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Fire Damage to Boreal Forests of Siberia Estimated Based on the dNBR Index †

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Abstract: The impact of fire on the boreal forests of eastern Siberia was analyzed using the normalized burn ratio (NBR) and its pre- versus post-fire difference (dNBR) applied to Landsat-8/OLI data. We provided the classification of fire impact in relation to dominant tree stands and vegetation types. For post-fire areas of different disturbance levels, we evaluated the 5-year dynamics of restoration processes in terms of anomalies in the surface temperature ($\Delta T/T_{bg}$, %) and in the Normalized Difference Vegetation Index ($\Delta NDVI/NDVI_{bg}$, %), which can indirectly characterize the post-fire state of vegetation and recovery.

Keywords: boreal forests; wildfires; normalized burn ratio; fire impact; surface temperature; NDVI; anomalies

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1. Introduction

Up to 1% of the forested area is exposed to wildfires annually in Siberia [1,2], which accounts for a significant proportion of post-fire damage to the boreal forests of the world [3,4]. Considering the climate changes, a further increase in burned areas in Siberia is predicted [5–8]. In addition to the direct post-fire tree stands mortality [9,10], environmental consequences in post-fire plots have been manifest for decades [11–13].

Spectral indices based on satellite information allow quantitative assessment of the degree of pyrogenic disturbance of forests [14]. These data are very important characteristics of the forest state on the scale of Siberia. One such index is the Normalized Burn Ratio (NBR) and its pre- versus post-fire difference (dNBR) [15,16]. The dNBR characterizes the degree of forest damage depending on the type of wildfire and the intensity of burning [17]. Preliminary classification of the fire impact within a post-fire plot [16] allows for remote controlling and predicting the rate and success of vegetation recovery processes. As a rule, the vegetation index is widely used, which was proposed by Rouse et al. in 1973 [18,19]. The Normalized Difference Vegetation Index (NDVI) is the most well-known vegetation index [20].

Post-fire damage and vegetation restoration can also be inspected in terms of reducing the surface reflectivity (albedo) and changing the thermal-insulating properties of the soil and vegetation cover, while post-fire plots are characterized by long-term surface thermal anomalies compared to the temperature of non-disturbed areas [13,21]. Such techniques of quantitative control of post-fire plots are effective for up to 20–40 years, depending on the initial fire impact [22].

Although post-fire tree stands mortality in Siberia is discussed widely [9,10,16], the issue of remote assessment of recovery processes (taking into account the characteristics of dominant tree stands of Siberia) remains not fully studied. Thus, the main aim of this study was to estimate the relation between the degree of fire impact and the dynamics of restoration processes, based on remote spectral indices and on data for dominant tree stands of Siberia.

We investigated the following issues: (a) the variation of the NBR/dNBR index on a series of post-fire sites in relation to the dominant tree stands; (b) the 5-year dynamics of surface temperature anomalies and the NDVI anomalies relative to background values which were restored to characterize post-fire restoration for various variants of the vegetation cover of Siberia.

2. Material and Methods

For the research, we used satellite data for Siberia (50–75° N, 60–150° E). Landsat–8/OLI/TIRS (Operational Ground Thermal Imager/Thermal Infrared Sensor) images of moderate spatial resolution were obtained from United States Geological Survey (USGS) free-access database (https://earthexplorer.usgs.gov/, accessed on 25 August 2022). The spatial resolution of the survey is 30 m for OLI data, and 100 m for TIRS data. A 5-year time series of satellite data (42 images in total) was processed for eight post-fire plots (total area of 218 thousand hectares) in four variants of the dominant tree stands: Larch (*Larix sibirica*) and Scots pine (*Pinus sylvestris*) (light coniferous stands), as well as Spruce (*Abies sibirica*) and Fir (*Picea obovata*) (dark coniferous stands). Vegetation cover was controlled based on the materials of the “Vega-service” (Database of the Institute of Space Research of the Russian Academy of Sciences, IKI RAS, Moscow, http://pro-vega.ru/maps/, accessed 27 July 2022) [23].

Firstly, we classified fire polygons based on the NBR/dNBR ranges to differentiate the initial fire impact. We used the QGIS program and the Semi-Automatic Classification Plugin (Quantum Geographic Information System, version 3.16.3, https://www.qgis.org, accessed on 25 August 2022) to evaluate the NBR/dNBR using standard approaches [15,17,20]. The threshold method was used to identify four classes (undamaged vegetation, low, moderate, and high fire impact) of initial damage to the vegetation cover, corresponding to the dNBR ranges (Table 1) [15,20,24].

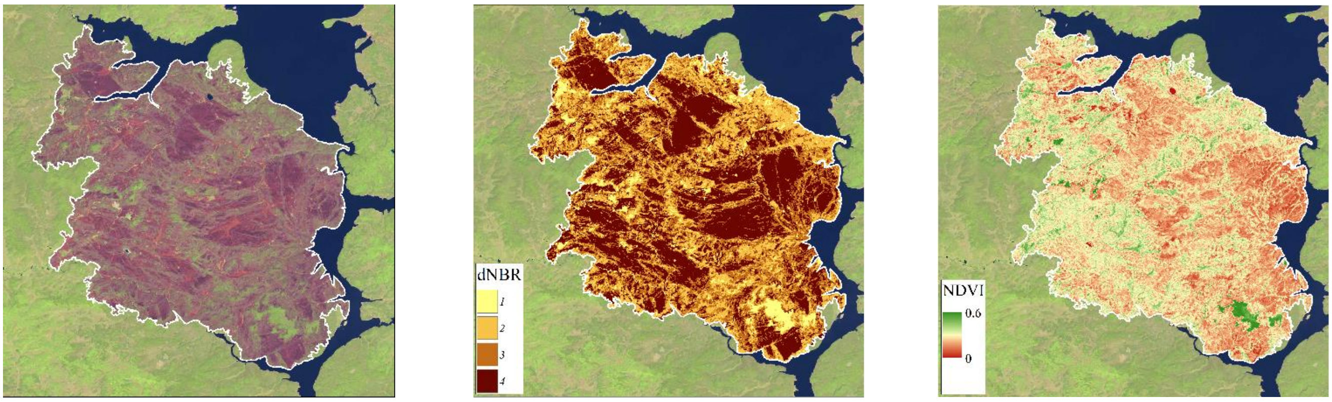
Table 1. Classification of fire impact based on the ranges of the dNBR index.

Class Number	dNBR Range	Degree of Fire Impact	Fire Severity
1	<0.099	Non	Non burned
2	from 0.101 to 0.439	Low	Low severity
3	from 0.440 to 0.659	Moderate	Moderate severity
4	>0.660	High	Moderate-high/High severity

Next, the long-term series of the NDVI and surface temperature was restored from >160 satellite images over a 5-year period after exposure to fire. We used data from the thermal channel B10 (TIR, λ = 10.30–11.30 μm) to calculate the brightness temperature of the surface. Preliminary atmospheric correction was performed for the initial standard product “Landsat Collection 1 Level 1”. Data from channels B4 (RED, λ = 0.63–0.68 μm) and B5 (NIR, λ = 0.85–0.89 μm) were used to calculate the NDVI.

Surface temperature data were averaged over the growing season for each post-fire plot. Temperature anomalies ($\Delta T/T_{bg}$, %) were calculated as the ratio of the average values within the post-fire plot (ΔT) and background values (T_{bg}) of the non-disturbed area. Similarly, relative NDVI anomalies were determined ($\Delta NDVI/NDVI_{bg}$, %). At least 20 measurements were carried out for each post-fire plot (Figure 1). Averaging over the vegetation season was performed by 3–6 values per month.

Finally, we analyzed the 5-year post-fire trends of $\Delta T/T_{bg}$ and $\Delta NDVI/NDVI_{bg}$ anomalies for each variant of the dominant tree stand. Trends were considered separately for low, medium, and high degrees of initial fire impact.



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

Figure 1. Processing of Landsat-8/OLI images of a post-fire plot of 2021 in Larch tree stands (*Larix sibirica*): (**a**) post-fire plot; (**b**) dNBR index values; (**c**) distribution of NDVI.

3. Results and Discussion

3.1. Fire Impact Ratio in Dominant Tree Stands

We evaluated the ratio of areas with different levels of post-fire impact in terms of dNBR (Table 2). In general, the proportions of low, moderate, and high fire severity were 37%, 39%, and 24% of the total area burned, respectively, in dense tree stands. The proportions varied to 30%, 57%, and 13%, respectively, for sparse stands and tundra vegetation dominant in the north of Siberia.

Table 2. Fire area proportion and standard deviation (SD) according to severity/fire impact level from dNBR ranges under the conditions of Siberian forests.

Tree Stand	Burned Area Proportion ± SD, %		
	Low Severity	Moderate Severity	High Severity
Larch (*Larix sibirica*)	20.9 ± 4.3	45.8 ± 8.2	33.2 ± 11.6
Scots pine (*Pinus sylvestris*)	50.3 ± 13.5	36.2 ± 11.6	12.6 ± 13.5
Dark Coniferous (*Abies sibirica*, *Picea obovata*)	39.3 ± 17.09	34.4 ± 9.8	26.4 ± 20.11

Fires in Siberian Larch forests annually account for up to 65% of the total area of burnt forests [1]. In larch forests, up to 80% of the total area of post-fire sites is attributed to moderate (>45% of the total area) and high levels (33%) of fire impact. Fires in pine forests on average account for up to 18% of the total area burned annually. Post-fire plots in Pine stands were attributed to low (~50%) and medium (36%) fire impact. A high level of post-fire damage was recorded only in 12.6% of territories (SD = 13.5 for $\alpha = 0.05$). The ratio of wildfires in the dark coniferous stands (*Abies sibirica*, *Picea obovata*) of Siberia is about 5.6% [1]. In this regard, we were able to consider a limited number of fires in these stands. We summarized the statistics for wildfires in Spruce and Fir in Table 2. The area of fires were 39%, 34%, and 26% for low, medium, and high fire severity/initial impact, respectively. Significant SD was evaluated for high severity (SD = 20.1 for $\alpha = 0.05$). These results correspond to the previously obtained data for a larger sample of fires in Siberia [16].

3.2. Long-Term Temperature Anomalies

The fire impact reduces the reflectivity of the surface (albedo). The heat-insulating properties of the soil and vegetation cover are also changing. It was previously shown that long-term anomalies of the surface thermal regime in relation to the background are typical for post-fire areas [13,21,22].

We found that the values of temperature anomalies ($\Delta T/T_{bg}$, %) are determined by the initial level of fire impact and by the type of tree stand (Figure 2a–d). Within 5 years after the fire, an exponential decrease in temperature anomalies is observed. The highest level of initial thermal anomaly in the first year after the fire is observed in Pine plantations (exceeding by 45% relative to the background) under the conditions of high initial fire impact in terms of dNBR (Figure 2a). The initial level of $\Delta T/T_{bg}$ was ~35% for post-fire plots in Larch forests, and was 25% and 20%, respectively, for plots of Spruce and Fir.

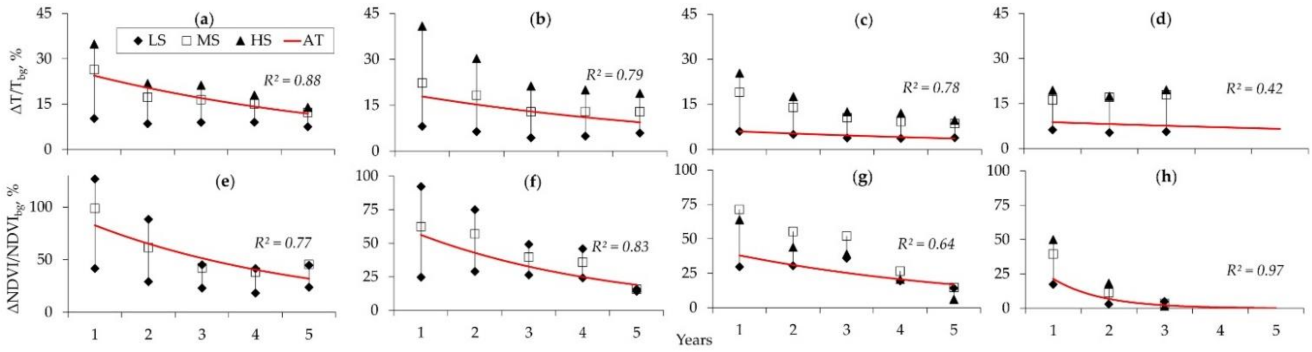


Figure 2. 5-year dynamics of $\Delta T/T_{bg}$ (**a**–**d**) and $\Delta NDVI/NDVI_{bg}$ (**e**,**f**) anomalies in post-fire plots in dominant tree stands: (**a**,**e**) Larch (*Larix sibirica*); (**b**,**f**) Scots pine (*Pinus sylvestris*); (**c**,**g**) Spruce (*Abies sibirica*); (**d**,**h**) Fir (*Picea obovata*). LS is a low degree of severity in terms of dNBR, MS is a moderate degree of severity, HS is a high degree of severity, and AT is an exponential approximation of the averaged values.

The values of $\Delta T/T_{bg}$ are stabilized over a 5-year period. An exponential trend (R^2 = 0.42–0.88) describes the rate of decrease of the temperature anomaly for all variants of the initial fire severity (Figure 2. AT), although the residual $\Delta T/T_{bg}$ still remains significantly high (~15%) in post-fire plots with a predominance of light conifers (Pine, Larch). In dark conifers stands, the residual $\Delta T/T_{bg}$ (~5–7%) are twice as low as in light conifers. At the same time, the rate of the recovery process (in terms of thermal anomalies) is significantly lower than in light coniferous forests (Figure 2, AT for a, b versus c, d).

3.3. NDVI Anomalies

A relatively high recovery rate was recorded for the $\Delta NDVI/NDVI_{bg}$ anomalies during the first 3 years after fire impact. Furthermore, the values are stabilized at a level of at least 5–15% understatement of the background, depending on the dominant tree stands (Figure 2e–h). We found high level of $\Delta NDVI/NDVI_{bg}$ anomaly (~40–45%) in Larch forests after 5 years of post-fire recovery, because of significant disturbance of the ground cover [25]. Such consequences can stay significant, as a rule, no more than 7–10 years after fire impact [12]. For other considered tree stands, the level of residual $\Delta NDVI/NDVI_{bg}$ anomaly does not exceed 5–15% of the background values after 5 years of restoration. Such ranges may be statistically insignificant for further assessment of recovery processes (5 years or more) according to satellite vegetation indices.

An exponential trend (R^2 = 0.64–0.97) describes the rate of decrease of $\Delta NDVI/NDVI_{bg}$ anomaly for all variants of the initial fire severity (Figure 2. AT).

4. Conclusions

Spectral indices allow us to estimate both the degree of fire impact on tree stands and the rate of recovery processes in terms of $\Delta T/T_{bg}$ and $\Delta NDVI/NDVI_{bg}$.

We quantified the proportions of low (37%), moderate (39%), and high (24%) fire severity in dense tree stands. The proportions were varied to 30%, 57%, and 13%, respectively, for sparse stands and tundra vegetation dominant in the north of Siberia.

We evaluated the most significant level of $\Delta T/T_{bg}$ anomaly in Pine stands (~40%), next in Larch stands (~35%), and in dark coniferous spruce (~25%) and fir (~20%) forests. An exponential decrease in temperature anomalies is observed within 5 years after the fire impact. A high recovery rate was recorded for the ΔNDVI/NDVI$_{bg}$ anomalies during the first 3 years after fire impact, and finally the values stabilized at 5–15% understatement of the background.

Thus, for effective satellite monitoring of recovery process, it is necessary to consider both the initial level of fire damage and the differences caused by the dominant tree stands of Siberia. This is the least costly and most effective approach for Siberia, despite all the limitations.

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