Influence of logging on the effects of wildfire in Siberia

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Abstract

The Russian boreal zone supports a huge terrestrial carbon pool. Moreover, it is a tremendous reservoir of wood products concentrated mainly in Siberia. The main natural disturbance in these forests is wildfire, which modifies the carbon budget and has potentially important climate feedbacks. In addition, both legal and illegal logging increase landscape complexity and affect burning conditions and fuel consumption. We investigated 100 individual sites with different histories of logging and fire on a total of 23 study areas in three different regions of Siberia to evaluate the impacts of fire and logging on fuel loads, carbon emissions, and tree regeneration in pine and larch forests. We found large variations of fire and logging effects among regions depending on growing conditions and type of logging activity. Logged areas in the Angara region had the highest surface and ground fuel loads (up to 135 t ha\(^{-1}\)), mainly due to logging debris. This resulted in high carbon emissions where fires occurred on logged sites (up to 41 tC ha\(^{-1}\)). The Shushenskoe/Minusinsk and Zabaikal regions are characterized by better slash removal and a smaller amount of carbon emitted to the atmosphere during fires. Illegal logging, which is widespread in the Zabaikal region, resulted in an increase in fire hazard and higher carbon emissions than legal logging. The highest fuel loads (on average 108 t ha\(^{-1}\)) and carbon emissions (18–28 tC ha\(^{-1}\)) in the Zabaikal region are on repeatedly burned unlogged sites where trees fell on the ground following the first fire event. Partial logging in the Shushenskoe/Minusinsk region has insufficient impact on stand density, tree mortality, and other forest conditions to substantially increase fire hazard or affect carbon stocks.Repeated fires on logged sites resulted in insufficient tree regeneration and transformation of forest to grasslands. We conclude that negative impacts of fire and logging on air quality, the carbon cycle, and ecosystem sustainability could be decreased by better slash removal in the Angara region, removal of trees killed by fire in the Zabaikal region, and tree planting after fires in drier conditions where natural regeneration is hampered by soil overheating and grass proliferation.

Keywords: light conifer stands, Pinus, Larix, fire, clear-cuts, partial logging, legal and illegal logging, fuel consumption, carbon emissions, regeneration

1. Introduction

Wildfire is one of the main disturbances in the Russian boreal zone. Currently, several million ha burn annually in Russia,
most of which is in Siberia (Vivchar 2011). Forest areas account up to 55% of the total area burned in Russia (Bartalev et al. 2012) and up to 75% in Siberia (Kukavskaya et al. 2013). The majority of fire ignitions are caused by humans (Achard et al. 2008). Wildfires in the boreal forest are projected to increase in both frequency and severity as climate changes (Flannigan et al. 2009).

In addition to fires, logging is an important disturbance factor in many forest areas of Siberia (Achard et al. 2006). Russia accounts for over 22% of the world’s forested area and 21% of its estimated standing timber volume, and its forests provide the largest land-based carbon storage in the world. Of Russia’s total forested area, 78% is located in Siberia and the Far East, and 22% is in Europe (The World Bank 1997). Although the national harvest volume is presently much lower than during Soviet times, logging activity has remained high in some areas (e.g., Angara region) with good road access. Non-recovered logged sites (areas with no regeneration) total about a million ha in Siberia (Valendik et al. 2011). These logged areas appear highly susceptible to fire due to a combination of high fuel loads and accessibility for human-caused ignition. Moreover, they typically experience higher severity fires than unlogged forests. Fire hazard in logged areas is determined by fuel types, structure, and loads: time since timber harvest, logging methods, and species composition of regeneration (coniferous versus deciduous) (Valendik et al. 2000). Fires often begin on logged sites, which have drier fuels that become readily ignitable earlier than fuels under forest canopies, and then spread to the adjacent forest (Moskalchenko 2009, Ivanov et al. 2011, figure 1). The total forest area burned in the unlogged forests surrounding these logged sites can be as much as 5–12 times the area burned in the logged areas where the ignition occurred (Ponomarev 2008, Ivanov et al. 2009).

In addition to legal cutting, illegal logging has become one of the most significant threats facing the forests of Siberia and the Russian Far East since the 1990s (Vandergert and Newell 2003). Illegal logging activities are widespread in certain regions due to proximity of the border with China, good access to transportation and wood markets, and the absence of other income sources for the local populations (Sheingauz 2004, Lankin 2005). According to official data up to 15% of the wood in Russia is harvested illegally or has doubtful provenance (www.rosleshoz.gov.ru). However, Sheingauz (2004) estimated that illegal logging in the Far East is up to 50–70% of the total timber volume. In the Primorsky krai alone, the total volume of illegally logged wood increased from 22 thousand cubic meters in 2007 to 58 thousand cubic meters in 2010 (Zherebkin 2011).

Both fire and logging result in significant forest cover loss in the boreal zone (Potapov et al. 2008). Fire consequences on logged sites vary widely depending on forest characteristics and weather conditions before and during burning (Valendik et al. 2011). Fires can result in insufficient regeneration on logged areas due to consumption of organic matter, a diminished soil seed bank, and damage to seed trees left on the logged site (Panarin 1966).

The objective of our research was to investigate the influence of logging on the effects of wildfires in light-coniferous (Pinus sylvestris, Larix sp.) forests in Siberia. We analyzed and compared the impacts of fire and logging on fuel loads, carbon emissions, and tree regeneration in three distinct regions of Siberia.

2. Study area and methods

The investigations of logging impacts on wildfire effects were carried out in three regions of Siberia: Angara, Shushenskoe/Minusinsk, and Zabaikal regions (figure 2). The Angara and Shushenskoe/Minusinsk regions are in Krasnoyarsk Krai, Central Siberia, while the Zabaikal region is southeast of Lake Baikal, East Siberia. These regions were chosen due to their high degree of disturbance by logging and high fire occurrence (Achard et al. 2006, Kukavskaya et al. 2013). In addition, studied regions represent different ecozones (Angara region—southern taiga, Shushenskoe/Minusinsk region—forest-steppe, and Zabaikal region—mountain taiga) and are characterized by different dominant types of logging activities (clear-cuts versus partial logging, legal logging versus illegal logging, etc).

The Angara region, on the northern and southern sides of the Angara River, is a hilly upland terrain. The climate of the region is continental, with the annual sum of daily mean temperatures above 10 °C (effective accumulated temperatures) ranging from 1400 to 1600 °C. The annual precipitation is 320–450 mm, with precipitation in summer 2–6 times that in winter. Snow depth is 30–80 cm and is not enough to protect soil from frost penetration. The length of the growing season is 140 days, and the average summer frost-free period is 103 days. Light-coniferous Scots pine stands (Pinus sylvestris) dominate this region, with dark-coniferous forests, dominated by spruce and fir, covering less than 30% of the territory (Central Siberia 1964).

The Shushenskoe/Minusinsk region is in the southern part of Krasnoyarsk krai, in the ‘pine and birch forest-steppe’ vegetation zone (Smagin 1980). The climate is continental with an annual temperature range of 92 °C. Annual precipitation is 300–475 mm. Relative humidity varies from 40 to 60%. Snow depth is 140–200 mm. High productivity Scots pine stands with grass and feather moss as
ground cover dominate in the region (up to 80%) (Zhukov et al. 1969).

The Zabaikal region has complex terrain and geology, with over 50 mountain ridges in the region. The distribution of the territory by altitude above sea level is: 300–600 m—12.6%, 600–1000 m—44.3%, 1000–2000 m—40.4%, and >2000 m—2.7%. The climate is strongly continental with annual temperature range of 86–88 °C. Mean annual temperature is −0.5 to −6.0 °C and the annual precipitation varies from 200 to 350 mm. Winter is characterized by deep soil frost penetration, absence of wind, and low snow cover. Larch (Larix gmelinii, L. sibirica) and Scots pine forests of low-to-moderate productivity dominate the region with litter as the dominant ground cover under the forest canopies (Encyclopaedia of Zabaykalye 2000).

In 2009–2013 we measured fire impacts on the overstory and subcanopy tree layers, young regeneration, and surface and ground biomass at 23 study areas in Scots pine and larch forests of Siberia. Four 3–4 ha sites representing different histories of logging and fire were typically examined in each study area: (i) unlogged/unburned; (ii) logged/unburned; (iii) unlogged/burned; and (iv) logged/burned. All fire sites had been burned within the previous 3 years. Fires on unlogged sites spread as surface fires, which are typical for light conifer forests in the study regions. We classified fire severity as low-to-moderate or high based on average fire char heights on the trees (Kurbatsky 1962) and the completeness of combustion of ground fuels (Rosleskhoz directive 1998). Fires were considered to be low-to-moderate severity when the char height was up to 2.0 m and ground fuels were consumed down to mineral soil on up to 60% of the burned area. Times since harvest varied from 1 to 5 years. Additionally, eight field sites that had experienced repeat burns (e.g., unlogged repeatedly burned or burned then logged then burned again) were investigated. Four of these had experienced their first fire resulting in total tree mortality more than 10 years previous to our sampling. All field sites within a study area were located in immediate proximity or within 1 km of each other in the same growing conditions, and selected stands in each site had comparable characteristics before fire and logging disturbance. In total, there were 100 individual field sites studied in different regions of Siberia (table 1).

On each field site (treatment type within a study area) a set of nine sampling triangles 5 m on a side was established (figure 3). A base transect starting at least 50 m from the road was set up perpendicular to the road access. Then three sample transects were located in different directions perpendicular to the base transect. There were three sampling triangles along each of three sample transects spaced about 50 m apart. Projected cover of each plant species was estimated inside each sample triangle. We measured dead and down woody fuels (surface fuels) on triangle sides using a line intercept method developed by Van Wagner (1968) and adapted from McRae et al. (1979). Ground fuels (lichen, moss, litter, duff) were sampled on 27 (20-cm × 25-cm) subplots within the field site (three rectangular subplots inside each sampling triangle). Litter layer consisted of foliage, bark, cones, and cured grasses that were easily recognizable. Measurements of the ground layer depth (to the nearest 0.1 cm) were taken in each subplot corner (four measurements per subplot). Estimates of fuel loads of the surface vegetation included grasses and small shrubs were also obtained from
| Study region       | Species composition\(^a\) | Age       | Basal area (m\(^2\) ha\(^{-1}\)) | Number of field sites | Partial cutting          |            |            |            |            |            |            |            |
|-------------------|----------------------------|-----------|----------------------------------|-----------------------|--------------------------|------------|------------|------------|------------|------------|------------|------------|
|                   |                            |           |                                  | Forest                | Clear-cut                | Legally logged| Illegally logged|
|                   |                            |           |                                  | Unburned | Burned | Repeatedly burned | Unburned | Burned | Repeatedly burned | Unburned | Burned | Unburned | Burned |
| Angara            | 7Pine 3Larch + Fir, Spruce | 110–200  | 30–50                            | 6            | 6       | —               | 8          | 8       | —               | —         | —         | —         | —         |
| Shushenskoe/ Minusinsk | 10Pine                      | 60–80    | 20–60                            | 6            | 6       | —               | 2          | 2       | —               | —         | 4         | 4         | —         |
| Zabaikal         | 7Pine 2Larch 1Birch        | 80–100   | 25–35                            | 8            | 11      | 4               | 5          | 8       | 4               | —         | —         | 4         | 4         |

\(^a\) In Russia, forest woody vegetation composition is determined using a 10-unit scale on the basis of the proportion of total stand volume for each tree species (for example, 7Pine means that 70% of tree stand volume is pine).
the ground sample subplots. All samples were later taken to the laboratory and oven-dried to a constant weight.

The diameter at stump height and at 1.35 m for tall regeneration and trees as well as height by species were estimated using a circular 9-m radius sample plot at each sample triangle to determine stand characteristics (figure 3). In dense stands a square plot (16 m × 16 m) was used. The center of the sample plots for measuring of tree characteristics corresponded to the center of the triangles. On logged sites stand characteristics were reconstructed for each study area on the basis of relationships between the diameter at stump height and breast height in undisturbed forest sites. Regeneration shorter than breast height was characterized inside the triangle. Data included species, stem height, and diameter at 3 dm above the soil surface. Carbon emissions from fires on both logged and unlogged sites were estimated based on fuel consumption data. Fuel consumption values were calculated by subtracting fuel loads on burned sites from those on unburned sites. Carbon content in combusted materials was assumed to be 0.5 of the absolutely dry mass (Alexeyev and Birdsey 1998).

3. Fire and logging characteristics of the study regions

The annual area burned in Krasnoyarsk krai (where the Angara and Shushenskoe/Minusinsk study regions are located) by estimates of satellite data for the last decade varied from 0.1 to 3.0 million ha (Kukavskaya et al. 2013). The area logged in Krasnoyarsk krai in 2008–2012 was 67–100 thousand ha/year. The majority of trees cut (75–90% of logged area) were coniferous species.

The Angara region is the major forest harvesting zone in Krasnoyarsk krai and one of the regions most disturbed by logging in Siberia (Achard et al. 2006). Clear-cuts dominate in the region, with individual harvest unit of up to 50 ha. The construction of the Karabula branch railway in the 1970s resulted in intensive logging on the southern side of the Angara River. At the end of the 1980s, the majority of forest resources there had been exhausted. The area on the northern side of the Angara River was cut in two stages. First, pine stands near the river were cut, and the wood was floated to mills downriver. In the addition to floating, later on in the 1990s, motor vehicles were used to transport wood to railway stations. In recent years logging activities have moved further from rivers as more roads are built. According to official data, the total area burned in Angara region from 1992 to 2006 accounted for 55% of the total area burned in Krasnoyarsk krai over this period. In some dry years the burns in the Angara region accounted for up to 90% of the total area burned in Krasnoyarsk krai. Every year, about 30 thousand ha are logged, and approximately 700 ha of logged sites are burned in wildfires (Moskalchenko 2009). Illegal logging also occurs in the Angara region. After both legal and illegal logging in this region, a large amount of slash is left onsite (figure 4(a)). Due to substantially increased direct sunlight, this slash dries quickly and increases the fire hazard on logged areas.

In the Shushenskoe/Minusinsk region of Krasnoyarsk krai, the forests grow in belts on strips of sandy alluvial soils that were left behind as rivers migrated across the landscape. These forest strips are an important intrazonal phenomenon that prevents soil erosion (Zhukov et al. 1969). Unfortunately, in the last few decades, these forests have experienced high fire occurrence (Buryak et al. 2011). Only partial cutting is allowed, as these forests belong to the protected territory (4(b)). However, if trees die due to natural disturbance (e.g. fire or insects), clear-cut logging is allowed, and this can affect large areas. For example, clear-cut logging was allowed after huge fires burned about 8.5 thousand ha in two days in 2007. Crown fires dominated the burning and resulted in total tree mortality on many sites. The fires of 2007 burned more than...
10% of the total area of forest in the Minusinsk region. Both clear-cuts and partial logging in the Shushenskoe/Minusinsk region are characterized by good slash reduction, either by mechanical removal or by piling and burning.

The Zabaikal region is characterized by one of the highest levels of fire activity in Russia. Unusually dry weather from 1995 to 2008 resulted in an increase in fire season duration (up to eight months). The Russian Fire Danger index exceeded 40 thousand (urgent fire hazard situation) in July 2003 (www. aviales.ru). According to official data, the number of fires in the Zabaikal region in the recent decade (2000–2009) increased by 310%, and the area burned increased more than 2000% from that in the 1980–1989 period. Currently, it is rare to find forests that have not burned for longer than 25 years in the southern and south-eastern parts of the Zabaikal region. Because of the large areas burned over the last decade, legal cutting is conducted mainly in areas exposed to fires. Logged areas in this region are characterized by good slash removal (figure 4(c)). While the size of individual logged areas formerly did not exceed 5 ha, recently the areas have increased to 50 ha. Currently, the area logged in the Zabaikal region reaches up to 30 thousand ha/year with coniferous species being the majority (75–95%) of trees cut. Illegal logging activities are widespread in the region due to the proximity to the Chinese border, which increases ease of transport and the market for wood products. According to official data, the tree volume illegally logged in the Zabaikal region in 2010–2012 accounted for up to 50 thousand cubic meters/year, and in reality this number could be much higher. During illegal logging, the trees with the largest diameters that have not been damaged by fire or insects are cut and only the first 4-m segment is taken, with the rest of the tree left onsite (figure 4(d)). Tree volume cut can account for 25–100% of the total stand volume that is equivalent to the 50–600 trees ha$^{-1}$ depending on the stand characteristics (tree species, age, diameter, and density). Illegal logging increases fire severity and the probability of fire spreading to tree crowns.

While in the Shushenskoe/Minusinsk region dead trees were within 1–5 years after fire due to high population density (local demand for wood is high), in the Angara and Zabaikal regions, large areas of old burned sites have accumulated because of the absence of demand for burned wood.

4. Results and discussion

4.1. Fire and logging impacts on fuel loads

The Angara region was characterized by the highest surface and ground fuel loads on logged sites (figure 5). Their loads varied from 52 to 135 t ha$^{-1}$ across the study areas with average value being 95 t ha$^{-1}$. This is 180–800% higher than ground and surface fuel loads on unlogged unburned sites, due to the large volume of woody debris (up to 85% of the total surface and ground fuel loading) left onsite after logging. Our data are comparable to those for logged areas in pine forests found by Valendik et al (2011), who estimated surface and ground fuel loads of 65–117 t ha$^{-1}$ in the same region. The variation in fuel loadings among our study areas was a function of logging methods and forest characteristics. For example, in mixed stands, usually only the best timber
Changes in surface and ground fuel loads after fires and logging in the (a) Angara, (b) Shushenskoe/Minusinsk, and (c) Zabaikal regions.

(pine and larch) are harvested, while subcanopy trees and some deciduous (Betula sp., Populus sp.) and dark-coniferous (Picea sp., Abies sp.) tree species that are typically poorer quality and in less demand are left onsite. On the contrary, in pure pine stands of the Angara region, where timber is in demand for its good quality, there was less slash on the ground. Fuel loads after fires on logged sites were 190% higher than loads on unlogged sites. The lowest fuel loads occurred in forests that had experienced high-severity fires (on the average 20 t ha\(^{-1}\)) and on repeatedly burned logged sites (up to 25 t ha\(^{-1}\)).

Undisturbed forests in the Shushenskoe/Minusinsk region were characterized by the highest ground fuel loads (40–85 t ha\(^{-1}\)) compared to other study regions (figure 5(b)). This is a result of high productivity of Scots pine stands and good fire prevention measures, which resulted in long absence of fire in some areas and accumulation of ground fuels with depths reaching as high as 25–40 cm. Also, forests found here accounted for the lowest amount of down woody debris (up to 1 t ha\(^{-1}\)) as they are generally represented by pure even-aged 60–80 year old pine stands where the active process of tree mortality is already over with almost dead no older trees. Changes in surface and ground fuel loads after partial logging were insignificant and generally attributed to a 15–30% decrease in the moss layer due to damage during cutting and increase of down woody fuels by up to 2–4 t ha\(^{-1}\).

While surface fires of low-to-moderate severity decreased fuel loads by only 10–20%, after high-severity surface-to-crown fires spread in the Minusinsk region, surface and ground fuel loads did not exceed 15 t ha\(^{-1}\). The lowest surface and ground fuel loads (up to 6 t ha\(^{-1}\)) were on logged repeatedly burned sites.

Surface and ground fuel loads in forests of the Zabaikal region varied from 20 to 55 t ha\(^{-1}\) with an average of 35 t ha\(^{-1}\) (figure 5(c)). Fuel loads averaged 30 and 16 t ha\(^{-1}\) after low-to-moderate and high-severity fires, respectively. In all cases, the largest component (up to 90%) of the total fuel load was duff and litter. Down woody fuel loads on illegally logged sites (10–25 t ha\(^{-1}\)) were up to 8 times higher than those on legally logged sites (3–12 t ha\(^{-1}\)). The lowest surface and ground fuel loads were in repeatedly burned unlogged sites where trees were still standing and in repeatedly burned logged sites (1–4 t ha\(^{-1}\)). Duff was almost absent on open repeatedly burned logged sites, and grasses accounted up to 65% of the total load for these sites. Our data on ground fuels in forests and on logged sites are in good correspondence with those of Vedrova et al. (2008), who estimated average fuel loads in undisturbed pine forests of East Zabaikal region of 34.9 in undisturbed forest and 32.9 t ha\(^{-1}\) on logged sites.

In addition to the sites presented on figure 5, we studied four unlogged sites burned 10–12 years ago in the Zabaikal region. These sites had the highest surface and ground fuel loads (on average 108 t ha\(^{-1}\)) as the trees had already begun to fall to the ground and no logging was done to remove dead stems. After repeated fires, 65–90% of the pre-fire loads were left onsite because large pieces of down woody debris were not consumed by fire.

4.2. Estimated carbon emissions on different sites in the study regions

Estimated carbon emissions from fires in unlogged forests of our study regions varied from 0.7 to 25.0 tC ha\(^{-1}\) (figure 6).
Burned moss, lichen and duff were the major (up to 95%) emissions contributors. The variation of carbon emissions estimates among study sites was due to a combination of factors such as differences in fuel types, fuel loads and fire severity (Ivanova et al. 2011). Carbon emissions in the Shushenskoe/Minusinsk region were on average 55% ($p < 0.05$) higher than in the Angara and Zabaikal regions. We attribute this to higher fuel loads available to burn in the Shushenskoe/Minusinsk region (figure 5). Our carbon emission estimates are in good correspondence with experimental data obtained in light-coniferous forests of the central and southern taiga of Central Siberia during experimental burns in the course of the FIRE BEAR project and Bor Island experiment, where estimated emissions varied from 2 to 17 tC ha$^{-1}$ depending on fire severity (FIRESCAN 1994, McRae et al. 2006, Kukavskaya and Ivanova 2006, Ivanova et al. 2007, 2011).

Carbon emissions due to fire on logged sites differed significantly among the study regions (figure 6). This is mainly due to differences in logging methods and in slash removal. Thus, the largest carbon emissions (5.0–40.9 tC ha$^{-1}$) were estimated in the Angara region where the highest fuel loads are due to poor slash removal (figures 4(a) and 5(a)). The majority of burned material in the Angara region (up to 70% of the total fuel consumption) was down woody debris. However, usually no more than 40% of the pre-fire down woody fuel loads was consumed due to the dominance of large woody pieces (more than 7 cm in diameter). Estimated carbon emissions on logged sites in Angara region were 55–560% ($p < 0.05$) higher than on unlogged sites under the same weather conditions and in the same forest types. Valendik et al (2011) estimated fuel consumption on logged sites in dark-coniferous forests of the southern taiga of Central Siberia to be 37.1–102.2 t ha$^{-1}$. Carbon emissions estimated for dark conifer forest averaged 36.5 tC ha$^{-1}$, which is about 45% higher than we observed on logged sites in light conifer forests of the Angara region. We attribute this to higher pre-fire fuel loadings (up to 219.1 t ha$^{-1}$) due to greater slash accumulation after logging in the uneven-aged dark-coniferous forests.

The Shushenskoe/Minusinsk region was characterized by the smallest amount of carbon emitted to the atmosphere due to fires on logged sites (from 0.4 to 8.2 tC ha$^{-1}$) because slash was removed after logging. Estimated carbon emissions on logged sites were 10–80% of those on unlogged sites ($p < 0.05$). The amount of carbon released during the combustion of duff consisted of up to 96% of the overall emissions. While only 0.1–2.1 t ha$^{-1}$ of woody debris was consumed, it made up to 94% of the pre-fire load due to the dominance of small branches.

In the Zabaikal region estimated carbon emissions varied from 1.2 to 16.0 tC ha$^{-1}$ and 10.0–18.5 tC ha$^{-1}$ on legally and illegally logged sites, respectively. Carbon emissions on unlogged sites were 55–90% of those on legally logged sites and 40–70% of those on illegally logged sites ($p < 0.05$). The contribution of down woody debris to the overall carbon emissions changed from 18% to 55% between legally and illegally logged sites. Carbon emissions on repeatedly burned sites in forests of the Zabaikal region, where trees continued to fall for years following the first fire event, reached 18.2–28.8 tC ha$^{-1}$, which is 4–20 times more than that on repeatedly burned logged sites (figure 6).

### 4.3. Fire and logging impacts on tree regeneration

The Shushenskoe/Minusinsk region was characterized by the highest density (33.4 thousand ha$^{-1}$) of healthy regeneration in undisturbed forests among the studied regions (table 2). This is due to favorable climate conditions for regeneration survival. Also, there is less competition from grass proliferation due to the dominance of sandy-loam soils in the region (Central Siberia 1964).

The lowest density of regeneration was found in the Zabaikal region. While a large amount of seedlings appeared there initially, many later died, and not much healthy regeneration was possible due to the extreme climate, lack of

![Figure 6.](image-url)
precipitation (especially in winter period), soil freezing and occasional rapid temperature drops in winter, and poor soil conditions.

After fires on unlogged sites, the amount of regeneration increased in all regions by 20% or more because of consumption of feather moss and lichen layers, improvement of physical and chemical soil properties, and competition reduction from living ground vegetation and the subcanopy tree layers (Sannikov 1973, Buzikin and Popova 1978). Our data on pre- and post-fire regeneration are similar to those found in the literature for the same study regions (e.g., Pobedinsky 1965, Perevoznikova 1991, Sannikov 1992).

In the Shushenskoe/Minusinsk region, pine dominated regeneration in all sites, with up to 20% of the total number of seedlings being birch and aspen. The majority of seedlings in undisturbed forests of the Angara region were dark-coniferous species, while light-coniferous trees dominated after fire impacts. In unburned and burned forests of the Zabaikal region, light-coniferous seedlings (*Pinus* and *Larix*) dominated, with deciduous species accounting for up to 30% of seedlings. On logged areas on mesic sites, deciduous species prevailed, with light-coniferous species dominating on sandy soils in the Angara and Zabaikal regions. In their studies of Scots pine regeneration in Siberia, Sokolov and Farber (2006) also found that while birch and aspen accounted for about 40% of forest regeneration on mesic sites, these broadleaf species were not an important component of post-fire vegetation succession on sandy soils. On our logged sites exposed to fire, the proportion of light-coniferous species increased (up to 20%) compared to unburned logged sites.

We observed significant (from 75 to 97%) decrease in regeneration in all regions on sites disturbed by both logging and fire. Panarin (1966) found no regeneration for the first two post-fire years on logged sites in the Zabaikal region, with seedlings densities increasing to 2 thousand ha$^{-1}$ by 6–7 years after fire. He did not consider this seedling density sufficient for successful regeneration. On our field sites, repeated fires together with logging activities also resulted in insufficient relatively low density of healthy regeneration (<1–2000 ha$^{-1}$). This was likely due to soil overheating, erosion, absence of seed sources, and proliferation of tall grasses (primarily *Calamagrostis* sp.). We observed forests converted to grassland ecosystems after repeated fires and logging on large burned areas and in drier conditions, which further inhibits forest regeneration (figure 7).

### 5. Conclusions

We have analyzed logging impacts on the effects of wildfires in light-coniferous (pine and larch) forests situated in three distinct regions of Siberia. All of these regions are highly disturbed by both fire and logging but they differ in climate and growing conditions, fuel characteristics and logging methods. We compared the impacts of fire and logging on fuel loads, carbon emissions, and tree regeneration in the Angara, Shushenskoe/Minusinsk, and Zabaikal regions. The southern taiga of Angara region is one of the most logging-disturbed regions in Siberia, where clear-cuts with a significant amount of down woody material left onsite are typical. In the forest-steppe of the Shushenskoe/Minusinsk region partial logging dominates on unburned sites, but after high-severity fires resulting in total tree mortality, clear-cuts are conducted. However, both partial and clear-cut logging activities are characterized by good slash removal. Mountain forests in the Zabaikal region experienced a significant number of fires in recent decades. A majority of these burned forests were logged after fires with good slash removal. Also, illegal logging that leaves significant woody debris onsite is widespread in the Zabaikal region. The Shushenskoe/Minusinsk region had the highest (up to 85 t ha$^{-1}$) surface and ground fuel loads in undisturbed forests, while on logged sites the highest loads (up to 135 t ha$^{-1}$) were in the Angara region. Dead down woody fuel loads were significantly lower on unburned/logged sites in the Zabaikal and Shushenskoe/Minusinsk regions (due to good slash removal) than in the Angara region. This resulted in less fuel consumption during fire. Logging in the Angara region increased fire hazard and severity and resulted in a higher amount of fuels consumed and of carbon emitted to the atmosphere (up to 560% of that from fires in unlogged forest). Partial logging in the Shushenskoe/Minusinsk region did not significantly increase fire hazard and fuel consumption during burning. While after illegal logging in the Zabaikal region down woody debris accounts for no more than 25 t ha$^{-1}$ (that

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**Table 2.** Density of healthy seedlings in different types of field sites (thousand per ha ± standard error).

| Region              | Unlogged/ unburned | Unlogged/ burned | Logged/ unburned | Logged/ burned | Logged/ repeatedly burned |
|---------------------|--------------------|------------------|------------------|----------------|--------------------------|
| Angara              | 21.2 ± 4.2         | 24.5 ± 3.8       | 44.3 ± 8.2       | 6.3 ± 1.7      | 1.5 ± 0.6                |
| Shushenskoe/Minusinsk | 33.4 ± 3.2         | 63.8 ± 9.7       | 38.2 ± 3.2       | 2.4 ± 0.4      | 0.8 ± 0.5 or none        |
| Zabaikal            | 6.1 ± 1.5          | 9.0 ± 1.4        | 5.1 ± 0.2        | 2.2 ± 0.4      | 0.4 ± 0.2 or none        |

*Figure 7.* Grassland in the Zabaikal region (51°49′; 113°09′) established on a former pine forest site after three fires (2000, 2001, and 2008) and logging (2004). Photo was taken in August 2009.
is less than 30% of that in logged site in the Angara region), it substantially increases fire severity and the probability of fires spreading to tree crowns. Carbon emissions from fires were estimated the highest (up to 41 tC ha\(^{-1}\)) on logged sites in the Angara region. While recently burned sites in the Zabaikal region do not have much fuel available to burn, older (10 or more years) burned areas are characterized by high surface and ground fuels loads due to trees falling to the ground. Here, repeated fires result in high fuel consumption and carbon emitted to the atmosphere (up to 29 tC ha\(^{-1}\) on our field sites). To decrease the negative impact of fire and logging disturbances better slash removal on logged sites of the Angara regions is required. Also, we recommend construction of firebreaks around logged areas to prevent fire spreading from logged sites to a forest. In the Zabaikal region, removal of dead trees after fires would help to prevent higher fuel consumption and carbon release during repeated fires.

We observed an increase in the density of healthy regeneration after fire in unlogged forests. However, repeated fires together with logging activities in drier conditions and on large burned sites resulted in insufficient regeneration, or even total lack of tree seedlings. Without replanting on these sites post-fire, we expect the forested area will decrease and large areas will transition to steppe ecosystems. An active fire management program is needed in Russia to preserve existing boreal forests (Bradshaw et al 2009) and to decrease risk of repeated fires, especially in southern regions where forest ecosystems are the most vulnerable.

In summary, fire and logging effects are region and site specific and depend on forest types, logging methods, and fire severity. Accurate regional assessment of fire effects on carbon cycle, fire emissions, and ecosystem recovery must include effects related to the logged sites that occupy vast areas of Siberia. Understanding current interactions between fire and logging is important for modeling ecosystem processes and for managers to develop strategies of sustainable forest management. Because Russia contains a large proportion of the world’s forests, the management and dynamics of forests of Siberia may have a substantial impact on the global carbon cycle, climate change, and the availability of forest products. Changing patterns in the harvest of wood products increase landscape complexity and can be expected to increase emissions and ecosystem damage from wildfires, inhibit recovery of natural ecosystems, and exacerbate impacts of wildland fire on changing climate and air quality.

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