Case study: Changing fire regimes in boreal forests

The boreal forest, or taiga, is a region dominated by coniferous trees that occurs between 50° and 70°N and makes up approximately 29 per cent of the Earth's forested regions (Kuusela 1992; Brandt et al. 2013). These forests are characterised by a continental climate with extremely cold winters that last for six to eight months each year (mean temperatures from -10 to +2°C, with temperatures as low as -60°C). The growing season is short (100–150 days) with warmer temperatures (mean temperatures from 10 to 20°C) (Kuusela 1992). These harsh conditions have led to the development of relatively species-poor forests when compared with other biomes, with as few as one to six tree species typically present (La Roi 1967). The area is experiencing some of the fastest rates of climate change globally (an estimated 1–2.5°C warming from 1901–2012 (IPCC 2013); Chapter 2), with cascading impacts on fire regimes, permafrost, and biodiversity. In the coming century, this region is expected to continue to warm at up to twice the rate of the rest of the Earth.

Fire is the chief natural disturbance in the boreal forest (Safford and Vallejo 2019) but recent fire regimes in parts of the boreal forest are more extreme than fire regimes of the past. Many boreal species are well-adapted to fire. For instance, black spruce (*Picea mariana*) has serotinous cones that only open with exposure to high temperatures during fire. Other species like larch (Larix spp.) have much higher rates of regeneration following fires that reduce soil organic layer depths (Sofronov and Volokitina 2010; Alexander et al. 2018) or decrease competition from other plants (Mateeva and Mateev 2008). But as the climate warms and permafrost thaws, the frequency, severity and extent of forest fires is increasing across the northern-hemisphere boreal forests (Kasischke and Turetsky 2006; Liu et al. 2012; Shvidenko and Schepaschenko 2013; Ponomarev, Kharuk and Ranson 2016). The major changes in fire regimes disrupt the adaptive strategies of plants (see Figure 4.2) and can reduce ecosystem resilience and negatively affect biodiversity (Johnstone et al. 2016; Safford and Vallejo 2019; Whitman et al. 2019).

Siberian taiga

The boreal forests of Siberia are classified as either "light" or "dark" coniferous taiga. They have different species composition and are characterised by different fire regimes. Light coniferous taiga is dominated by Scots pine (*Pinus sylvestris*) and larch (primarily *Larix cajanderi* and *Larix gmelinii*), while the dark coniferous taiga is dominated by spruce (*Picea* spp.) and fir (*Abies* spp.) (Shorohova et al. 2009). Across the region, fires are caused by both lightning and anthropogenic intervention (Figure 2.1, chapter 2). However, there is a greater prevalence of lightning-caused fires in the most remote, northern latitudes, and a greater prevalence of human-ignited fires in the more populated, southern latitudes (Kharuk et al. 2011; Liu et al. 2012).

The typical fire return interval (FRI) in the light coniferous taiga varies with latitude. The historical FRI ranges from 350 to 80 years with longer FRIs in the larch-dominated forests of the north and shorter FRIs in the pine-dominated forests of the south (Kharuk et al. 2011; Ponomarev et al. 2016). Most fires in the north are stand-replacing surface fires (Krylov et al. 2014) that cause larch mortality through damage to the roots (Sofronov and Volokitina 2010; Volokitina 2015). Even-aged stands develop following these stand-replacing fires and remain even-aged up until approximately 180 years post-fire when eventual windthrow or gap dynamics influence the development of uneven-aged stands (Shorohova et al. 2009). In the southern portion of the light coniferous taiga, the larger-diameter larch trees and pine trees can withstand surface fires (Krylov et al. 2014), and fires provide an environment suitable for larch regeneration, leading to the development of multimodal stand structures (Shorohova et al. 2009). In portions of central and southern Siberia, successional dynamics also occur, with birch (Betula spp.) and aspen (Populus tremula) dominating post-fire stands and eventually being replaced by larch (Shorohova et al. 2009).

Forest regeneration in the light coniferous taiga is strongly limited by both deep soil organic layers (Sofronov and Volokitina 2010; Alexander et al. 2018) and seed source availability (Cai et al. 2013), both of which are affected by changing fire regimes. Surface fires consume a portion of the soil organic layer, with the most severe fires leading to the greatest reduction in soil organic layer depths, generally improving seedbed conditions. When seeds are not limiting, the highest levels of larch regeneration tend to occur in these areas with the highest soil burn severities (Alexander et al. 2018). Thus, changing fire regimes that lead to increase soil burn severity could promote increased larch regeneration (Alexander et al. 2018). In contrast, seed source availability becomes increasingly limiting with increases in the frequency and extent of fires. Cajander larch (Larix cajanderi) produce wind-dispersed seeds, have masting every two to three years, and do not produce a seed bank (Abaimov 2010). Therefore, successful larch regeneration following a stand-replacing fire requires wind dispersal of seeds from nearby unburnt areas, or from surviving trees within the burnt area (Greene and Johnson 1995; Figure 4.4). If fire extent is greater than the distance that larch are able to disperse, or if fire frequency becomes so short that mature larch trees are not able to grow between fires, then forest loss or declines in forest density may occur. In these cases, forests can convert to low-density forests or to grassland or shrub-dominated communities (Sofronov and Volokitina 2010; Scheffer et al. 2012; Cai et al. 2013; Alexander et al. 2018). In the southern portion of the light coniferous taiga, there is also evidence of conversion of formerly Gmelin's larch-dominated (*Larix gmelinii*) forests to increased dominance by birch (*Betula* spp.) or aspen (*Populus tremula*) due to rapid FRIs (Zyryanova et al. 2007; Cai et al. 2013). These changes in the overstory structure and composition of larch forests can have consequences for the understory plant community, as different plant communities are associated with variation in tree density, light availability, and overstory tree composition (Ma et al. 2016; Zhang et al. 2017; Kumar et al. 2018). These shifts in forest composition also have consequences for albedo (Loranty et al. 2014), above-ground carbon storage (Alexander et al. 2012), nutrient cycling (Nilsson and Wardle 2005; Campioli et al. 2009), and permafrost stability (Abaimov et al. 2002).

In the past, fires rarely occurred in central Siberia's dark coniferous taiga, with FRIs ranging from 300–900 years (Mollicone et al. 2002; Feurdean et al. 2020). When a fire does occur, it often results in high levels of tree mortality (Tautenhahn et al. 2016). The current fire regime in the dark coniferous taiga is now outside the historical range of variability of the past 5,000 years, with increases in both fire frequency and severity (Feurdean et al. 2020).

In the dark coniferous taiga, deciduous hardwoods like aspen or birch are the first species to gain dominance following fire, due to their ability to resprout from underground reserves, long-distance seed dispersal, and fast growth rates (Furyaev et al. 2001; Schulze et al. 2005; Tautenhahn et al. 2016). Evergreen conifers like *Abies sibirica*, *Abies nephrolepis*, *Picea abies*, and *Picea obovata* establish around the same time as deciduous hardwoods but have much slower growth rates and do not gain dominance until more than 70 years post-fire (Schulze et al. 2005; Shorohova et al. 2009). Seed availability is strongly limited by dispersal for *Abies* spp. and *Picea* spp., and therefore, increases in fire activity that limit the availability of nearby seed sources can spark a transition in forest successional trajectories to continued dominance and self-replacement by deciduous hardwoods following fire (Tautenhahn et al. 2016). At the landscape scale, this could lead to a decline in the evergreen conifer fire "avoider" species like *Abies* spp. and *Picea* spp., that promote cool, moist conditions in the understory (Tautenhahn et al. 2016; Feurdean et al. 2020). As with compositional and structural changes in the Siberian light taiga, the shifts in species composition that result from intensifying fire regimes could lead to changes in albedo (Loranty et al. 2014) and above-ground carbon storage (Alexander et al. 2012; Alexander and Mack 2016).

Figure 4.4. Light coniferous taiga near Chersky in the Sakha Republic, Russia, burnt in 2001, with complete tree mortality. This forest has only a single tree species – Cajander larch (*Larix cajanderi*). There is abundant regeneration of larch seedlings close to the edge of the burn, but very little regeneration further into the burnt area where seed sources are more limiting.