

## Article

# Wildfire Intensity and Fire Emissions in Siberia

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**Abstract:** An analysis of fire characteristics in the boreal forests of Siberia (50–75° N, 60–140° E) was performed for the period 2002–2022. We found a positive trend in the proportion of high-intensity fires in dominant forest stands of Siberia based on long-term series of variations in the Fire Radiative Power (FRP) measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS). Our results showed that there was an increase in the proportion of areas of high-intensity fires over the past decade on about ~30% of the boreal forests of Siberia, including the Arctic zone. For the sample group of fires, the level of correlation ( $R^2 = 0.80\text{--}0.94$ ) between the fire impact, classified according to the NBR/dNBR technology, and the integral FRP values was revealed. The intensity of combustion in terms of FRP is associated with the volume of burned biomass and determines the dynamics of specific emissions values per unit area. The results suggest that further increase in fire emissions in Siberia will be determined not only by an increase of burned areas, but also by a redistribution of low- and high-intensity burning and an increase in specific emission values. Finally, we estimated that Siberian fires are responsible for about 5–20% of the total volume of greenhouse gas emissions in the Russian Federation, depending on the fire season scenario. The recurrence of extremely high emissions (296–350 Tg C/year) will make it possible to consider part of Siberian forests as a source of carbon in the nearest future.



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**Keywords:** wildfires; Siberia; normalized burn ratio; fire severity; fire radiative power; fire emissions

## 1. Introduction

Siberian forests account for up to 20% of the world’s forest areas [1], where up to  $45.05 \pm 7.64$  Pg of carbon is concentrated [2]. Currently, a positive carbon balance of Siberian forests is recorded (excess of carbon sink volumes over carbon emissions), varying according to various estimates from  $+0.56$  Pg C year<sup>−1</sup> [3] to  $+0.30$  Pg C year<sup>−1</sup> [4], or to  $+0.02$  PgC year<sup>−1</sup> [5]. At the same time, vegetation fires are one of the most significant factors regulating both the state of Siberian forests and the annual carbon balance.

Since the end of the 20th century, the territory of Siberia is characterized by an increase in the number of forest fires and the annual burned areas [6,7]. Such a scenario causes the formation of qualitatively new fire regimes in the region in the near future [8,9]. As a result, an increase in direct carbon emissions from fires into the atmosphere is predicted. According to the highest estimates [4,10,11], since the early 2000s, the annual amount of fire carbon emissions for the territory of Siberia is 300–500 Tg C/year. For comparison, Canadian fire emissions did not exceed 300 Tg C/year [12]. However, the adapted calculation methods show more conservative values of average long-term emissions in Siberia of ~100–150 Tg C/year with a positive trend [13]. This increasing trend is mainly associated with an increase of the burned area. At the same time, it is noted that the increasing

emission trend can be also caused by an increase in the intensity of fires under a more warm and arid climate in the region. Modern estimates show a wide variability in the annual carbon sink for different forest types in Siberia ranging from 200 to 700 Tg C/year [2,14,15]. A further increase in average annual emissions from fires may be a primary reason for the transition of Siberian taiga forests from carbon sink to carbon source [3,5].

The problem of a reliable assessment and forecasting of wildfire emissions cannot be solved without considering the fire energy characteristics and combustion intensity, as a parameter that determines specific emissions per unit area. The variety of forest conditions, dominant forest stands, and the variability of forest fuels in Siberia determine a wide range of fire energy characteristics for each fire event. Therefore, new methods based on satellite measurements of high temporal resolution are required to control combustion characteristics in a near real-time mode [16].

In world practice, the determination of carbon fire emissions is based on the Seiler–Crutzen’s empirical relationship [17]. The parameters include the mass of forest fuels, the total burned area, and the coefficient of combustion completeness. The use of this approach implies expert assessments for all input parameters, while the combustion intensity, which determines the variation of all components in a wide range, is assumed to be constant.

Satellite-based measurements of Fire Radiative Power (FRP) allow instrumental assessment of the combustion intensity and subsequent classification of individual fire phases considering the variations of fire intensity [18–20]. Measurements made in the mid-IR and thermal IR wavelength ranges allow estimation of the energy released by the zone of active combustion [19]. The MODIS instrument on the Terra and Aqua satellites has become the first sensor that allows estimation of the Fire Radiative Power on a global scale [18]. The instantaneous FRP measurements from the zone of active combustion are directly related to the fireline intensity and are related to the biomass combustion rate [21,22]. At the same time, fire radiative energy (FRE) released during the fire life time is proportional to the amount of combusted biomass [23]. In addition, data on fire radiative power from wildfires are used in the analysis of the burning intensity [24], to detect crown fires [25], and also to assess the fire-related forest disturbance degree [26,27]. The dynamics of fire intensity in Siberia under the current climate conditions is usually described at a qualitative level. At the same time, there are very few quantitative estimates. In this regard, it is important to reliably assess the contribution of fires to the annual pool of carbon emissions [5], since this can reduce the level of uncertainty in the carbon emissions estimates [13].

We assumed that the increase in fire emission is associated with an increase in fire intensity. Therefore, the main hypothesis of the study was that the change in the intensity of combustion would result in a change of fire radiative power obtained from satellite imagery. We assumed that increasing trends in fire intensity would be less significant if we consider the entire set of data. However, we expected that the significance would increase if we consider fires in different types of vegetation, as well as if we preliminarily link fire areas to the degree of damage to vegetation by fire. Further, in our opinion, calculation of actual fire emissions will allow us to estimate the change in specific values of emissions for fires of different intensity.

In this work, we considered the following problems: (1) the dynamics of fire intensity in Siberia using fire radiative power estimates from the zone of active combustion, (2) the relationship between the integral FRP values and fire-related forest disturbance degree and values of specific emissions, and (3) the assessment of direct carbon emissions from fires considering the energy characteristics of combustion.

## 2. Materials and Methods

We used data on wildfires in Siberia (50–75° N, 60–140° E) for the period from 2002 to 2022. Initial fire data with a spatial resolution of 1000 m was obtained from the satellite imagery obtained from NOAA/AVHRR and TERRA/AQUA/MODIS that were processed into a geospatial database of satellite monitoring at the Federal Research Center (Krasnoyarsk, Russia). We also used standard MODIS (Moderate Resolution Imaging Spec-

troradiometer) burned area product MCD64A1 [28] to refine the spatial locations of burned areas with a spatial resolution of ~500 m. Fire radiative power (FRP) was estimated using MODIS thematic thermal anomaly product MOD14/MYD14 [28]. The product contains data on coordinates, the detection time of a thermal anomaly, and FRP values with a spatial resolution of ~1000 m. To refine the spatial reference of individual fire pixels we additionally used MODIS geolocation product MOD03/MYD03.

FRP values in standard MODIS products MOD14/MYD14 of collection 6 (<https://ladsweb.modaps.eosdis.nasa.gov/>, accessed on 1 May 2023) are calculated using the following ratio [28]:

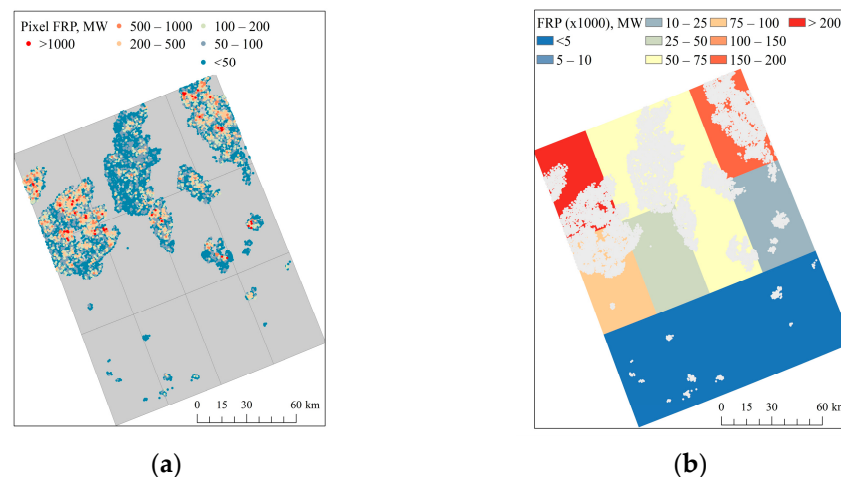
$$FRP = \frac{S \times \sigma}{a} (L_4 - \overline{L_4}), \quad (1)$$

where  $L_4$  and  $\overline{L_4}$ —are the 4- $\mu\text{m}$  radiances (MODIS band #21) of the fire pixel and background, respectively;  $\sigma = 5.6704 \times 10^{-8} \text{ W} \times \text{m}^{-2} \times \text{K}^{-4}$ —is the Stefan–Boltzmann constant;  $S$ —is the area of the MODIS pixel, and  $a = 3.0 \times 10^{-9} \text{ W} \times \text{m}^{-2} \times \text{sr}^{-1} \times \mu\text{m}^{-1} \times \text{K}^{-4}$ —is a sensor-specific empirical constant.

To test the hypothesis that an increase in the fire frequency and in the burned area in Siberia is accompanied by an increase in the intensity of fires, we compared mean and integral FRP values for the first and second half of our study period (2002–2012 vs. 2013–2022). FRP data for each year between 2002 and 2022 were converted into raster GIS layers using a regular grid with a cell size of  $0.5^\circ \times 0.625^\circ$  (Figure 1). Following we calculated mean and integral/total FRP values for each grid cell considering two time periods (2002–2012 and 2013–2022). Then we created raster layer containing a relative change in FRP between two periods as follows:

$$FRP = 100\% \times (FRP_{2013-2022} - FRP_{2012-2002}) / FRP_{2012-2002}, \quad (2)$$

where  $FRP_{2002-2012}$  is the total FRP value for 2002–2012 and  $FRP_{2013-2022}$  is the total FRP value for 2013–2022.



**Figure 1.** Scheme of the FRP raster layers generation: (a) Spatial alignment of the centers of “fire” pixels with various FRP values and cells of the raster grid ( $0.5^\circ \times 0.625^\circ$ ); (b) Color gradient of the output grid cells corresponds to integral values of FRP.

Thus, we assessed how the values of the FRP have changed in different regions of Siberia as well as the spatial redistribution of both average and integral FRP values.

FRP threshold values determining the categories of combustion intensity were obtained from statistical data, which are mean FRP value ( $FRP_m$ ) and standard deviation ( $\sigma$ ) of fire pixels within the fire polygon [29]. Such a threshold method enabled estimation of the fire areas burned by three categories of fires (of low, medium, and high intensity), and then, the long-term statistics were used to identify trends in the redistribution of

the proportion of fires of each category of intensity in the overall fire statistics in Siberia between 2002 and 2022.

At an intermediate stage, a sample of fires was processed to determine the degree of fire impact on vegetation considering the dominant forest stands. We have studied 35 fires with a total area of ~20 thousand km<sup>2</sup> within 7 types of forest stand, including: larch stands and sparse larch forests (*Larix sibirica*), pine stands (*Pinus sylvestris*), tundra vegetation and Cedar Elfin Wood (*Pinus pumila*), Siberian pine (*Pinus sibirica*) and spruce stands (*Picea obovata*).

At this stage, we used Landsat-8/OLI/TIRS (Operational Land Imager/Thermal Infrared Sensor) images obtained from open access catalogs (<https://earthexplorer.usgs.gov/>, accessed on 1 May 2023). We used Landsat images for the selected fire events (with burned areas > 2000 ha) in different tree stands of Siberia to evaluate fire impact on vegetation based on the normalized burn ratio method, described below. Area threshold was selected for reliable classification results. Information on the dominant forest stand was assigned to fire data based on an open access vegetation map (Vega service, ISR RAS, Moscow (<http://pro-vega.ru/maps/>, accessed on 1 May 2023)).

For a representative sample of fires (Table 1), the level of fire impact on vegetation was assessed using the normalized burn ratio (NBR/dNBR) and standard threshold classification procedures (Table 2) [30,31]. Post-fire polygons were classified in terms of NBR/dNBR by per-pixel calculations:

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)}, \quad (3)$$

where *NIR*—is reflection in near-infrared (*NIR*) band ( $\lambda = 0.85\text{--}0.89 \mu\text{m}$ ), and *SWIR*—is reflection in short wave-infrared (*SWIR*) band ( $\lambda = 2.10\text{--}2.30 \mu\text{m}$ );

$$dNBR = NBR_{pre} - NBR_{post}, \quad (4)$$

where *NBR<sub>pre</sub>*—is pre-fire *NBR* value, *NBR<sub>post</sub>*—is post-fire *NBR* value.

**Table 1.** Dates of Landsat images used.

| Tree Stand                          | Number of Fire Event | Pre-Fire Image Data | Post-Fire Image Data |
|-------------------------------------|----------------------|---------------------|----------------------|
| Larch<br>( <i>Larix sibirica</i> )  | 7                    | 2 July 2017         | 14 September 2018    |
|                                     |                      | 27 June 2019        | 16 August 2020       |
|                                     |                      | 15 June 2019        | 4 August 2020        |
|                                     |                      | 21 July 2020        | 21 September 2021    |
|                                     |                      | 9 September 2020    | 12 September 2021    |
|                                     |                      | 21 May 2020         | 28 August 2021       |
|                                     |                      | 23 August 2020      | 18 September 2021    |
| Sparse larch                        | 5                    | 12 July 2018        | 28 July 2018         |
|                                     |                      | 21 July 2017        | 12 September 2018    |
|                                     |                      | 4 July 2019         | 16 August 2020       |
|                                     |                      | 1 September 2019    | 6 September 2021     |
| Pine<br>( <i>Pinus sylvestris</i> ) | 6                    | 22 June 2021        | 26 September 2021    |
|                                     |                      | 5 August 2017       | 25 September 2018    |
|                                     |                      | 6 August 2017       | 10 September 2018    |
|                                     |                      | 22 July 2020        | 11 September 2021    |
|                                     |                      | 5 June 2021         | 9 September 2021     |
|                                     |                      | 24 August 2020      | 12 September 2021    |
| Tundra vegetation                   | 5                    | 17 June 2019        | 1 September 2021     |
|                                     |                      | 8 June 2019         | 11 August 2019       |
|                                     |                      | 8 June 2019         | 18 August 2019       |
|                                     |                      | 25 June 2019        | 13 September 2019    |
|                                     |                      | 25 June 2019        | 13 September 2019    |
|                                     |                      | 9 August 2019       | 13 September 2019    |



Table 1. Cont.

| Tree Stand                                  | Number of Fire Event | Pre-Fire Image Data | Post-Fire Image Data |
|---------------------------------------------|----------------------|---------------------|----------------------|
| Cedar elfin wood<br>( <i>Pinus pumila</i> ) | 5                    | 20 August 2018      | 16 August 2020       |
|                                             |                      | 9 June 2018         | 14 August 2019       |
|                                             |                      | 28 June 2017        | 1 September 2019     |
|                                             |                      | 28 June 2017        | 1 September 2019     |
|                                             |                      | 9 September 2020    | 12 September 2021    |
| Siberian pine<br>( <i>Pinus sibirica</i> )  | 5                    | 23 July 2017        | 10 September 2018    |
|                                             |                      | 6 August 2017       | 10 September 2018    |
|                                             |                      | 16 June 2016        | 19 June 2017         |
|                                             |                      | 23 July 2015        | 11 September 2016    |
|                                             |                      | 23 August 2020      | 25 July 2021         |

Table 2. Threshold Dnbr values for classification of fire disturbance degree.

| Category | Dnbr        | Disturbance Degree |
|----------|-------------|--------------------|
| 1        | <0.269      | Low                |
| 2        | 0.270–0.439 | Low-moderate       |
| 3        | 0.440–0.659 | Moderate           |
| 4        | >0.660      | High               |

We obtained the dates of fires using the geospatial database of satellite monitoring by the Federal Research Center (Krasnoyarsk, Russia) in 1996–2022. Pre- and post-fire images in the Landsat data catalog were selected with reference to the date of the fire event. The time interval between pre- and post-fire Landsat images was 1 year on average, in accordance with the requirements of the method [30,31]. Longer intervals in several cases were due to the lack of a cloud-free image (Table 1).

Using the Dnbr ranges, 4 categories of fire disturbance degree of vegetation are distinguished [30,31]. Further, in this work, we defined 3 classes of fire impact (Table 2): low level of disturbance (Dnbr < 0.269), moderate level (Dnbr < 0.659), significant level of disturbance (Dnbr > 0.659).

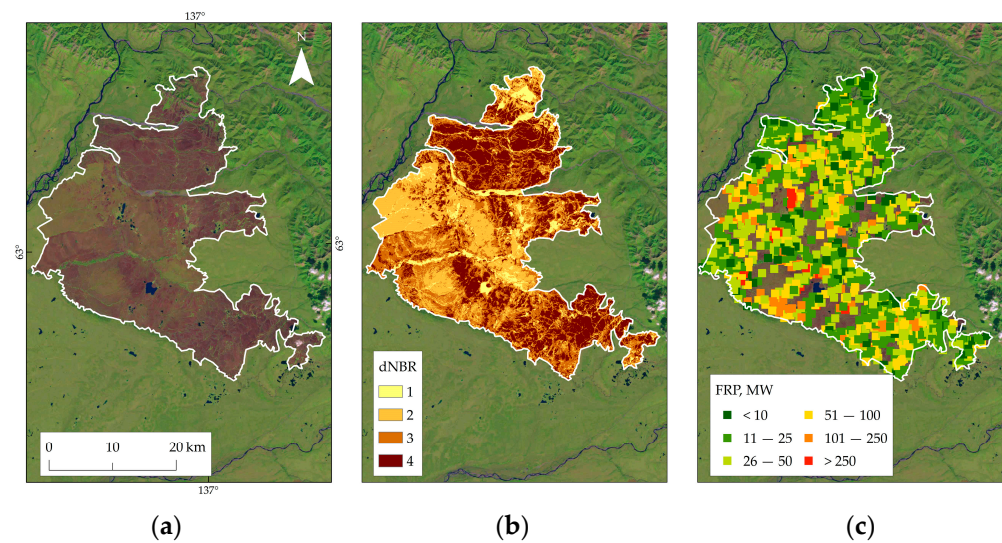
The relationship between the NBR/Dnbr and FRP was estimated taking into account the dominant forest stands of Siberia (Figures 2 and 3). For this purpose, we considered the integral FRP value over all fire pixels for each fire disturbance class identified using the NBR/Dnbr values. We analyzed the diagrams of the correlation field (Pearson correlation) of the dependence of the integral FRP on the Dnbr category for different types of forest stands with an estimate of the coefficient of determination  $R^2$ .

In current conditions, an increase in fire emissions is caused not only by an increase in burned areas but also by an increase in the specific value of emissions per unit area during high-intensity combustion. Burned areas of low-, moderate-, and high- combustion intensity in Siberia have characteristic specific values of emissions per unit area of ~8.7, 12.0, and 15.4 t C/ha, respectively [13,16].

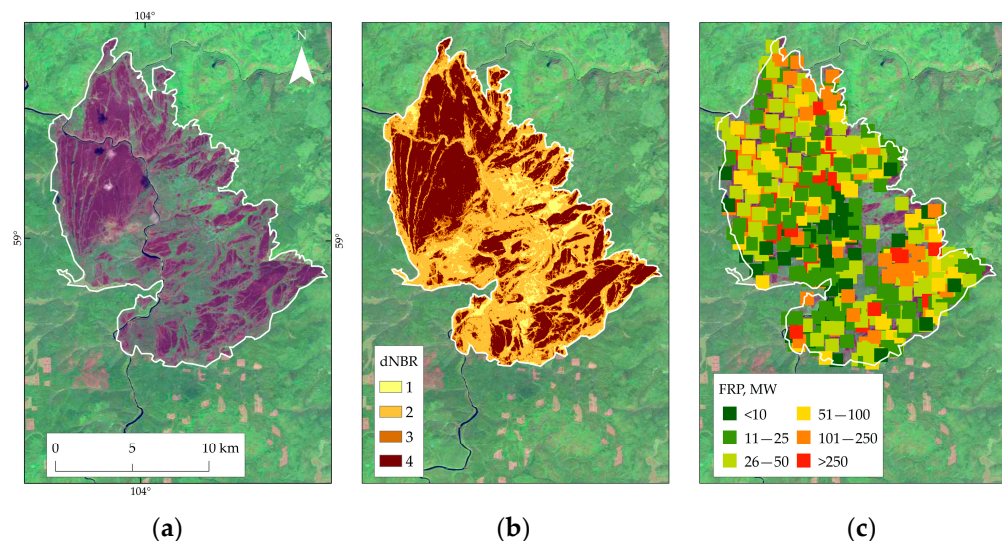
At the final stage, we classified “fire” pixels taking into account categories of combustion intensity and calculated fire emissions using the threshold method. The total emissions were determined using the modified [29] relation of Seiler–Crutzen [17], where the combustion intensity determines the variation of the input parameters:

$$C = CE \times \sum_i S_i(FRP) \times \beta_i(FRP) \times B_i(FRP) \quad (5)$$

where  $C$  is direct carbon emissions (g);  $S_i(FRP)$  is total burned area ( $m^2$ ), calculated as the sum of different burning intensity areas;  $\beta_i(FRP)$  is a combustion efficiency coefficient;  $B_i(FRP)$  is fuel load ( $kg/m^2$ ), and  $CE$  is emission factor relating the amount of combusted fuels and carbon emission (g/kg). Input parameters were considered as functions of fire radiative power (FRP) for each  $i$ -th burned plot of fire.



**Figure 2.** Burned area in Siberian larch (*Larix sibirica*) forest on Landsat-8 image of 16 August 2020: (a) Original image of burned area; (b) Variation of dNBR values with 4 categories of fire impact on vegetation; (c) FRP values.



**Figure 3.** Burned area in Siberian pine (*Pinus sibirica*) forest on Landsat-8 image of 10 September 2019: (a) Original image of burned area; (b) Variation of dNBR values with 4 categories of fire impact on vegetation; (c) FRP values.

Considering the results of field studies [19,32], the coefficient  $\beta_i(FRP)$  varied between 0.35 and 0.40 for low-intensity fires, for moderate-intensity fires it was 0.40–0.55, and it was 0.55–0.65 for high-intensity fires.

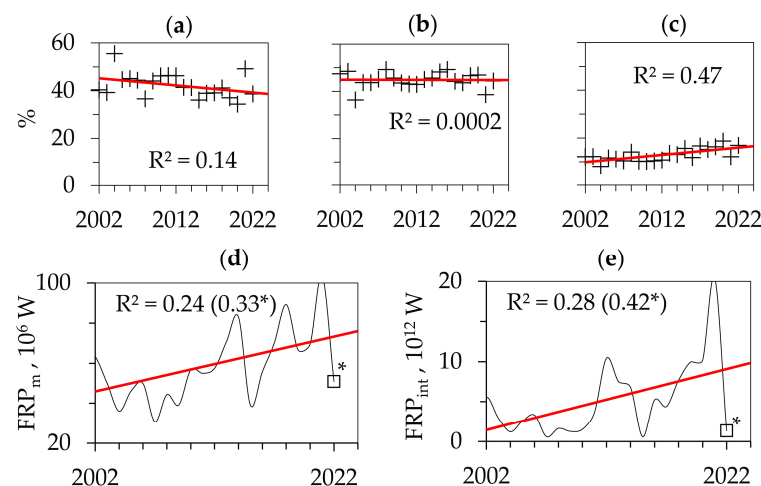
Fuel loads  $B_i(FRP)$  in various forest stands of Siberia are estimated in a wide range of 5.0–60.0 t/ha [33–40]. At the same time, in Equation (4), the specific values of combusted fuels (kg/m<sup>2</sup>) were taken as follows: 0.11–0.97 kg/m<sup>2</sup>, 0.86–2.15 kg/m<sup>2</sup>, and 2.25–5.36 kg/m<sup>2</sup> for low-intensity, moderate-intensity and high-intensity combustion, correspondingly [10,41]. The recalculation of these values gives estimates of specific emissions from fires of different intensity in the range of 5.4, 15.1, 38.1 t C/ha. Variation of combusted fuel loads in fires of various characteristics determines a significant dispersion in the values of the integral FRP [22] and subsequent estimates of fire emissions by method (5).

Finally, we analyzed long-term emissions variety for 2002–2022 from the point of view of the dynamics of fire intensity in Siberia, characterizing the general patterns of trends

and the predicted proportion of fire emissions in the total annual volume of greenhouse gas emissions in the Russian Federation.

### 3. Results

A positive trend ( $R^2 = 0.47$ , for  $p < 0.05$ ) was revealed for high-intensity fires (HIF) in terms of FRP (Figure 4) for the territory of Siberia in 2002–2022. The result shows the percentage of the total area of fires without taking into account differences that may occur in different dominant tree stands. Therefore, the trend for HIF shows a slight increase. The redistribution is associated with a reduction of the areas of low-intensity fires (LIF) (Figure 4a,c). At the same time, the proportion of medium-intensity fires (MIF) actually remained unchanged with slight decreasing trend ( $R^2 = 0.0002$ ) (Figure 4b). According to our data (Table 3), the proportion of high-intensity burning increased from 10% to 15.9% of the total area of wildfires, which is  $0.63 \pm 0.31$  million ha/year, respectively, in 2002–2011, and  $1.40 \pm 0.49$  million ha/year in 2012–2019. Seasons 2020 and 2021 with a proportion of high-intensity fires about  $\sim 2.5 \pm 0.95$  million ha should be considered as sporadic extremes of the last decade.



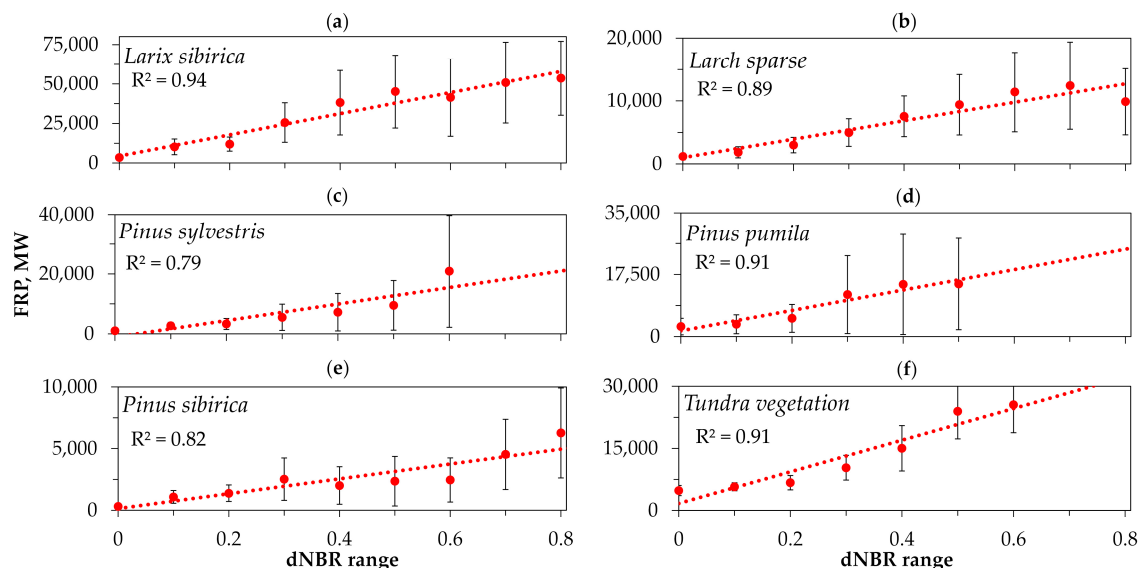
**Figure 4.** Trends in the proportions of fire areas, taking into account the intensity of burning in terms of FRP: (a) Low-intensity, (b) medium-intensity, (c) high-intensity fires. Dynamics of average  $FRP_m$  values (d) and integral  $FRP_{int}$  values (e), calculated from all detected fires in Siberia.  $R^{2*}$  values are obtained without taking into account the minima of 2022, which were marked on the graph with (\*).

**Table 3.** Long-term average values of areas (million ha) of low-intensity (LIF), medium-intensity (MIF), and high-intensity (HIF) burning in Siberia.

| Years     | Average Area, mln ha |               |               |
|-----------|----------------------|---------------|---------------|
|           | LIF                  | MIF           | HIF           |
| 2002–2011 | $2.3 \pm 1.5$        | $2.5 \pm 1.8$ | $0.6 \pm 0.4$ |
| 2012–2019 | $3.4 \pm 3.0$        | $3.6 \pm 3.0$ | $1.4 \pm 0.5$ |
| 2020–2022 | $6.6 \pm 2.9$        | $6.9 \pm 2.4$ | $2.5 \pm 1.0$ |

At the same time, the dynamics of the average and integral FRP values also demonstrated positive trends ( $R^2 = 0.24$ – $0.28$ , at  $p < 0.05$ ) against the background of rapidly periodic interseasonal variations (Figure 4d,e). This trend is even more reliable ( $R^{2*} = 0.33$ – $0.42$ , at  $p < 0.05$ ) without the outlier of 2022 for average and integral FRP, which were marked on the graph with (\*). Average values increased from  $FRP_m = 45 \times 10^6$  W in 2002 to  $FRP_m = 65 \times 10^6$  W, i.e., by  $\sim 150\%$  from the initial level. The integral FRP values calculated for all fires of the season showed a threefold increase with  $FRP_{int} = 2.42 \pm 0.93 \times 10^{12}$  W in 2002–2011 to  $FRP_{int} = 7.69 \pm 3.18 \times 10^{12}$  W in 2012–2022 (Figure 4e).

For the considered sample of fires, the integral values of FRP varied at the level of 10,000–75,000 MW in light coniferous tree stands, 5000–30,000 MW in the sparse larch forests and in tundra zone, and 1800–7000 MW in dark coniferous stands. It was instrumentally confirmed that high-intensity fires (integral FRP values within a single fire event exceed  $50 \times 10^3$  MW) are mainly recorded in light coniferous (*Larix sibirica*, *Pinus sylvestris*) stands, where the fire impacts of medium and high degree were also the largest and amounted to ~46% of the total damage area per year [31]. The results are consistent with the available estimates of the degree of fire impact on vegetation in Siberia [26,31]. Thus, according to Krylov et al., 2014 [42], light conifer stands comprised 65% of all non stand-replacement and 79% of all stand-replacement fire in Russia. Spatially, these estimates are detected on the Landsat-based global forest cover change product (<https://glad.earthengine.app/view/global-forest-change/>, accessed on 7 June 2023) by Hansen et al., ver. 1.10, updated in 2022 [43]. For the class of Deciduous Needle-Leaf Forests (i.e., larch forests of Siberia), the highest probability of annual fire impact [26] and post-fire mortality [7] was also recorded. The majority of fires in Siberia are detected in light coniferous forests [6]. The level of fire impact in these forests is twofold excess of the intensity in comparison with other forest stands (Figure 5). At the same time, the linear dependence of FRP vs. dNBR is the same in all types of forest.

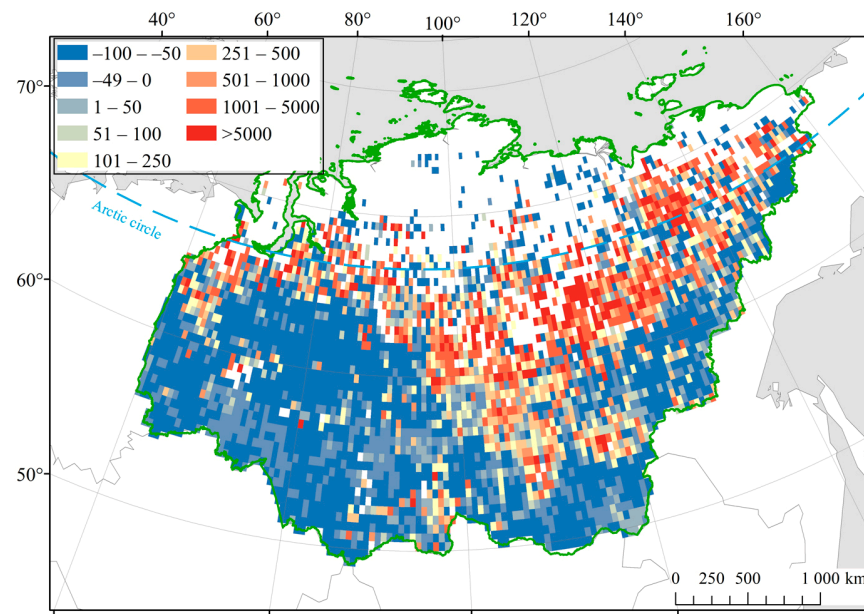


**Figure 5.** Correlation between FRP and categories of vegetation disturbance in terms of dNBR for the prevailing types of forest stands and vegetation cover in Siberia. Prevailing types of vegetation: (a) Larch forests (*Larix sibirica*), (b) larch sparse, (c) pine stands (*Pinus sylvestris*), (d) cedar elfin wood (*Pinus pumila*), (e) siberian pine (*Pinus sibirica*) and (f) tundra vegetation.

We found a direct correlation ( $R^2 = 0.80\text{--}0.94$ ) between FRP intensity and vegetation disturbance categories in terms of dNBR (Figure 5). This result is also consistent with the idea that an increase in the intensity of combustion determines an increase in the volume of fuel loads burning and the corresponding volumes of direct emissions from fires [16,21].

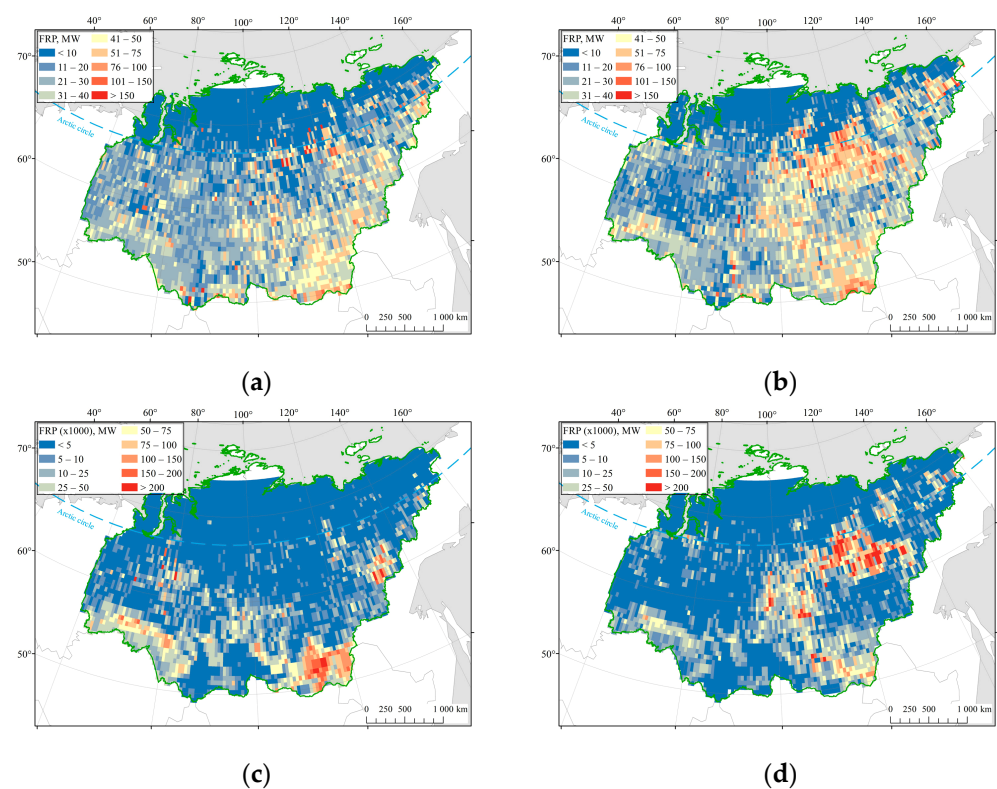
Interpolation of integral  $FRP_{int}$  using a regular grid with a cell of  $0.5^\circ \times 0.625^\circ$  (Figure 6) demonstrates the spatial distribution of the increase in FRP values over a large area, on about ~30% of the boreal forests of Siberia, including the Arctic zone. At the same time, in several regions of Siberia, the integral  $FRP_{int}$  increased by 2.5–50.0 times relative to the values for the previous decade.





**Figure 6.** Changes in the integral values of FRP (in %) for fires in Siberia detected between 2013 and 2022 relative to integral FRP values detected in 2002–2012. FRP values were gridded using  $0.5^\circ \times 0.625^\circ$  cell size.

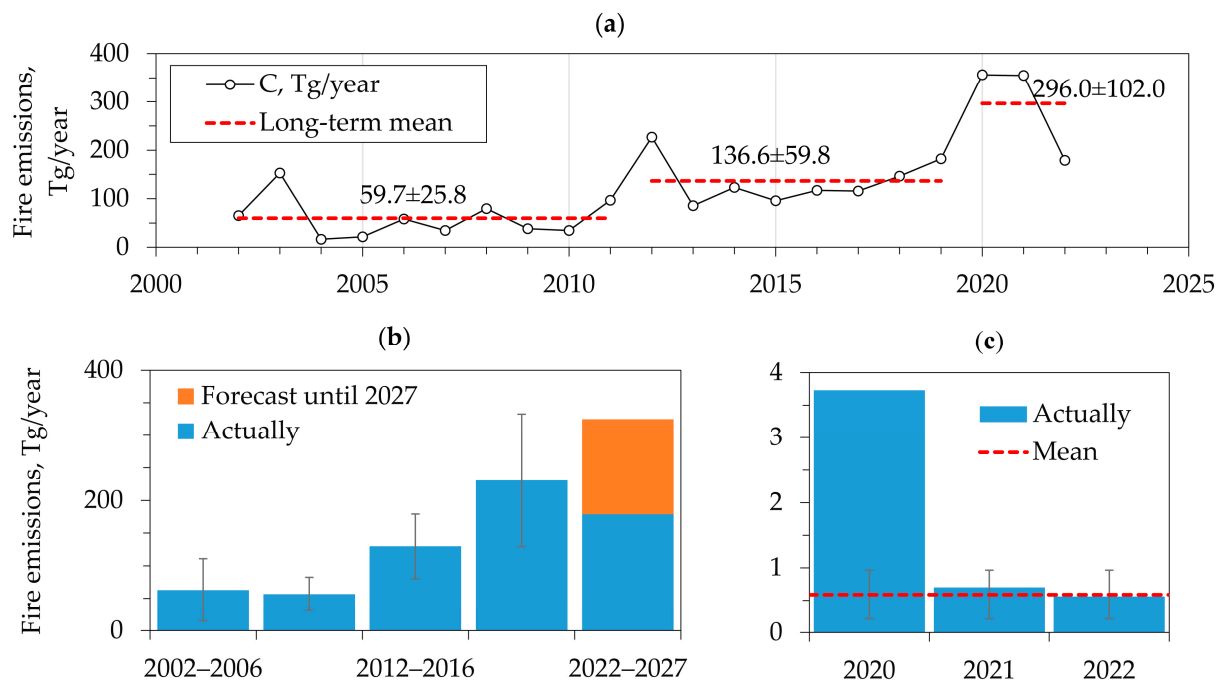
The spatial redistribution of both average and integral FRP values in the grid cells is shown in Figure 7. We note an increase in the average/integral FRP in large areas north of  $60^\circ$  N in the northeastern part of Siberia, attributing this to two factors: (1) an increase in the number (and areas) of fires, and (2) an increase in the level of burning intensity.



**Figure 7.** Regular grids (cell size  $0.5^\circ \times 0.625^\circ$ ) of mean (a,b) and integral (c,d) FRP values for the territory of Siberia. Panels (a,c) correspond to 2002–2012 and panels (b,d) correspond to 2013–2022.



Thus, the zone where fires intensity increases is located to the north of  $60^{\circ}$  N, mainly in the territory of larch (*Larix sibirica*, *L. gmelinii*) forests and sparse larch forests. Fires here and in the adjacent areas of peatlands and tundra ( $>67^{\circ}$  N) can potentially provide a significant additive contribution to the annual volumes of emissions, as it was recorded during the season of extreme burning in the Arctic in 2020 [44]. The sporadic maximum (Figure 8c) demonstrates a significant excess of fire emissions in the northern part of the region in 2020 ( $\sim 3.7$  Tg C/year), which is 5 times higher than the long-term average ( $\sim 0.59$  Tg C/year). The recurrence frequency of such events is estimated at 1 time per 8–10 years [44].



**Figure 8.** Estimates of direct emissions from fires in Siberia for 2002–2022: (a) Variation of the average level; (b) Forecast until 2027 with interannual fluctuation filtering; (c) Extreme emissions in 2020 against the background of long-term average values of emissions from fires in the peatlands and tundra zone ( $>67^{\circ}$  N) of Siberia.

The values of direct fire emissions for the considered period varied from 58 Tg/year (2006) to 120 Tg/year (2014) and reached extreme values of  $\sim 350$  Tg/year (in 2020, 2021). The average long-term level of fire emissions increased three times from  $60.0 \pm 25.8$  Tg/year in 2002–2011 up to  $137.0 \pm 60.0$  Tg/year in 2012–2019 and up to  $296.0 \pm 102.0$  Tg/year in the last three seasons of 2020–2022 (Figure 8a).

Filtering high-frequency variations after averaging over five-year intervals allows us to speak of an exponential trend in the growth of emissions (Figure 8b). Projected maximum annual emissions from fires can be  $\sim 325$  Tg C/year in the short term of 2022–2027.

#### 4. Discussion

Currently, remote sensing is the most important tool for obtaining data on wildfires in Siberia [6]. First of all, this is due to the low population of the region and the lack of alternative methods for detecting and controlling fires over large areas. Therefore, modern technologies for both studying fires and assessing fire effects are based on the use and generalization of satellite data. In particular, this applies to the issues of assessing the fire impact on vegetation cover [7,26,27,31] or calculating fire emissions [10,13]. Satellite estimates complement and allow extrapolation of single ground-based experiments [11,32,37,45] in matters of wildfire and post-fire processes.

According to various estimates the characteristic specific emissions values per unit area in Siberia vary from  $\sim 8.7$ , 12.0, and 15.4 t C/ha [16] to 5.0, 11.0, 27.4 t C/ha [10,41]

for low-, medium-, and high-intensity combustion, respectively. In our opinion, for the considered period 2002–2022, an increase of fire emissions in Siberia was determined by: (1) an increase in annual burned areas; (2) redistribution of low- and high-intensity combustion (Figure 4a,c); and (3) increasing the values of specific emissions.

Based on the results of instrumental data processing, we found a change in the areas burned by fires of various intensities (Table 3) for three time periods, as well as average long-term estimates of fire emissions (Figure 8a). Thus, the calculation of specific emissions for fires of various intensities comes down to the analytical solution of the system in matrix form, which has the form

$$A \times x = B$$

$$A = \begin{pmatrix} 2.3 & 2.5 & 0.6 \\ 3.4 & 3.6 & 1.4 \\ 6.6 & 6.9 & 2.5 \end{pmatrix}, \quad x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}, \quad B = \begin{pmatrix} 59.7 \\ 136.6 \\ 296.0 \end{pmatrix} \quad (6)$$

where variables  $x_1, x_2, x_3$  determine the specific emission for fires of low, medium, and high intensity, respectively,  $B_i$  are the average long-term estimates of fire emissions (see Figure 8a), and  $A_{ij}$  are coefficients equal to the average long-term values of fire areas in accordance with intensity categories (see Table 3).

The exact solution of system (6) with respect to the variables  $x_1, x_2, x_3$  does not correspond to the characteristic limits of possible values of specific emissions due to the uncertainty of the used coefficients  $A_{ij}$  for areas and  $B_i$  for average annual emissions. Nevertheless, approximate solutions of specific emissions for three time ranges were obtained using the least squares method (standard plugin of MS Office Excel, ver. 2013) with optimization of Residual Sum of Squares (RSS) of model calculations of annual emissions (Table 4).

**Table 4.** Solutions for the values of specific emissions (t C/ha) for three times.

| Years     | Specific Emissions, t C/ga |       |       |
|-----------|----------------------------|-------|-------|
|           | $x_1$                      | $x_2$ | $x_3$ |
| 2002–2011 | 9.0                        | 12.0  | 15.0  |
| 2012–2019 | 10.0                       | 12.4  | 20.3  |
| 2020–2022 | 10.0                       | 14.5  | 38.8  |

It is indicative that specific emissions for high-intensity fires at the present stage (38.8 t C/ha) more than doubled (Table 4). A significant increase in high-intensity fire areas from  $0.63 \pm 0.31$  million ha/year in 2002–2011 up to  $1.70 \pm 0.49$  million ha/year in 2012–2019 and up to  $2.5 \pm 0.92$  in 2020–2021 is spatially typical for the zone of light coniferous forests of Central/Eastern Siberia (*Larix sibirica*, *L. gmelinii*, *Pinus sylvestris*) (Figure 6). According to published data (Table 5), the fuel loads can reach 45–60 t/ha in these territories.

**Table 5.** Data on the fuel loads in the forests of Siberia.

| Tree stands                                                                                             | Subregion                                          | Loads, t/ha | Reference                                             |
|---------------------------------------------------------------------------------------------------------|----------------------------------------------------|-------------|-------------------------------------------------------|
| Light coniferous forests<br>( <i>Larix sibirica</i> , <i>L. gmelinii</i> ,<br><i>Pinus sylvestris</i> ) | Larch forests/Eastern Siberia, Yakutia             | 14.5–23.0   | Chevychelov, 2019 [37]                                |
|                                                                                                         | Larch forests/Central Siberia                      | 18.0–18.8   | Pleshikov et al., 2002 [33],<br>Prokushkin, 2006 [34] |
|                                                                                                         | Larch forests/waterlogged taiga of Central Siberia | 21.0–60.0   | Sergeeva et al., 2020 [38]                            |
|                                                                                                         | Larch forests/southern taiga of Central Siberia    | 48.6–65.0   | Ivanova et al., 2022 [40]                             |
|                                                                                                         | Pine forests/Eastern Siberia, Yakutia              | 5.7–7.8     | Chevychelov, 2019 [37]                                |
|                                                                                                         | Pine forests/Central Siberia                       | 6.6–14.5    | Vedrova, 2012 [36],<br>Pleshikov, 2002 [33]           |
|                                                                                                         | Pine forests/southern taiga of Central Siberia     | 37.5–49.5   | Ivanova et al., 2022 [40]                             |
| Dark coniferous forests<br>( <i>Pinus sibirica</i> , <i>Picea obovata</i> ,<br><i>Abies sibirica</i> )  | Southern taiga of Central Siberia                  | 5.0–7.5     | Vedrova, 2012 [36]                                    |
|                                                                                                         | Central Siberia                                    | 9.0–14.0    | Pleshikov, 2002 [33]                                  |
| Deciduous forests<br>( <i>Betula</i> spp.,<br><i>Populus tremula</i> )                                  | Central Siberia                                    | 5.0–6.0     | Pleshikov, 2002 [33]                                  |
| Tundra and<br>cedar elfin wood ( <i>Pinus pumila</i> )                                                  | Tundra of Western Siberia                          | 15.0        | Gerber, 2021 [39]                                     |

Indirectly, the volumes of burning biomass are confirmed by the conjugate analysis of satellite estimates of the degree of post-fire ground cover disturbance and the spatial variation of FRP, where a high ( $R^2 = 0.80\text{--}0.94$ ) positive correlation was recorded (Figure 5). At the same time, the combustion intensity which depends on the amount of forest fuels consumed, determines both the overall level of fire impact [26,31] and the variety of post-fire effects on all components of forest ecosystems. In particular, deep burning of the ground cover in high-intensity fires is indirectly confirmed by long-term thermal anomalies observed on soils at the sites of degradation of heat-insulating covers [45].

Most modern forecasts of forest fire regimes in Siberia [6,8,9,41] identify climate change as the most important driver of the increase in fire areas. Nowadays, it is noted that the high burning of Siberian forests directly depends on the increasing anthropogenic factor. Human disturbances, such as forest logging, may further intensify the fire activity in the Siberian forests [46]. It can be assumed that an increase in the fuel loads could affect the probability of high-intensity fires under the conditions of increased climate aridity of the region in the future [47]. In this vein, an increase in fire emissions of carbon compounds in the nearest perspective is a generally accepted and justified point of view. The results of our study show that, in addition, the dynamics of annual emissions will be determined by the increase in high-intensity combustion, as well as an increase in the values of specific emissions per unit area. Such effects can be typical for a large area of Siberia, which makes up to ~30% of all forests in the region. Potentially, this conclusion is also applicable to a significant part of the Arctic in the conditions of extreme fire seasons.

A separate issue for discussion is the problem of assessing the carbon balance in the forests of Siberia [2,15]. In this matter, it is very important to have instrumentally confirmed characteristics of fire emissions.

It can be expected that the increasing trend of high-intensity combustion will continue further, resulting in additional volumes of fire emissions. If we take into account the volume of greenhouse gas emissions in the Russian Federation, which is estimated at 1584–2155 Tg C/year [4,48], then fires are responsible for 5% of the total emissions during low fire seasons and up to 20% during extreme seasons as demonstrated in 2020 and 2021 (~350 Tg/year). At the same time, the annual carbon sink for various forests of Siberia is about 200–700 Tg C/year [2,14,15], which can be compensated by fire emissions of the same order, even if the average level of the last decade ( $\sim 296.0 \pm 102.0$  Tg/year) is maintained. A further increase in average annual emissions from fires may be the primary reason for

the transition of Siberian taiga forests from an atmospheric carbon sink to the source of carbon [3,5].

## 5. Conclusions

According to the results, ~30% of Siberian boreal forests, including the Arctic zone, are characterized by an increase in the proportion of areas of high-intensity fires over the last decade. A significant increase in areas burned by high-intensity fires is observed in the zone of light coniferous forests of Central/Eastern Siberia (*Larix sibirica*, *L. gmelinii*, *Pinus sylvestris*). Fires here and in the adjacent areas of peatlands and tundra (>67° N) can potentially provide a significant additive contribution to the annual volumes of emissions. Direct correlation ( $R^2 = 0.80\text{--}0.94$ ) between FRP intensity and vegetation disturbance categories in terms of dNBR was typical for all types of tree stands in Siberia.

At the same time, a further increase in fire emissions in Siberia will be determined not only by an increase of burned areas, but also by a redistribution of low- and high-intensity burning and an increase in specific emission values. Currently, we estimated that specific emissions for high-intensity fires in 2020 (38.8 t C/ha) increased more than twice since 2000 (~15.0 t C/ha).

We estimated the predicted maximum annual fire emissions at ~325 Tg C/year for the short term 2022–2027. Siberian fires are responsible for about 5–20% of the total volume of greenhouse gas emissions in the Russian Federation. Probably, in the perspective of available climatic scenarios, the regular recurrence of extreme emissions will make it possible to consider part of Siberian forests as a source of carbon in the near future.

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## References

1. Keenan, R.J.; Reams, G.A.; Achard, F.; de Freitas, J.V.; Grainger, A.; Lindquist, E. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. *For. Ecol. Manag.* **2015**, *352*, 9–20. [CrossRef]
2. Zamolodchikov, D.G.; Grabowsky, V.I.; Chestnykh, O.V. Dynamics of Carbon Budget in Forests of Federal Districts of Russian Federation. *For. Sci. Issues* **2018**, *1*, 1–24. [CrossRef]
3. Shvidenko, A.Z.; Schepaschenko, D.G. Carbon Budget of Russian Forests. *Sib. For. J.* **2014**, *1*, 69–92. (In Russian)



4. Ptichnikova, A.V.; Shvartsa, E.A.; Kuznetsova, D.A. On the potential of greenhouse gas absorption by forests of Russia to reduce the carbon footprint of domestic products export. *Rep. Russ. Acad. Sci. Earth Sci.* **2021**, *499*, 181–184. (In Russian) [\[CrossRef\]](#)
5. Fan, L.; Wigneron, J.P.; Ciais, P.; Chave, J.; Brandt, M.; Sitch, S.; Yue, C.; Bastos, A.; Li, X.; Qin, Y.; et al. Siberian carbon sink reduced by forest disturbances. *Nat. Geosci.* **2023**, *16*, 56–62. [\[CrossRef\]](#)
6. Kharuk, V.I.; Ponomarev, E.I.; Ivanova, G.A.; Dvinskaya, M.L.; Coogan, S.C.P.; Flannigan, M.D. Wildfires in the Siberian taiga. *Ambio* **2021**, *50*, 1953–1974. [\[CrossRef\]](#)
7. Bartalev, S.A.; Stytsenko, F.V. An assessment of the forest stands destruction by fires based on the remote sensing data on a seasonal distribution of burnt areas. *Contemp. Probl. Ecol.* **2021**, *2*, 115–122. [\[CrossRef\]](#)
8. Hayasaka, H. Rare and Extreme Wildland Fire in Sakha in 2021. *Atmosphere* **2021**, *12*, 1572. [\[CrossRef\]](#)
9. Hayasaka, H. Fire Weather Conditions in Boreal and Polar Regions in 2002–2021. *Atmosphere* **2022**, *13*, 1117. [\[CrossRef\]](#)
10. Soja, A.J.; Cofer, W.R.; Shugart, H.H.; Sukhinin, A.I.; Stackhouse, P.W., Jr.; McRae, D.J.; Conard, S.G. Estimating fire emissions and disparities in boreal Siberia (1998–2002). *J. Geophys. Res.* **2004**, *109*, D14S06. [\[CrossRef\]](#)
11. McRae, D.J.; Conard, S.G.; Ivanova, G.A.; Sukhinin, A.I.; Baker, S.; Samsonov, Y.N.; Blake, T.W.; Ivanov, V.A.; Ivanov, A.V.; Churkina, T.V.; et al. Variability of fire behavior, fire effects, and emissions in Scotch pine forests of Central Siberia. *Mitig. Adapt. Strateg. Glob. Chang.* **2006**, *11*, 45–74. [\[CrossRef\]](#)
12. de Groot, W.J.; Cantin, A.S.; Flannigan, M.D.; Soja, A.J.; Gowman, L.M.; Newbery, A. A comparison of Canadian and Russian boreal forest fire regimes. *For. Ecol. Manag.* **2013**, *294*, 23–34. [\[CrossRef\]](#)
13. Ponomarev, E.I.; Yakimov, N.D.; Ponomareva, T.V.; Yakubailik, O.E.; Conard, S.G. Current Trend of Carbon Emissions from Wildfires in Siberia. *Atmosphere* **2021**, *12*, 559. [\[CrossRef\]](#)
14. Sergienko, V.G. The expected impact of climate change on carbon balance and ecosystem productivity in the forest sector of the Russian Federation. *Proc. St. Petersburg For. Res. Inst.* **2018**, *1*, 74–90. (In Russian) [\[CrossRef\]](#)
15. Vaganov, E.A.; Porfiriev, B.N.; Shirov, A.A.; Kolpakov, A.Y.; Pyzhev, A.I. Assessment of the contribution of Russian forests to climate change mitigation. *Econ. Reg.* **2021**, *17*, 1096–1109. [\[CrossRef\]](#)
16. Ponomarev, E.I.; Shvetsov, E.G.; Kharuk, V.I. The Intensity of Wildfires in Fire Emissions Estimates. *Russ. J. Ecol.* **2018**, *49*, 492–499. [\[CrossRef\]](#)
17. Seiler, W.; Crutzen, P.J. Estimates of Gross and Net Fluxes of Carbon between the Biosphere and the Atmosphere from Biomass Burning. *Clim. Chang.* **1980**, *2*, 207–247. [\[CrossRef\]](#)
18. Justice, C.O.; Giglio, L.; Korontzi, S.; Owens, J.; Morissette, J.T.; Roy, D.; Descloitres, J.; Alleaume, S.; Petitcolin, F.; Kaufman, Y. The MODIS fire products. *Remote Sens. Environ.* **2002**, *83*, 244–262. [\[CrossRef\]](#)
19. Wooster, M.J.; Roberts, G.; Perry, G.L.W.; Kaufman, Y.J. Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. *J. Geophys. Res.* **2005**, *110*, D24311. [\[CrossRef\]](#)
20. Kumar, S.S.; Roy, D.P.; Boschetti, L.; Kremens, R. Exploiting the power law distribution properties of satellite fire radiative power retrievals: A method to estimate fire radiative energy and biomass burned from sparse satellite observations. *J. Geophys. Res.* **2011**, *116*, 1–18. [\[CrossRef\]](#)
21. Wooster, M.J.; Zhukov, B.; Oertel, D. Fire radiative energy for quantitative study of biomass burning. Derivation from the BIRD experimental satellite and comparison to MODIS fire products. *Remote Sens. Environ.* **2003**, *86*, 83–107. [\[CrossRef\]](#)
22. Ponomarev, E.I.; Shvetsov, E.G.; Litvintsev, K.Y. Calibration of Estimates on Direct Wildfire Emissions from Remote Sensing Data. *Izv. Atmos. Ocean. Phys.* **2019**, *55*, 1065–1072. (In Russian) [\[CrossRef\]](#)
23. Vermote, E.; Ellicott, E.; Dubovik, O.; Lapyonok, T.; Chin, M.; Giglio, L.; Roberts, G. An approach to estimate global biomass burning emissions of organic and black carbon from MODIS fire radiative power. *J. Geophys. Res.* **2009**, *114*, 1–22. [\[CrossRef\]](#)
24. Shvetsov, E.G.; Ponomarev, E.I. Estimating the Influence of External Environmental Factors on Fire Radiative Power Using Satellite Imagery. *Contemp. Probl. Ecol.* **2015**, *8*, 337–343. [\[CrossRef\]](#)
25. Ponomarev, E.I.; Shvetsov, E.G.; Usataya, Y.O. Determination of the Energy Properties of Wildfires in Siberia by Remote Sensing. *Izv. Atmos. Ocean. Phys.* **2018**, *54*, 979–985. [\[CrossRef\]](#)
26. Loupian, E.A.; Lozin, D.V.; Balashov, I.V.; Bartalev, S.A.; Stytsenko, F.V. Study of the dependence of forest fire damage degree on burning intensity based on satellite monitoring data. *Sovrem. Probl. Distantionnogo Zondirovaniya Zemli Iz Kosm.* **2022**, *19*, 217–232. (In Russian) [\[CrossRef\]](#)
27. Shvetsov, E.G. Study of the influence of fire radiative power of forest fires on forest disturbance degree in southern regions of Central Siberia using satellite data. *Sovrem. Probl. Distantionnogo Zondirovaniya Zemli Iz Kosm.* **2022**, *19*, 136–146. (In Russian) [\[CrossRef\]](#)
28. Giglio, L.; Schroeder, W.; Justice, C. The collection 6 MODIS active fire detection algorithm and fire products. *Remote Sens. Environ.* **2016**, *178*, 31–41. [\[CrossRef\]](#)
29. Ponomarev, E.I. A Method for Calculating Direct Fire Carbon Emissions, Taking into Account the Threshold Classification of Vegetation Fire Intensity from Satellite Imagery in the IR Range. Russian Patent RU 2755936 C1, 28 January 2021. (In Russian).
30. dos Santos, S.M.B.; Bento-Gonçalves, A.; Franca-Rocha, W.; Baptista, G. Assessment of Burned Forest Area Severity and Postfire Regrowth in Chapada Diamantina National Park (Bahia, Brazil) Using dNBR and RdNBR Spectral Indices. *Geosciences* **2020**, *10*, 106. [\[CrossRef\]](#)

31. Ponomarev, E.; Zabrodin, A.; Ponomareva, T. Classification of Fire Damage to Boreal Forests of Siberia in 2021 Based on the dNBR Index. *Fire* **2022**, *5*, 19. [CrossRef]
32. Tsvetkov, P.A. Adaptation of *Larix gmelinii* to Fires in the Northern Taiga of Central Siberia. *Sib. Ecol. J.* **2005**, *1*, 117–129. (In Russian)
33. Pleshikov, F.I.; Vaganov, E.A.; Vedrova, E.F. *Lesnye Ekosistemy Eniseyskogo Meridiana (Forest Ecosystems of the Yenisei Meridian)*; Izd-vo: SO RAN, SB RAS: Novosibirsk, Russia, 2002; 356p. (In Russian)
34. Prokushkin, S.G.; Abaimov, A.P.; Prokushkin, A.S.; Masyagina, O.V. Biomass of the Soil Cover and Underbrush in Larch Associations of the Cryolithozone of Middle Siberia. *Sib. Ecol. J.* **2006**, *2*, 131–139. (In Russian)
35. Vedrova, E.F. The Intensity of Organic Matter Decomposition in Gray Soils of Forest Ecosystems in the Southern Taiga of Central Siberia. *Soil Sci.* **2008**, *8*, 973–982. [CrossRef]
36. Vedrova, E.F.; Evdokimenko, M.D.; Bezkorovainaya, I.N.; Mukhortova, L.V.; Cherednikova, Y.S. Carbon Reserves in Organic Matter of Postfire Pine Forests in Southwestern Lake Baikal Basin. *For. Sci.* **2012**, *1*, 3–13. (In Russian)
37. Chevychelov, A.P. Forest fires in Yakutia and their impact on soil cover in terms of predicted climate change. *NEFU Bull. Earth Sci. Ser.* **2019**, *13*, 1889.
38. Sergeeva, O.V.; Mukhortova, L.V.; Krivobokov, L.V. Distribution of forest litter and live ground cover biomass in northern taiga of the central Evenkia depending on relief. *Sib. For. J.* **2020**, *1*, 38–46. (In Russian)
39. Gerber, A.A.; Loiko, S.V.; Lim, A.G.; Istigichev, G.I.; Kulizhsky, S.P. Estimation of carbon stocks in tundra landscapes of Western Siberia. In Proceedings of the Materials IV All-Russian Conference with International Participation, Ulan-Ude, Russia, 15–18 June 2021; pp. 102–104. (In Russian).
40. Ivanova, G.A.; Kukavskaya, E.A.; Bezkorovainaya, I.N.; Bogorodskaya, A.V.; Zhila, S.V.; Ivanov, V.A.; Kovaleva, N.M.; Krasnoshchekova, E.N.; Tarasov, P.A. *The Impact of Fires on the Light Coniferous Forests of the Lower Angara Region*; Nauka (Science): Novosibirsk, Russia, 2022; 204p. (In Russian)
41. Conard, S.G.; Sukhinin, A.I.; Stocks, B.J.; Cahoon, D.; Davidenko, E.P.; Ivanova, G.A. Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia. *Clim. Chang.* **2002**, *55*, 197–211. [CrossRef]
42. Krylov, A.; McCarty, J.L.; Potapov, P.; Loboda, T.; Tyukavina, A.; Turubanova, S.; Hansen, M.C. Remote sensing estimates of stand-replacement fires in Russia, 2002–2011. *Environ. Res. Lett.* **2014**, *9*, 1–8. [CrossRef]
43. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R. High-resolution global maps of 21st century forest cover change. *Science* **2013**, *342*, 850–853. Available online: <https://glad.earthengine.app/view/global-forest-change/> (accessed on 7 June 2023). [CrossRef]
44. Conard, S.G.; Ponomarev, E.I. Fire in the North—The 2020 Siberian Fire Season. *Wildfire* **2020**, *29*, 26–32.
45. Ponomareva, T.V.; Ponomarev, E.I.; Litvintsev, K.Y.; Fennikov, K.A.; Yakimov, N.D. Thermal state of disturbed soils in the permafrost zone of Siberia according the remote data and numerical simulation. *J. Comput. Technol.* **2022**, *27*, 16–35. [CrossRef]
46. Bowd, E.J.; Banks, S.C.; Strong, C.L.; Lindenmayer, D.B. Long-term impacts of wildfire and logging on forest soils. *Nat. Geosci.* **2019**, *12*, 113–118. [CrossRef]
47. Kirillina, K.; Shvetsov, E.G.; Protopopova, V.V.; Thiesmeyer, L.; Yan, W. Consideration of anthropogenic factors in boreal forest fire regime changes during rapid socio-economic development: Case study of forestry districts with increasing burnt area in the Sakha Republic, Russia. *Environ. Res. Lett.* **2020**, *15*, 035009. [CrossRef]
48. Strategy of Socio-Economic Development of the Russian Federation with Low Greenhouse Gas Emissions Until 2050. Order of the Government of the Russian Federation dated 29.10.2021.—No. 3052-R. Available online: <http://publication.pravo.gov.ru/Document/View/0001202111010022> (accessed on 1 May 2023). (In Russian)

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