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

Evgenii Ponomarev [1,2*], Evgeny Shvetsov [1], Kirill Litvintsev [3], Irina Bezkorovaynaya [4], Tatiana Ponomareva [1,4], Alexander Klimchenko [1], Oleg Ponomarev [4], Nikita Yakimov [4], Aleksey Panov [1]

[1] V.N. Sukachev Institute of Forest SB RAS, Krasnoyarsk 660036, Russia; evg@ksc.krasn.ru
[2] Regional Center for Remote Sensing, Federal Research Center SB RAS, Krasnoyarsk 660036, Russia; evg@ksc.krasn.ru
[3] S.S. Kutateladze Institute of Thermophysics SB RAS, Novosibirsk 1630090, Russia; sttupick@yandex.ru
[4] Siberian Federal University, Krasnoyarsk 660041, Russia; birinik-2011@yandex.ru
* Correspondence: evg@ksc.krasn.ru; Tel.: +7 391-249-40-92

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Abstract: The study was carried out for Siberia using the Terra/Modis satellite data (2002–2016), the data of ground surveys on burned areas of different ages, long-term meteorological information and numerical simulation results. Based on meteorological and wildfire databases we evaluated the probability (~18%) of the extreme fire danger scenario that occurred each 8±3 year in the different parts of the region. Next we used adopted Fire Radiative Power (FRP) measurements to classify the varieties of burning condition for the each wildfire in the database. The classification of annually burned forest area was obtained in accordance with the assessments of burning intensity ranges categorized by mean FRP. Depending on 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 the each wildfire, taking into account the variable intensity of burning within fire polygon. The total annual emissions were also calculated for Siberia for the last 15 years from 2002 to 2016. Averaged estimate of direct carbon emission was 83±21 Tg/year, which is lower than the result (112±25 Tg/year) we obtained also using the standard procedure.

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

1. Introduction

According to the long-term satellite observations there is a significant trend to increase wildfire numbers and area burnt in Siberian forests [1]. Wildfires in the boreal forests of Siberia are responsible for 70–90% of annual area burnt 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 as it was forecasted 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 consideration of the variations in the combustion parameters that occur even within the same fire polygon. To solve it remote sensing approach for wildfire's energy estimating [12–14] could be used.

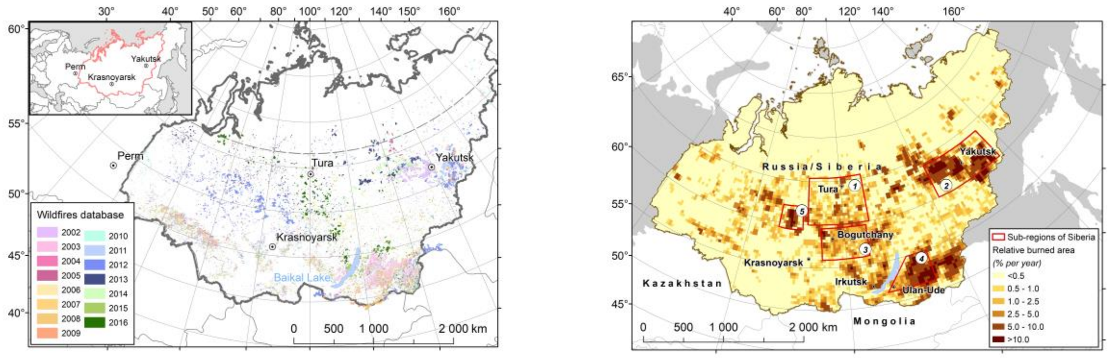
The aim of the study was to implement available satellite data on wildfires in Siberia and Fire Radiative Power (FRP) measurements [12] to quantitative estimate of the direct wildfire emissions. It was proposed to classify the burned areas according to the energy released and the intensity of wildfires.

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*, *L. gmelinii*) range over an area 270–300 MHa; the area of Scots pine (*Pinus sylvestris*) stands is 120 MHa, dark coniferous stands occupy 100 MHa and mixed forests about 77 MHa. We considered all forest fires detected in Siberia (50°–67°N and 60°–150°E) from 2002 to 2016 (Figure 1a). Data on forest types was derived from [15].



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

Figure 1. Study area: (**a**) Spatial distribution of wildfires in Siberia in 2002–2016. Wildfires with area of >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 of Siberia were taken from Climatic Research Unit (http://www.cru.uea.ac.uk), Weather Archive (http://rp5.ru) and NCDC Climate Data (http://www7.ncdc.noaa.gov/CDO/cdo).

Active fire products 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 own wildfires database collected using Terra/Modis in the V.N. Sukachev Institute of Forest (Krasnoyarsk, Russia) [18]. In the analyses we used statistically significant wildfires sample (7394 fire).

2.3. Methods

Firstly, we analyzed fire danger season 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 the 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 numbers of extreme fire seasons occurred at the local area. Minimum and maximum probabilities for sub-regions (Figure 1b) are summarized in the Table 1.

Next, we classified the fire pixels into three categories of FRP using thresholds calculated based on the statistical parameters of fire radiative power distribution. All fire pixels were separated into three categories: category I corresponds 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. According to these categories we distinguished areas of fires corresponding to low, medium and high FRP. As it was shown in [19] biomass combustion rate is linearly related to FRP. So refinement of the combusted biomass and direct emissions estimates was performed by accounting for variations in the combustion characteristics within the each fire polygon. Biomass combusted 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 – biomass combusted (kg), C – carbon emissions (g); A – burned area (m^2), β – combustion completeness, B – pre-fire fuel load (kg/m^2), CE – emission factor (g/kg).

Pre-fire fuel loads (B = 1.38–5.4 kg/m^2) for sub-regions of Siberia were summarized from published data [21–22]. At the stage of numerical modeling we used a generalized data on on-ground fuels in the 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 the 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 the equation (1) taking into account variable values of combustion completeness β. The value of β for each area was determined according to 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 original approach (1):

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

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

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

3. Results and Discussion

3.1. Fire danger scenarios and relative burned area

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

Table 1. Fire danger scenario statistics for Siberia.

N	Scenario	P{E} (min–max)	Period, years	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

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/km². The mean FRP value for the 95% confidence level was 37.4 MW/km² (σ = 17.1 MW/km²). Two threshold values were defined to separate fire pixels by FRP categories: 20.3 MW/km² and 54.5 MW/km². Based on 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

Instrumental based estimation of areas burned by fires of various intensities for Siberia was performed for the first time. In previous studies, empirically obtained data were 22%, 38.5% and 38.5% for low-, medium- and high-intensity fires, respectively [2]. Previously we estimated (Ponomarev et al., 2017) that area burned by high-intensity and crown fires areas is 8.5% of total burned forested area in Siberia. Similar assessments made using satellite data are presented in [25], 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 the other studies [2,22].

3.3. Assessment of combusted biomass and direct carbon emissions

Our field measurements of ground layer fuel were 0.7–1.3 kg/m² for post-fire plots in Larch and Pine tree stands of 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/m², 0.86–2.15 kg/m² and 2.25–5.36 kg/m², respectively, for low-, medium- and high-intensity fires [2,5,28]. The coefficient of combustion completeness varied [11,21] depending on the FRP category. The coefficient β was 0.35–0.40 for the low FRP, 0.40–0.45 for medium FRP and 0.45–0.55 for high FRP.

Table 3. Mean long-term values of biomass combusted and direct carbon emissions calculated using equations (1), (2) and using described approach considering (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		

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

5. Conclusions

We performed a classification of fire areas, taking into account the combustion intensity according to FRP range. It has been quantitatively established for Siberia that low-intensity fires are 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%. 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 also using the standard method. The result of calculation is strongly depended on fire danger scenario of the season, as well as the relative burned area (0.01%–14.5%). Direct emission varied ten times from 20 Tg/year in low fire danger scenario seasons up to 227 Tg/year in extreme fire danger season of 2012.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FRP: Fire Radiative Power
RBA: Relative Burned Area

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