion from adjacent temperate forests (Makoto et al., 2007). The region is characterized by a terrestrial monsoon climate with a long, severe winter. Mean annual temperature is about −4.7 °C and mean annual precipitation is 500 mm. The region is characterized by gently sloping uplands, and the valley bottom is frequently underlain by discontinuous permafrost or seasonally frozen ground (Xu, 1998).

Much of the forested area is dominated by Gmelin's larch (*L. gmelinii*), a late successional species that is adapted to moist and cool sites. The primary deciduous broadleaf trees are white birch (*Betula platyphylla*) and two aspen species (*Populus davidiana*, *Populus suaveolens*), which are early successional species, mixed with larch in most areas owing to fire disturbance. Other species, such as Scots pine (*Pinus sylvestris* var. *mongolica*), Koyama spruce (*Picea koraiensis*), Manchurian Ash (*Fraxinus mandshurica Rupr.*) and Siberian dwarf pine (*Pinus pumila*) are interspersed with larch forest and have a small area of distribution (<2%). We focused our study specifically on mature larch forest, the dominant forest type in this region.

Fire regime in this region is characterized by frequent, surface fires mixed with infrequent stand-replacing crown fires, with fire return interval ranged from 30 to 120 years (Conard and Ivanova, 1997; Xu, 1998). A large burned patch in this region often exhibits great heterogeneity in burn severity due to the variations in site conditions and fuel loading. The combination of mixed-severity fire with spatially heterogeneous environmental conditions often results in a highly variable mosaic of tree recruitment patches with different species composition.

2.2. Sampling design

Our sampling was conducted in August of 2011 on an 8700 ha burned area in Huzhong Natural Reserve (Fig. 1). The pre-fire vegetation was mature larch forest with stand ages of at least 80 years. The mixed-severity fire, which occurred on 17th June 2000 and lasted for 7 days, generated mosaics with high- and low-severity burned patches. To test the effect of burn severity and environmental conditions on post-fire tree recruitment, we used a stratified random sampling design to select sites according to burn severity class and landscape position that encompassed the range of burn severities, site moisture and topographic positions.

Burn severity is defined as the degree of ecosystem change owing to fire disturbance (Morgan et al., 2001; Lentile et al., 2006). It is often quantified by the index of differenced normalized burn ratio (dNBR), which is particularly useful when ground assessment data are not available due to time and/or resource constraints. dNBR is widely used in mapping burn severity in various forest ecosystems (Cocke et al., 2005; Allen and Sorbel, 2008; Hoy et al., 2008; Soverel et al., 2011), and has been proved applicable to our study area by comparing dNBR values with ground burn assessment data in an adjacent recently burned fire scar (data