Fire impact on carbon storage in light conifer forests of the Lower Angara region, Siberia

G A Ivanova¹, S G Conard², E A Kukavskaya¹ and D J McRae³

¹ V N Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, 50/28, Akademgorodok, Krasnoyarsk 660036, Russia
² Rocky Mountain Research Station, US Forest Service, Missoula, MT 22209, USA
³ Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, ON, P6A 2E5, Canada

E-mail: GAIvanova@ksc.krasn.ru

Received 24 June 2011
Accepted for publication 19 September 2011
Published 21 October 2011
Online at stacks.iop.org/ERL/6/045203

Abstract

This study focused on structural analysis of ground carbon storage following fires in light conifer stands of the Lower Angara region (Siberia, Russia). Experimental fires of varying frontal intensity were conducted at Scots pine and mixed larch forests of southern taiga. Considerable amounts of surface and ground forest fuels (21–38 tC ha⁻¹) enhanced low- to high-intensity fires. Post-fire carbon storage decreased by 16–49% depending on fire intensity and rate of spread, with depth of burn being 0.9–6.6 cm. Carbon emissions varied from 4.48 to 15.89 t ha⁻¹ depending on fire intensity and forest type. Depth of burn and carbon emissions for four major site types were correlated with a weather-based fire hazard index.

Keywords: light conifer stands, carbon storage, fire, biomass consumption, carbon emissions, forest type, depth of burn

1. Introduction

Tens of thousands of forest fires covering millions of hectares occur annually in Russia, and increases in their frequency and extent under current global warming are predicted to result in changing of forest growing conditions (Kasischke et al 1995, Soja et al 2007, Tchebakova et al 2010). Up to 60% of all forest fires in Russia occur in Scots pine (Pinus sylvestris L.) stands. Fires in larch stands account for about 15% of the total number of fires. The dominant ground covers burned are grass, lichen and green moss (Korovin 1996). Wildfires are characterized by high spatial and temporal variations in fire behavior and fire effects. Fires in southern boreal forest account for up to 39% of the total area burned in Russia and up to 70% in Siberia (Ivanova 2005). Light conifer stands dominated by Scots pine or larch (Larix sibirica Ledeb.) account for up to 90% of the total coniferous forest area of the Lower Angara region (Zhukov 1969).

Forest understory vegetation and dead plant materials are the main fuels burned in these fires, over 80 per cent of which are surface fires of varying severity and intensity. Fire rarely consumes this organic layer completely. The amount, structure and moisture content of these forest surface fuels affect fire behavior (rate of spread, fire-line intensity), and fuel consumption (Kurbatsky 1962, Stocks 1989, McRae et al 2006, Kukavskaya 2009). Fuel characteristics are determined by site conditions, forest type, precipitation pattern and fire periodicity (Kurbatsky 1970, Furyaev 1996, Ivanova 2005).

Carbon consumption estimates for wildfires in Russia that include fire weather severity and ecosystem type vary by an order of magnitude, and estimates of annual total emissions vary accordingly (Dixon and Krankina 1993, Conard and Ivanova 1997, Shvidenko and Nilsson 2000, Kajii et al 2002, Conard et al 2002, Isaev et al 2002, Soja et al 2004, Kasischke et al 2005). None of these estimates have been based on actual measurements of fuel consumption. Our study was conducted...
as a part of the FIRE BEAR (Fire Effects in the Boreal Eurasia Region) project. A major objective of the project, started in 1998, was to obtain field data on fire behavior, pre-fire fuel loads, and fuel consumption from fires in light conifer forests burned under a range of fire weather (fuel hazard) conditions. The results of fire behavior and fire effects in Scots pine forest of Siberian central taiga were already provided in several publications (McRae et al 2005, 2006, 2009, Kukavskaya and Ivanova 2006, Ivanova et al 2007).

The objective of this study was to investigate the structure and carbon biomass of surface and ground fuels and their changes after fire, as a basis for estimating carbon emissions from experimental fires in light conifer forest stands of the southern taiga Lower Angara region.

2. Study area and methods

This investigation was conducted in southern taiga Scots pine and mixed larch stands representative of the Lower Angara region, central Siberia, Russia (figures 1 and 2). The soils are illuvial-ferruginous sandy podzol at Scots pine forest and sod-carbonate soil at mixed larch forest (classification and description of Russia’s soils, Shishov et al 2004). The climate of the study region is strongly continental, with an average annual air temperature ranging –2.0–2.4 °C. Annual precipitation is 320–380 mm, with large year-to-year variations. The average summer frost-free period is 103 days (Gerasimov 1964).

Nine experimental plots ranging from 1 to 4 ha were laid out in Angara river basin: plots 1, 2, 5, 6, 7, 8, and 9 on the left bank (58°35’ N; 98°55’ E) and plots 3 and 4 on the right bank (58°42’ N; 98°25’ E) of the river. The forest characteristics on the experimental plots are summarized in table 1.

A Scots pine/lichen/feather moss stand (plots 1 and 2) is situated on a flat, step-like part of a slope. The plots have well-pronounced microrelief and nanorelief formed mainly by old and a small amount of fresh down deadwood decomposed to different rates. Trees average 90 years old and 25 cm in diameter. The stand mean height is 20 m and has a relative stocking of 0.8. The tall shrub layer is made up by willow (Salix caprea L.), dog-rose (Rosa acicularis Lindl.) and mountain ash (Sorbus sibirica Hedl.). Ground vegetation was dominated by cowberry (Vaccinium vitis-idaea L.), feather moss ssp and lichen sp. The projective coverage of the grass/small shrub layer dominated by cowberry, blueberry (Vaccinium myrtillus L.) and ledum (Ledum palustre L.) varied from 30% to 80% of the total plot area depending on stand canopy closure. Feather mosses, mainly Pleurozium schreberi (Brid.) Mitt., covered up to 100% of the plot areas. Cladonia rangiferina (L.) Web. was the major genus among lichens covering up to 40% of the plots.

A Scots pine/herb/feather moss stand (plots 3 and 4) is found on a gentle slope. This is a level site with unpronounced microrelief and nanorelief formed by old and fresh down deadwood. Trees average 100–120 years old and 30 cm in diameter. The stand mean height is 22 m and has a relative stocking of 0.8. The tall shrub layer characterized by high (0.8–0.9) density of stocking is 3.5 m high on average and contains mainly alder (Alnus fruticosa Rupr.), with few individuals of willow, dog-rose, honeysuckle (Lonicera tatarica L.) and spirea (Spiraea media Franz Schmidt). The grass/small shrub layer was dominated by small herbs. Well-developed mosses, mainly Pleurozium schreberi, formed a layer 5–7 cm high covering up to 100% of the plot areas. Lichens were dominated by Cladonia rangiferina and covered less than 1% of the plots.

A larch forest with a considerable proportion of Scots pine and herbs and feather mosses as ground vegetation (plots 5–9) is situated in the lower part of a 3°–5° slope having well-pronounced microrelief. The overstory is dominated by larch and co-dominated by Scots pine, both species aging 140 on average, with few individuals as old as 200–300 years. The subcanopy wood layer is represented by dark conifers, such as fir (Abies sibirica Ledeb.), spruce (Picea obovata Ledeb.), Siberian pine (Pinus sibirica Du Tour) and deciduous species, such as birch (Betula pendula Roth.) and aspen (Populus tremula L.). The stand canopy and subcanopy closure

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4 Surface and ground fuel includes surface vegetation (grasses, herbs, shrubs, mosses, lichens), down woody fuels, litter and duff.
A method developed by Van Wagner (1968) and adapted for this study. Quantities of dead and down woody fuels were reinventoried after each fire by remeasuring the permanent line transects. Ground fuel biomass consumption was determined using depth of burn pins that were installed near the sample grid points prior the burning (McRae et al 1979).

3. Results and discussion

The absence of fire at the experimental plots for a long time resulted in accumulation of considerable amount (21–38 tC ha$^{-1}$) of surface and ground carbon storage (table 2). Duff and down tree branches and stems accounted for the highest biomass percentages (34–82% and 13–53%, respectively) both in Scots pine and larch stands. Litter accounted for up to 4% and small shrubs and grasses never exceeded 1% of the total surface and ground carbon storage.

The average depth of burn ranged from 0.9 to 6.6 cm depending on fire severity. The biomass consumed by fire calculated based on depth of burn as the difference between the pre- and post-fire biomass ranged from 4.48–15.89 tC ha$^{-1}$. Lichens and litter were burned completely, >0.5 cm diameter

### Table 1. The characteristics of forest on the experimental plots.

| Plot # | Tree species composition by layers$^a$ | Ground vegetation | DBH (cm) | Height (m) | Relative stocking$^b$ | Site quality$^c$ | Regeneration ($\times 1000$/ha) |
|--------|--------------------------------------|--------------------|----------|------------|----------------------|----------------|-----------------------------|
| 1      | 10SP                                 | Lichen/feather moss| 24       | 18         | 0.90                 | III            | 72.0                        |
| 2      | 10SP                                 | Lichen/feather moss| 26       | 22         | 0.70                 | III            | 41.0                        |
| 3      | 10SPC + L                            | Alder/cowberry/feather moss | 32       | 21         | 0.60                 | III            | 20.0                        |
| 4      | 10SP + L, single A                   | Feather moss/small grasses | 28       | 22         | 0.80                 | III            | 27.0                        |
| 5      | I 5L5SP                              | Herb/feather moss   | 26       | 26         | 0.30                 | II             | 26.0                        |
| 6      | I 6L3SP1F + B, A                    | Sedge/feather moss  | 30       | 27         | 0.35                 | II             | 22.0                        |
| 7      | I 5L5B                               | Herb/feather moss   | 36       | 26         | 0.40                 | III            | 5.6                         |
| 8      | I 5L4SP1S + A                       | Herb/feather moss   | 36       | 26         | 0.30                 | III            | 6.6                         |
| 9      | I 9L1S                               | Herb/feather moss   | 44       | 26         | 0.30                 | II             | 9.2                         |

$^a$ In Russia, forest woody vegetation composition is determined using a 10-unit scale on the basis of tree species volume. SP is Scots pine, L is larch, SibP is Siberian pine, F is fir, B is birch, S is spruce, A is aspen. I—overstory, II—subcanopy layers.

$^b$ Relative stocking is the ratio between basal areas of individual stands and reference data for fully stocked stands.

$^c$ Forest vegetation index that shows stand productivity and depends on soil and climatic conditions. It is determined on the basis of average age and height of dominant species. In Russia, there are five classes of site quality; the higher the number, the less productive the forest (Anuchin 1982).
Forest types of interest (figure 4) due to structural variability conditions varied notably among the larch and Scots pine include needle and small twig consumption at tree canopy. And 16–23% for moderate- and low-intensity fires) and did not larch plots, these values appeared to be lower (47% for high- and 42% of the biomass, respectively, on Scots pine plots. On classes, and forest floor organics was partially consumed. Fires of high-to-moderate- and low-intensity consumed up to 50% and 42% of the biomass, respectively, on Scots pine plots. On larch plots, these values appeared to be lower (47% for high- and 16–23% for moderate- and low-intensity fires) and did not include needle and small twig consumption at tree canopy. The dependence of ground fuel depth of burn on weather conditions varied notably among the larch and Scots pine forest types of interest (figure 4) due to structural variability of ground vegetation and forest type-induced differences in its rate of drying. This dependence was described by a straight-line function (the correlation coefficients were reliable and ranged 0.75–0.91). Burning biomass is a source of heat and determines fire effects. Heat released during biomass burning directly depends on the amount of biomass consumed: the higher the biomass amount consumed by fire, the greater the heating of vegetation and soil. In addition, biomass consumption due to fire substantially affects the carbon budget of forest ecosystems (Vedrova et al 2002, Wirth et al 2002, Ivanova et al 2007, Kukavskaya 2009).

In our experiments, carbon emission from combustion of surface and ground fuels was 11.17–15.89 t ha⁻¹, 6.26–10.48 t ha⁻¹, and 4.48–9.10 t ha⁻¹ for fires of high, moderate, and low intensity, respectively (table 3), burning mosses, lichens, duff and down woody fuels being the major emission contributors.

In the southern taiga light conifer stands of interest, carbon emission from low-intensity fire (<2000 kW m⁻¹) was on
Figure 5. Relationship of fire caused carbon emission with weather conditions (PV-1) in Scots pine and mixed larch stands of central Siberia.

Table 3. Carbon emission (t ha$^{-1}$) from combustion of surface and ground fuels in light conifer forest stands.

| Plot # | Fire intensity | Grasses and small shrubs | Litter | Down woody fuels | Mosses, lichens and duff | Total |
|-------|----------------|--------------------------|--------|------------------|-------------------------|-------|
| Scots pine stands |
| 1     | Moderate       | 0.16                     | 0.80   | 0.91             | 8.61                    | 10.48 |
| 2     | High           | 0.28                     | 0.55   | 1.11             | 9.23                    | 11.17 |
| 3     | Low            | 0.18                     | 0.94   | 1.87             | 5.95                    | 8.94  |
| 4     | Low            | 0.27                     | 0.91   | 2.74             | 5.18                    | 9.10  |
| Larch mixed-wood stands |
| 5     | High           | 0.13                     | 1.12   | 7.74             | 6.90                    | 15.89 |
| 6     | Low            | 0.13                     | 1.31   | 1.15             | 2.01                    | 4.60  |
| 7     | Low            | 0.16                     | 1.05   | 1.32             | 2.72                    | 5.25  |
| 8     | Low            | 0.16                     | 0.70   | 1.45             | 2.17                    | 4.48  |
| 9     | Moderate       | 0.17                     | 0.75   | 1.11             | 4.23                    | 6.26  |

average 25% greater as compared with the central taiga Scots pine stands, where it was 4.80 t ha$^{-1}$. Carbon emission from high-intensity fire (>4000 kW m$^{-2}$) in the southern stands was on average 12% less than in central taiga Scots pine stands (13.53 t ha$^{-1}$ versus 15.40 t ha$^{-1}$) (McRae et al 2006, Ivanova et al 2007). Carbon losses due to fires in Alaskan boreal forests exceed our data by 3–7 times depending on season of burning (Turetsky et al 2011). Our experimental data on carbon emissions due to burning of surface and ground fuel material are comparable with those for Canada (de Groot et al 2009). However, in boreal forests of North America the dominant fire type is stand-replacing crown fires (Flannigan et al 2003) that consume crown fuels resulting in an increase of total carbon emissions.

A close correlation was found between carbon emission from fire and the Russian Fire Danger Index (correlation coefficients are 0.67 and 0.81 for pine and larch stands, respectively) (figure 5).

4. Conclusion

Our investigation showed that the pre-fire carbon storage accumulated in surface and ground fuels in southern taiga light conifer forests of central Siberia ranged from 21–38 tC ha$^{-1}$ among the experimental plots. The biomass consumption in light conifer stands of the Lower Angara region was controlled by fire severity. Fire decreased biomass by 16–49% depending on fire intensity. Carbon emissions ranged from 4.48 t ha$^{-1}$ from low-intensity fire to 15.89 t ha$^{-1}$ from high-intensity fire. Climate warming resulting in changing fire regimes would cause an increase in fire severity, area burned and amount of carbon emitted to the atmosphere.

Acknowledgments

The authors gratefully acknowledge financial support for this research from the National Aeronautics and Space Administration (NASA), the Land Cover Land Use Change (LCLUC) Science Program, the Russian Academy of Sciences, Siberian Branch, the Russian Fund of Fundamental Investigation, and International Science and Technology Center (project #3695).

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