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Remote Sensing Data for Calibrated Assessment of Wildfire Emissions in Siberian Forests †

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Abstract: This study was carried out for Siberia using Terra/Modis satellite data (2002–2016), data of ground surveys on burned areas of different ages, long-term meteorological information, and numerical simulation results. On the basis of meteorological and wildfire databases, we evaluated the probability (~18%) of an extreme fire danger scenario that was found to occur every 8 ± 3 years in different parts of the region. Next, we used Fire Radiative Power (FRP) measurements to classify the varieties of burning conditions for each wildfire in the database. The classification of the annually burned forest area was obtained in accordance with the assessments of burning intensity ranges categorized by FRP. Depending on the fire danger scenario in Siberia, 47.04 ± 13.6% of the total wildfire areas were classified as low-intensity burning, 42.46 ± 10.50% as medium-intensity fire areas, and 10.50 ± 6.90% as high-intensity. Next, we calculated the amount of combusted biomass and the direct emissions for each wildfire, taking into account the variable intensity of burning within the fire polygons. The total annual emissions were also calculated for Siberia for the last 15 years, from 2002 to 2016. The average estimate of direct carbon emission was 83 ± 21 Tg/year, which is lower than the result (112 ± 25 Tg/year) we obtained using the standard procedure.

Keywords: wildfire; Siberia; area burnt; remote sensing; intensity; fire radiative power; emissions

1. Introduction

According to long-term satellite observations, there is a significant trend of increase in the number of wildfires and in the extent of burnt area in Siberian forests [1]. Wildfires in the boreal forests of Siberia are responsible for 70–90% of annual burnt area in Russia. Direct wildfire carbon emissions in Siberia are currently 120–140 Tg/year [2,3], and this value can double up to 240 Tg/year, according to forecasts for the second half of the 21st century [4]. Currently, the problem of quantitative estimates of fire emissions is not completely solved. A number of studies discuss both the available emission estimates [3,5–8] and the factors that influence the accuracy of such numerical simulations [2,9–11]. The main problem of such estimates is the consideration of the variations in the combustion parameters that occur even within the same fire polygon. To solve it, a remote sensing approach for wildfire's energy estimate [12–14] could be used.

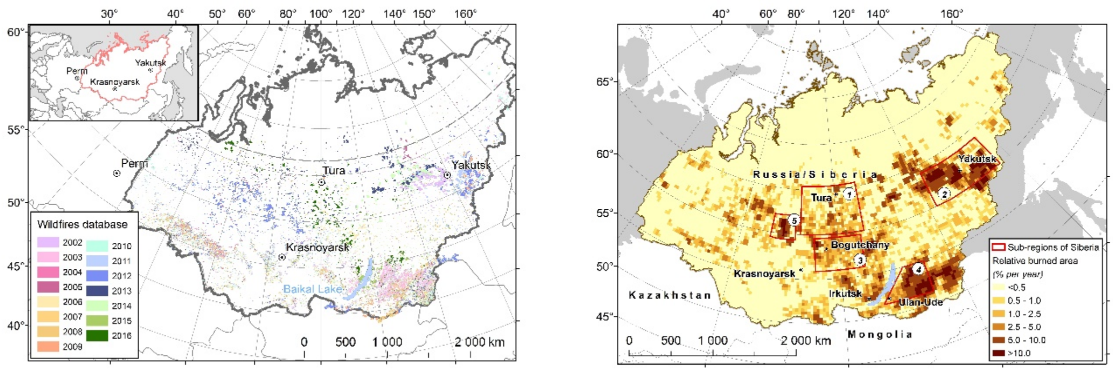
The aim of this study was to implement available satellite data on wildfires in Siberia and Fire Radiative Power (FRP) measurements [12] to quantitative estimate direct wildfire emissions. It was proposed to classify the burned areas according to the energy released and the intensity of the wildfires.

In this regard, the following aspects of the problem were considered: (1) analysis of the fire characteristics in relation to fire development scenarios; (2) classification of burned areas according to the estimation of the fire intensity; (3) estimation of combusted forest fuels and direct fire emissions and accuracy analysis.

2. Experiments

2.1. Study Area

The territory of Siberia covers 1000 MHa with a forested area of about 600 MHa. Forests dominated by larch (*Larix sibirica*, *Larix gmelinii*) range over an area of 270–300 MHa; an area of Scots pine (*Pinus sylvestris*) stands extends over 120 MHa, dark coniferous stands occupy 100 MHa, and mixed forest covers about 77 MHa. We considered all forest fires detected in Siberia (50°–67° N and 60°–150° E) from 2002 to 2016 (Figure 1a). The data on forest types was derived from reference [15].



(**a**) (**b**)

Figure 1. Study area: (**a**) Spatial distribution of wildfires in Siberia in 2002–2016. Wildfires in areas >1500 Ha are shown on the map; (**b**) Relative burned area (% per year). Sub-regions of Siberia: (1) Central Siberian flat taiga region; (2) Eastern Siberian taiga–permafrost region; (3) Angara river forest region; (4) mountain and permafrost forest region of Transbaikal; (5) Central Siberian plain–taiga region.

2.2. Data

Air temperature and precipitation data for the whole 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).

Active fire products of Modis data for fire detection (MOD14/MYD14) with estimates of fire radiative power (FRP) [16,17] were acquired from the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC) website (https://ladsweb.modaps.eosdis.nasa.gov/). We used also our own wildfires data collected using Terra/Modis in the V.N. Sukachev Institute of Forest (Krasnoyarsk, Russia) [18]. In the analyses, we used statistically significant wildfire samples (7394 fires).

2.3. Methods

Firstly, we analyzed fire danger seasonal statistics for different sub-regions of Siberia for the last N = 30 years, using meteorological daily data on temperature, precipitation, dew point temperature along with the data on relative burned area (RBA, %) per forested area per year. The probability of extreme fire danger scenario P{E} (according to weather conditions and wildfire numbers) was estimated as P{E} = N_E/N, where N_E is the number of extreme fire seasons occurred in a local area. The minimum and maximum probabilities for sub-regions (Figure 1b) are summarized in the Table 1.

Table 1. Fire danger scenario statistics for Siberia. P{E}: probability of extreme fire danger scenario, RBA: relative burned area.

N	Scenario	P{E} (Min–Max)	Period, Years	Relative Burned Area (RBA), % (Min–Max)
1	I (extreme)	0,18–0.20	8 ± 3	4.5–14.5
2	IIa (moderate/spring)	0.24–0.57	4 ± 1	0.5–1.5
3	IIb (moderate/summer)	0.24–0.38	3 ± 1	1.0–4.0
4	III (low)	0.19–0.48	4 ± 2	0.01–0.3

Next, we classified the fire pixels into three categories of FRP using thresholds calculated on the basis of the statistical parameter of fire radiative power distribution. All fire pixels were separated into three categories: category I corresponded to the low FRP fires (FRP < FRPmean − σ), category II to medium FRP fires (FRPmean − σ < FRP < FRPmean + σ), and category III to high FRP fires (FRP > FRPmean + σ), where FRPmean and σ are FRP mean value and standard deviation, respectively. According to these categories, we distinguished areas of fires corresponding to low, medium, and high FRP. As it was shown in reference [19], the biomass combustion rate is linearly related to FRP. So, a refinement of the combusted biomass and direct emissions estimates was performed by accounting for variations in the combustion characteristics within each fire polygon. The combusted biomass and carbon emissions were calculated as [20]:

$$M = A \times \beta \times B, \tag{1}$$

$$C = A \times \beta \times B \times CE \tag{2}$$

where M is the combusted biomass (kg), C is the carbon emissions (g), A is the burned area (m^2), β is the combustion completeness, B is the pre-fire fuel load (kg/m^2), CE is the emission factor (g/kg).

The pre-fire fuel loads (B = 1.38–5.4 kg/m^2) for the sub-regions of Siberia were summarized from published data [21,22]. At the stage of numerical modeling, 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 non-stationary model of surface fire was simulated using the author's software "SigmaFire" [23].

In Equations (1) and (2), the parameter A(m^2) was represented as the sum of the areas having various FRP values:

$$A = \sum_i A_i(FRP_i), \tag{3}$$

For each area $A_i(FRP_i)$, an estimate of combusted forest fuels was made using Equation (1), taking into account the variable values of combustion completeness β. The value of β for each area was determined according to the FRP category and based on the model values $\beta = \beta_i(FRP_i)$ = 0.35–0.60 [11,19].

We compared our results with the estimates obtained using the original approach (1):

$$\Delta M_{rel} = 100 \times (M - M_d)/M, \tag{4}$$

where ΔM_{rel} is the relative difference, M is the amount of combusted fuels calculated using approach (1), M_d is the amount of combusted fuels calculated using burned area separation, considering Equation (3).

Finally, we estimated direct carbon emissions (C) and relative difference according to Equation (4).

3. Results and Discussion

3.1. Fire Danger Scenarios and Relative Burned Area

The proportion of forested area burned with low, medium, or high FRP strongly depended on the fire danger scenario. Firstly, we obtained the spatial distribution of the relative burned area for Siberia by summarizing data on total burned areas in the last two decades (Figure 1b). The characteristics of the fire season scenarios were also evaluated (Table 1). The annual relative burned area varied from 0.3% to more than 10% of the total forested area. The average for Siberia was 1.5%, which was three times greater than the average annual burned area (0.56%) in western Canada [22,24].

3.2. FRP Data and 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 (σ = 17.1 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. On the basis of the FRP categories, we classified the fire polygons into areas of low, medium, and high intensity of burning (Table 2).

Table 2. Forest areas burned by fires of various intensities in 2002–2016.

Dominant Tree Species	Portion of the Total Burned Area						Number of Samples
	Low Intensity		Medium Intensity		High Intensity		
	%	σ	%	σ	%	σ	
Larch	42.28	15.8	46.04	11.48	11.68	7.88	4339
Pine	43.67	15.48	44.60	11.26	11.73	8.48	1646
Dark coniferous	47.32	12.76	41.74	8.00	10.94	7.10	985
Deciduous	43.64	17.25	42.92	13.20	13.44	7.15	424
For all types	47.04	13.6	42.46	10.50	10.50	6.90	7394

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 [2]. Previously, we estimated (Ponomarev et al., 2017) [25] that the area burned by high-intensity and crown fires was 8.5% of the total burned forested area in Siberia. Similar assessments made using satellite data were presented in reference [26], providing estimates of burned areas in larch forests (up to 50% of the total), dark coniferous (about 5%), light coniferous, and deciduous (18% and 19%, respectively), which is consistent with other studies [2,22].

3.3. Assessment of Combusted Biomass and Direct Carbon Emissions

Our 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 Central Siberian flat taiga region. 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 [2,5,27]. The coefficient of combustion completeness varied [11,21] depending on the FRP category. The coefficient β was 0.35–0.40 for low FRP, 0.40–0.45 for medium FRP, and 0.45–0.55 for high FRP.

The calculated estimate (Table 3) of direct carbon emissions from Siberian fires was 83 ± 21 Tg/year, which is lower than the result (112 ± 25 Tg/year) we obtained using Equations (1) and (2). Between 2002 and 2016, 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 value of 227 Tg/year in the extreme fire danger season of 2012. Taking into account the confidence interval, this corresponds to the range of values reported in publications for different scenarios of fire activity in Siberia [2,3,7,11].

Table 3. Mean long-term values of biomass combusted (M) and direct carbon emissions (C) calculated using Equations (1) and (2) and the described approach considering Equation (3).

Method	M			C			Relative Difference (4)	
	$\times 10^{12}$ kg	σ	Confidence Interval (α = 0.1)	Tg/Year	σ	Confidence Interval (α = 0.1)	%	σ
(1), (2)	0.192	0.131	0.067	111.9	68.4	25.4	17.3	1.8
(1), (2), (3)	0.159	0.108	0.055	83.1	56.5	21.0		

4. Conclusions

We performed a classification of fire areas, taking into account the combustion intensity according to the FRP range. It was quantitatively established that in Siberia low-intensity fires were responsible for 47.04 ± 13.6% of the total annual burned area, medium-intensity fires for 42.46 ± 10.50%, and high-intensity fires for 10.50 ± 6.90%. The mean annual direct fire emissions in Siberia between 2002 and 2016 were estimated as 83 ± 21 Tg/year, which is lower than the result (112 ± 25 Tg/year) we obtained using the standard method. The result of the calculation strongly depended on the fire danger scenario of the season, as well as on the relative burned area (0.01–14.5%). The direct emissions varied from 20 Tg/year in low fire danger scenario seasons up to 227 Tg/year in the extreme fire danger season of 2012.

Author Contributions: E.P. suggested the idea of the study; E.S., O.P., N.Y. processed the satellite database on wildfires; T.P., I.B., A.K., A.P. performed the field experiments; K.L., E.P. contributed numeric simulation materials and analysis tools; T.P., E.S. analyzed the meteorological data; E.P. wrote the paper.

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Abbreviations

The following abbreviations are used in this manuscript:

FRP	Fire Radiative Power
RBA	Relative Burned Area

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