

## Satellite monitoring of the wildfire in Siberia and fire emissions estimation

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**Abstract.** Using the threshold-based method for classifying thermally active pixels on Terra and Aqua / MODIS images we identified categories of combustion intensity for different parts of fires considering main types of forest stands in Siberia. The threshold values and the corresponding fire categories were determined based on the statistical values of the Fire Radiative Power (FRP) of the fire pixels. Using the long-term fire database (2002–2019, Sukachev Institute of Forest SB RAS, Federal Research Center KSC SB RAS), we obtained instrumental estimates of direct fire carbon emissions for the territory of Siberia. Direct emissions from fires varied from minima values of 20–40 Tg/year (2004, 2005, 2007, 2009, 2010) to maxima values of 200 Tg/year during the 2012 and 2019 extreme fire seasons. Preliminary estimation on carbon emission for 2020 is 180 Tg C/year. Fires in the larch forests of the flat-mountainous taiga region (Central Siberia) made the greatest contribution (more than 65 %) to the total emissions. Estimates of the probable level of emissions are provided considering various IPCC climatic scenarios. Considering RCP2.6, RCP4.0 and RCP8.5 climatic scenarios it is possible that the direct fire emissions will increase more than twice until the end of the XXI century. At the same time extreme climatic scenarios (RCP8.5) can result in a tenfold increase in emissions.

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### 1. Introduction

Wildfires in the boreal forests of Siberia are responsible for the major part of annual burned area in Russia [1, 2]. Periodic wildfires are a permanent, natural process of Siberian forests [3]. Although, in recent decades, elevated air temperatures in Siberia have led to an increase in wildfire frequency, burned area, and carbon emissions [2, 4, 5].

Fire emissions annually affect air quality over vast territories of Siberia and Asian part of Russia. Estimates of carbon emissions in Siberia are discussed for a long time [6–8]. However, there are some limitations in the accuracy of emission estimates. It is necessary to take into account the differences in the fire behavior, and therefore to calculate the emissions from various parts of burnt area separately, which could characterize the variety of combustion intensities [9, 10, 13]. With currently available satellite data it is possible to obtain fairly accurate information on the fire areas, including variations in the combustion intensity [11, 12]. There are great prospects for the use of such information for the purpose of assessing emissions.

The extreme estimates for the direct fire emissions from the fires in Siberia are  $>500$  Tg C/year [6], which seems to be overestimated, comparing to data for Canada ( $>300$  Tg C/year) [14] as well as averaged data for Siberia (120–140 Tg/year) [7]. Although, taking into account climatic changes, these estimates in Siberia are predicted to be up to 240 Tg/year in the second half of the XXI century [15]. Currently, the problem of quantitative estimates of fire emissions is not completely solved.

The aim of this study was to use available satellite data on wildfires in Siberia and Fire Radiative Power (FRP) measurements to quantify direct wildfire carbon emissions. It was proposed to classify the burned areas according to the energy released and the intensity of the wildfires. The following aspects of the problem were considered: (1) classification of burned areas according to the fire intensity in terms of FRP and intensity; (2) classification of burned areas by dominating tree stands; (3) direct fire emissions evaluation and forecasting of emission level under current climate trends in Siberia.

## 2. Data and methods

### 2.1. Study area

The territory of Siberia encompasses about 970 million ha. The forested area of Siberia is estimated to be about 600 million ha. The majority of Russian forests ( $\sim 70\%$ , including sparse stands) located in Siberia. The major Siberian forest types are formed by larch (*Larix sibirica*, *L. gmelinii*, and *L. cajanderi*), Scots pine (*Pinus sylvestris*), dark needled conifers (*Pinus sibirica*, *Abies sibirica*, *Picea obovata*), birch (*Betula spp.*), and aspen (*Populus tremula*). Forests dominated (based on data from Vega-service, <http://pro-vega.ru/maps/>) by larch range over an area of 270–300 million ha; an area of Scots pine stands extends over 120 million ha, dark coniferous stands occupy 100 million ha, and mixed forest covers about 77 million ha.

### 2.2. Data on wildfires and fire characteristics

We considered all forest fires detected in Siberia ( $50\text{--}67^\circ\text{N}$  and  $60\text{--}150^\circ\text{E}$ ) from 2002 to 2019. We used our own fire database collected using Terra and Aqua/MODIS imagery in the V. N. Sukachev Institute of Forest (Krasnoyarsk, Russia) [16]. This wildfire database was generated using a multistep process, including: (1) contextual active fire detection; (2) the creation of fire polygons from adjacent fire pixels; and (3) the correction of resulting polygons. The processing chain for MODIS data was based on the approach of Giglio [17], incorporating several adjustments in background characterization and detection probability estimation [18]. The algorithm used by the Institute of Forest differs mainly in its approach of aggregating fire detections into fire polygons and subsequent use of the correction procedure. This correction procedure was based on comparisons between the burned areas measured using low-resolution data (MODIS) and moderate resolution data (Landsat) for the test sample of fires and obtaining the linear regression equations for several fire size classes. Then, these equations were used to correct each fire polygon in the database [16].

Active fire products for MODIS (MOD14/MYD14) also containing estimates of fire radiative power (FRP) were acquired from the Level-1 and Atmosphere Archive and Distribution System (LAADS) Distributed Active Archive Center (DAAC) website (<https://ladsweb.modaps.eosdis.nasa.gov/>).

Air temperature and precipitation data for the Siberia were taken from the Climatic Research Unit (<http://www.cru.uea.ac.uk>), the Weather Archive (<http://rp5.ru>), and the National Climatic Data Center (NCDC Climate Data) (<http://www7.ncdc.noaa.gov/CDO/cdo>). Temperature anomalies over Siberia were evaluated from database of NOAA National Center for Environmental Prediction (NCEP) Reanalysis Products (NCEP Reanalysis Derived data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from <https://psl.noaa.gov/>).

### 2.3. Methods

Firstly, we analysed spatial distribution of wildfires by Siberian forest types. Geospatial tools of GIS were used to perform the intersection procedure for vector layers of wildfires and forests.

Next, we classified the fire pixels into three categories of FRP using thresholds, which were calculated based on statistics of fire radiative power distribution (FRP mean value and standard deviation). Three categories of fire pixels were distinguished as follows: fires of low FRP ( $\text{FRP} < \text{FRP}_{\text{mean}} - \sigma$ ), fires of medium FRP ( $\text{FRP}_{\text{mean}} - \sigma \leq \text{FRP} < \text{FRP}_{\text{mean}} + \sigma$ ), and fires of high FRP ( $\text{FRP} \geq \text{FRP}_{\text{mean}} + \sigma$ ) [5]. We distinguished areas of fires corresponding to low, medium,

and high FRP. As it was shown [19], the biomass combustion rate is linearly related to FRP. So, an assessment of the combusted biomass and direct emissions was performed by accounting for variations in the combustion characteristics within each fire polygon.

The combusted biomass and carbon emissions were calculated using the approach of Seiler and Crutzen [20], taking in account the combusted biomass (kg), the burned area ( $m^2$ ), the coefficient of combustion completeness ( $\beta$ ), the pre-fire fuel load ( $kg/m^2$ ), and the emission factor (g/kg). The pre-fire fuel loads ( $B = 1.38\text{--}5.4\text{ kg/m}^2$ ) for the sub-regions of Siberia were summarized from published data [8, 21, 22]. We used generalized data on on-ground fuels in forests with prevalence of larch, pine, dark coniferous and deciduous stands as the input parameter. The parameter of burned area ( $A, m^2$ ) was represented as the sum of the areas having various FRP values:

$$A = \sum_i A_i(\text{FRP}_i).$$

The value of  $\beta$  for each fire part was determined according to the FRP category  $\beta = \beta_i(\text{FRP}_i) = 0.35\text{--}0.60$ . The coefficient  $\beta$  was selected as 0.35–0.40 for low FRP, 0.40–0.45 for medium FRP, and 0.45–0.60 for high FRP. Field measurements indicated 0.7–1.3  $kg/m^2$  of ground layer fuel in post-fire plots of larch and pine tree stands in the forests of Siberia. We considered also various empirical estimates of forest fuels combusted during wildfires of various intensities: 0.11–0.97  $kg/m^2$ , 0.86–2.15  $kg/m^2$ , and 2.25–5.36  $kg/m^2$ , respectively, for low-, medium-, and high-intensity fires. All these parameters were summarized from field data [6, 8, 9].

### 3. Results AND discussion

#### 3.1. Wildfire occurrence in the main forest types of Siberia

Wildfires are the most important and permanent driver of forest dynamics in Siberia, but their impacts vary between different forest types. Maximal burning rates are observed within larch-dominated and Scots pine stands, while the lowest rates occur in dark needle coniferous stands (table 1).

**Table 1.** The percentage of total fire occurrences, burned area, and relative burned area (RBA) by Siberian forest types.

Forest type	Number of fires, % of total	Burned area, % of total	RBA, %
Dark needle coniferous ( <i>Pinus sibirica</i> , <i>Abies sibirica</i> , <i>Picea obovata</i> )	7.97	5.68	0.30
Larch ( <i>Larix sibirica</i> , <i>L. dahurica</i> , <i>L. cajanderi</i> )	41.2	65.15	1.13
Scots pine ( <i>Pinus sylvestris</i> )	26.17	17.95	0.78
Deciduous ( <i>Populus tremula</i> and <i>Betula</i> spp.)	22.26	10.15	0.50
Other types/Tundra	2.48	1.07	0.01

These assessments made using satellite data are similar to published data for burned areas in larch forests (up to 50 % of the total), dark coniferous (about 5 %), light coniferous, and deciduous (18 and 19 %, respectively) [6, 22].

Fires in the larch forests of the flat-mountainous taiga region (Central Siberia) made the greatest contribution (more than 65 %) to the total annual burned area. It is the reason for the highest value of direct emissions to originate from the fires in larch forests (see table 3).

#### 3.2. FRP data and the ratio of burned areas

Most of the MODIS fire pixels (up to 88 % of the total) had FRP values below 50  $MW/km^2$ . The mean FRP value at the 95 % confidence level was 37.4  $MW/km^2$  ( $\sigma = 17.1\text{ MW/km}^2$ ). Two threshold values were defined to separate fire pixels by FRP categories: 20.3  $MW/km^2$  and 54.5  $MW/km^2$ . According to the FRP categories, the proportion of low, medium, and high intensity of burning was calculated for different forests of Siberia in terms of dominant tree species (table 2).

An instrumental-based estimation of the areas burned by fires of various intensities in Siberia was performed for the first time. In previous studies, empirically obtained data indicated that the burned areas corresponded to 22, 38.5, and 38.5 % for low-, medium-, and high-intensity fires, respectively

[6]. Previously, we estimated [23] high-intensity crown fires part to be about 8.5 % of the total burned forested area in Siberia.

**Table 2.** Forest areas burned by fires of various intensities in 2002–2019.

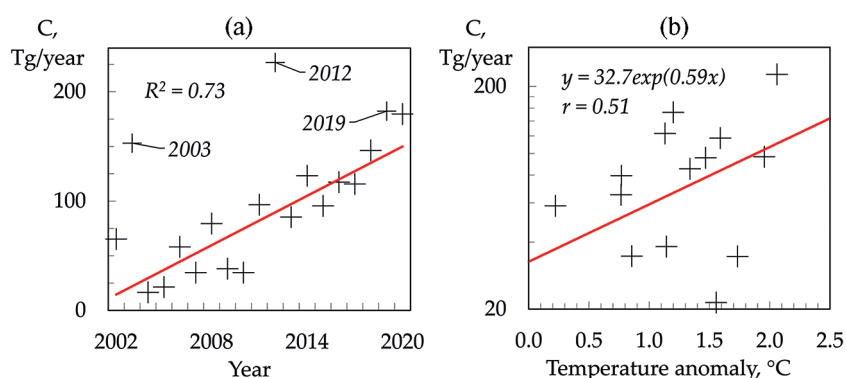
Dominant tree species	Portion of the total burned area		
	Low intensity, %±SD	Medium intensity, %±SD	High intensity, %±SD
Larch	42.3±15.8	46.0±11.5	11.7±7.9
Pine	43.7±15.5	44.6±11.3	11.7±8.5
Dark coniferous	47.3±12.8	41.7±8.0	10.9±7.1
Deciduous	43.6±17.3	42.9±13.2	13.4±7.2
For all types	47.0±13.6	42.5±10.5	10.5±6.9

### 3.3. Direct carbon emissions

The calculated estimates (table 3) of carbon emissions from Siberian fires were about  $85 \pm 20$  Tg/year. Between 2002 and 2019 direct fire emissions varied from the minimum values of 20–40 Tg/year (low fire danger scenarios of 2004, 2005, 2007, 2009, 2010) to a maximum of >200 Tg/year in the extreme fire danger seasons (2012 and 2019). This is significantly lower than the previous extreme assessments for Siberian fires, which were from 116 Tg C/year in 1999 up to >500 Tg C/year in 2002, obtained by Soja et al. [6]. Current estimates are significantly lower (~20 %) than estimates ( $120 \pm 25$  Tg C/year) [5] that do not take into account the fire intensity variety.

**Table 3.** Carbon emission estimates per year and per ha in Siberia for moderate and extreme fire seasons by forests.

Tree stand type	Fire season type				Range of annual emission, % of min and max
	Moderate		Extreme		
	$\times 10^{12}$ g C/year	$\times 10^6$ g C/ha	$\times 10^{12}$ g C/year	$\times 10^6$ g C/ha	
Larch	42.9	15.5	52.0	18.8	51.6–62.4
Scots pine	11.0	16.7	11.8	18.0	13.2–14.2
Dark needle coniferous	1.9	12.7	3.1	20.4	2.3–3.7
Deciduous/mixed	3.8	13.7	4.7	17.2	4.5–5.7



**Figure 1.** Variations of direct carbon emissions from Siberian fires in the time interval 2002–2020: (a) trend based on the multi-year series; (b) in relation with air temperature rising. Preliminary estimation on carbon emission for 2020 is 180 Tg C/year.

Long-term dynamics of carbon emissions shows a positive trend (Figure 1a) corresponding to increase of forest burning in Siberia [1, 2]. Thus, considering the positive trend of air temperature [2], we should expect a correlation between the fire emissions and temperature increase. Current relation (Figure 1b) could be used for forecasting of emission level under available climate scenarios [24].

In case of RCP2.6 scenario the average air temperature increases by 0.3–1.7 °C; in case of “harsh” scenario (RCP8.5) the temperature will rise by 2.6–4.8 °C. Thus, according to current trends

(Figure 1b), the fire emissions in Siberia may reach 220–700 Tg C/year at the end of XXI century. While extreme value of 2300 Tg C/year was evaluated for the conditions of “harsh” scenario.

#### 4. Conclusions

We performed a classification of fire areas, taking into account the combustion intensity according to the FRP measurements. It was quantitatively established that in Siberia low-intensity fires were responsible for  $47.04 \pm 13.6\%$  of the total annual burned area, medium-intensity fires for  $42.46 \pm 10.50\%$ , and high-intensity fires for  $10.50 \pm 6.90\%$ . For the last two decades, the value of direct emissions from the fires in Siberia was  $85 \pm 20$  Tg C/year on average.

The range of direct fire emissions was 20–250 Tg C/year. The direct emissions varied from 20 Tg/year in moderate fire seasons up to  $>200$  Tg/year in the extreme fire seasons. Sporadic maxima were fixed in 2003 ( $>150$  Tg C/year), in 2012 ( $>220$  Tg C/year) and in 2019 ( $>190$  Tg C/year). Preliminary estimation on carbon emission for 2020 is 180 Tg C/year. Fires in the larch forests of the flat-mountainous taiga region of Siberia made the greatest contribution (50–62 %) to the total emissions.

According to the current temperature trend as well as to the current forest burning trend in Siberia, the fire emissions may double (220 Tg C/year) or even increase by an order of magnitude ( $>2000$  Tg C/year) at the end of the XXI century depending on IPCC scenario (RCP2.6, RCP4.0, and RCP8.5).

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