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Persistent effects of fire severity on early successional forests in interior Alaska

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ABSTRACT

There has been a recent increase in the frequency and extent of wildfires in interior Alaska, and this trend is predicted to continue under a warming climate. Although less well documented, corresponding increases in fire severity are expected. Previous research from boreal forests in Alaska and western Canada indicate that severe fire promotes the recruitment of deciduous tree species and decreases the relative abundance of black spruce (*Picea mariana*) immediately after fire. Here we extend these observations by (1) examining changes in patterns of aspen and spruce density and biomass that occurred during the first two decades of post-fire succession, and (2) comparing patterns of tree composition in relation to variations in post-fire organic layer depth in four burned black spruce forests in interior Alaska after 10–20 years of succession. We found that initial effects of fire severity on recruitment and establishment of aspen and black spruce were maintained by subsequent effects of organic layer depth and initial plant biomass on plant growth during post-fire succession. The proportional contribution of aspen (*Populus tremuloides*) to total stand biomass remained above 90% during the first and second decades of succession in severely burned sites, while in lightly burned sites the proportional contribution of aspen was reduced due to a 40-fold increase in spruce biomass in these sites. Relationships between organic layer depth and stem density and biomass were consistently negative for aspen, and positive or neutral for black spruce in all four burns. Our results suggest that initial effects of post-fire organic layer depths on deciduous recruitment are likely to translate into a prolonged phase of deciduous dominance during post-fire succession in severely burned stands. This shift in vegetation distribution has important implications for climate-albedo feedbacks, future fire regime, wildlife habitat quality and natural resources for indigenous subsistence activities in interior Alaska.

1. Introduction

Black spruce (*Picea mariana*) forests are the most common forest type of interior Alaska (Van Cleve et al., 1983). Wildfire, being the primary driver of secondary succession in these forests, plays a major role in shaping forest structure and composition (Chapin et al., 2006). Black spruce stands typically follow a post-fire successional trajectory of self replacement, in which the pre-fire stand dominant replaces itself shortly after fire (Van Cleve et al., 1983). Alternatively, these stands may succeed to an early phase of deciduous tree dominance that may transition back to black spruce about 100 years following fire (Chapin et al., 2006) or be maintained as a deciduous-dominated stand until the next fire (Cumming et al., 2000). Recent observations of increased frequency and extent of fires in interior Alaska (Kasischke and Turetsky, 2006; Kasischke et al., 2010) are projected to continue under a warming climate (Flannigan et al., 2005). Statistical relationships between fire size and severity suggest that increases in fire extent are likely to be associated with increases in fire severity, or biomass consumption (Duffy et al., 2007). Fire consumption of the surface organic layer is an important dimension of fire severity in black spruce forests as the total depth of burning influences carbon loss through combustion (Kasischke et al., 2005), and the depth of the residual organic layer affects post-fire processes such as permafrost thaw (Yoshikawa et al., 2003) and vegetation recovery (Kasischke and Johnstone, 2005). Although a number of factors control the burning of the surface organic layer in boreal forests, fuel moisture content is a key constraint on combustion (Miyanishi and Johnson, 2002). Spatial variations in the moisture content of surface fuels are influenced by site drainage and topography (Harden et al., 2006; Kane et al., 2007) and the species composition and bulk density of the surface fuels (Miyanishi and Johnson, 2002; Shetler et al., 2008). These spatial factors interact with annual and seasonal variations in weather and soil thaw depth to influence the patterns of soil organic layer consumption within a particular fire (Wein, 1983; Kasischke and Johnstone, 2005).

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It is well established that mineral soil seedbeds exposed by severe surface fire are favorable for the germination and establishment of a number of boreal tree species (e.g. Chrosciewicz, 1974; Zasada et al., 1983; Charron and Greene, 2002; Johnstone and Chapin, 2006; Greene et al., 2007). Shallow organic layers also support greater above ground tree biomass than deep organic layers (Lecomte et al., 2006). In particular, fire severity is strongly linked to the relative dominance of deciduous versus coniferous species as there is a strong positive relationship between the depth of the residual organic layer and recruitment of small-seeded deciduous trees such as aspen (*Populus tremuloides*) (Johnstone and Kasischke, 2005; Johnstone and Chapin, 2006; Greene et al., 2007). Initial patterns of species composition and densities established during the first few years of post-fire succession are maintained through decades of stand development (Gutsell and Johnson, 2002; Fastie et al., 2003; Johnstone et al., 2004). Therefore, the influence of fire severity on recruitment and establishment is likely to be a critical process in determining later forest composition. Shifts in forest composition from dominance by conifers such as black spruce to deciduous trees are likely to be of regional importance because of effects on land–atmosphere energy exchange (Bonan et al., 1992), nutrient cycling and plant productivity (Chapin, 2003; Diaz et al., 2004), and wildlife habitat use (Nelson et al., 2008). Consequently, it is important to understand the mechanisms that favor and maintain deciduous versus coniferous dominated successional trajectories in boreal forests.

Most studies that have investigated patterns of vegetation development in relation to fire severity have focused on the seedling recruitment and establishment phase, during the first few years of post-fire succession (e.g. Charron and Greene, 2002; Kemball et al., 2006; Johnstone and Chapin, 2006; Johnstone et al., 2010a). A gap remains in our understanding of whether the effects of fire severity on boreal forest communities are solely driven by the response of seedling recruitment to variations in organic layer depths, or are also shaped by subsequent effects of fire on soil conditions that affect the growth of established individuals. Moreover, it is not yet known whether initial effects of post-fire soil organic layer depths on seedling density and biomass will be manifested in patterns of stand productivity for several decades after fire. The maintenance of initial fire severity effects through succession could lead to the development of alternate, persistent cycles of succession at a site. For instance, if deciduous dominance in severely burned parts of the landscape is sustained until the next stand-replacing fire, asexual regeneration is likely to result in the rapid recovery of deciduous dominance after fire (McIntire et al., 2005). Thus, stable deciduous-dominated stands could develop as an alternate stable state triggered by the drastic reduction of organic mat thickness by fire in stands previously dominated by black spruce, rather than merely as a transient stage in succession (Scheffer et al., 2001). Such a shift in canopy species dominance from coniferous to deciduous over large areas and for a prolonged period of time would have a significant impact on ecosystem structure and function in boreal forests (Chapin et al., 2000; Chambers and Chapin, 2003).

In this study we examined changes in the density and biomass of canopy species during early succession within a single 1994 burn in black spruce forest and related these patterns to variations in fire severity, as indicated by post-fire organic layer depths. The 1994 burn occurred in an area of relatively homogenous topography and pre-fire stand composition, but produced great variation in post-fire organic layer depths and vegetation regrowth (Johnstone and Kasischke, 2005). To expand our inference beyond the 1994 burn, we examined soil and vegetation relationships in three other burns within the same region, in an attempt to answer the following questions: (1) do the effects of organic layer depth on post-fire species recruitment and establishment persist beyond the initial seedling recruitment phase of succession and impact stand productivity? (2) Are the patterns observed in the 1994 burn representative of other burns in the region, or do they appear to be dependent on specific site conditions?

2. Materials and methods

2.1. Study site description

This research was conducted in burned black spruce stands located near the towns of Delta Junction (63°50′N, 145°40′W) and Tok Junction (61°21′N, 142°54′W) of interior Alaska. The study region consists of a relatively flat glacial outwash plain lying between the Alaska Range to the south, and the Tanana River to the north. The climate in the study region is continental, with an average annual temperature of −2.3 °C, and monthly average temperatures ranging from −19 °C in January to 16 °C in July (Big Delta, AK for 1971–2000, Shulski and Wendler, 2007). Average annual precipitation is about 28.6 cm, most of which is received during the months May to September. Our sampling was focused in four burns—the 1987 Granite Creek burn, the 1994 Hadjukovich Creek burn, and the 1999 Donnelly Flats burn, all located in the Delta Junction study area, and the 1990 Tok burn. The 1987 fire burned 20,000 ha during the period late May to early June in 1987. The 1999 fire burned approximately 8000 ha during two weeks in June 1999 (Harden et al., 2006). The 1994 fire burned 8900 ha during the months June-September 1994 (Michalek et al., 2000). The 1990 burn was the result of a series of fires that burned 40,000 hectares during the months of July and August 1990 (Bourgeau-Chavez et al., 2007). The pre-fire stands in all the burns studied here were dominated by black spruce with a few interspersed patches of trembling aspen and white spruce (*Picea glauca*).

Soils in the Delta Junction study area consisted predominantly of silt loam overlying sand and gravel deposits, with some areas having a layer of stream-deposited cobble on top of the silt (Johnstone and Kasischke, 2005). Unburned stands adjacent to the 1987 and 1994 burns had organic layers which were 20–25 cm deep, and were dominated by feather moss. They both had well established permafrost, with active layers 20–50 cm below the organic layer (Kasischke and Johnstone, 2005). The 1999 burn occurred in an area with more complex geomorphology. The southern portion of the 1999 burn occurred on a flat plain that formed as a result of alluvial outwash. The northern portion of the burn was located on a gradually undulating till plain formed during the retreat of the Gerstle glacier; the soils of this site contained unsorted gravel till, were extremely well drained and were permafrost-free. The 1990 burn area was underlain by permafrost, and the soils were fine-textured silt and clay lying on top of coarser-grained sand and gravel (O'Neill et al., 2002).

2.2. Field measurements

Field measurements were carried out during the months June–August of 2008. Within each of the four burns, sampling sites were selected so as to encompass a range of residual organic layer depths. Sampling in each burn included sites with residual organic layer depths of >8 cm, 4–8 cm, and <4 cm. In the 1990 burn, sampling did not include sites which had <4 cm organic layer depth, as these were not encountered. Twelve sites were sampled in the 1987 burn, 22 in the 1994 burn, 14 in the 1990 burn and 12 in the 1999 burn. In the 1994 burn, 15 of the 22 plots had been previously sampled in 2002 (Johnstone and Kasischke, 2005; Kasischke and Johnstone, 2005). These plots were re-located using GPS coordinates and sampled in order to compare aspen and spruce stem densities and biomass recorded 8 years following fire (Johnstone and Kasischke, 2005) to that observed 14 years following fire. The