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Post-fire effect modeling for the permafrost zone in Central Siberia on the basis of remote sensing data

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Abstract: The increasing trend of larch forests burning in the permafrost zone (60–65° N, 95–105°E) is observed in Siberia. Up to 10–15% of entire larch forests were damaged by wildfire during the last two decades. Current research analysed the reflectance and thermal anomalies of the post-pyrogenic sites under the conditions of permafrost. Studies are based on long-term Terra, Aqua/MODIS (Moderate Resolution Imaging Spectroradiometer) survey for 2006–2018. We used IR thermal range data of 10.780–11.280 microns (MOD11A1 product) and we evaluated NDVI from MOD09GQ product as well. The averaged temperature and NDVI dynamics were investigated in total for 50 post-fire plots under different stages of succession (1, 2, 5 and 10 years after burning) in comparison with non-disturbed vegetation cover sites under the same conditions. We recorded higher temperatures (20–47% higher than average background value) and lower NDVI values (9–63% lower than non-disturbed vegetation cover) persisting for the first 10 years after the fire. Under conditions of natural restoration thermal anomalies of the ground cover remained significant for more than 15 years, which was reflected on long-term satellite data and confirmed by ground-based measurements. To estimate impact of thermal anomalies on soil temperature and thawed layer depth we used the Stefan's solution for the thermal conductivity equation. According to results of numerical simulation, depth of the seasonal thawed layer could increase more than 20% in comparison with the average statistical norm under the conditions of excessive heating of the underlying layers. This is a significant factor in the stability of Siberian permafrost ecosystems requiring long-term monitoring.

Keywords: remote sensing, permafrost, larch forests, thermal anomaly, post-pyrogenic sites, seasonal thawed layer

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1. Introduction

Wildfire impact is the main factor, which affected strongly on the state of boreal ecosystems of Siberia. The postfire changes in the vegetation cover in the larch forests of Central Siberia form conditions for significant changes in thermal balance. These changes can affect the seasonal thawed layer and its dynamics. Significant and long-term post-fire effects are well-documented in the permafrost zone of Siberia [1–5]. A number of the problems associated with vegetation cover disturbances have been discussed, such as degradation of seasonal thawed layer of permafrost as well as variation of temperature and water regimes of soils [3,6–7]. Postfire changes in the thermal balance can result in the disturbance of the "transitional layer", which protects the upper horizons of permafrost [8]. Given the vast nature of the geographical area to be managed, satellite techniques are the primary means for wildfire monitoring in most part of the boreal forest zone of Russia. Evaluation of the effects of fires on Siberian ecosystems also requires the usage of remote data.

The main aims of study are (i) to perform a quantitative analysis of thermal anomalies in fire-damaged areas of the permafrost zone of Siberia and its dynamics according to the stages of post-fire succession, (ii) to obtain estimates of the depth of the seasonally thawed layer under conditions of excessive heat flux on the surface based on numerical modeling technique.

2. Experiments

2.1. Study area

The study area included the territory of Evenkia (central part of Siberia), covering the territory from 62° to 66° N and from 96° to 107° E (Fig. 1). This region belongs to the Central Siberian flat-mountainous taiga region of the boreal taiga zone. Siberian larch (*Larix sibirica*, *Larix gmelinii*) is the dominant species in the forest stands. The study area belongs to the continuous permafrost zone according to the Circum-Arctic permafrost and ground ice map by the National Snow and Ice Data Center [9]. Large-scale wildfires are typical for the territory, which are detected by satellite monitoring only and are not served by fire protection system.

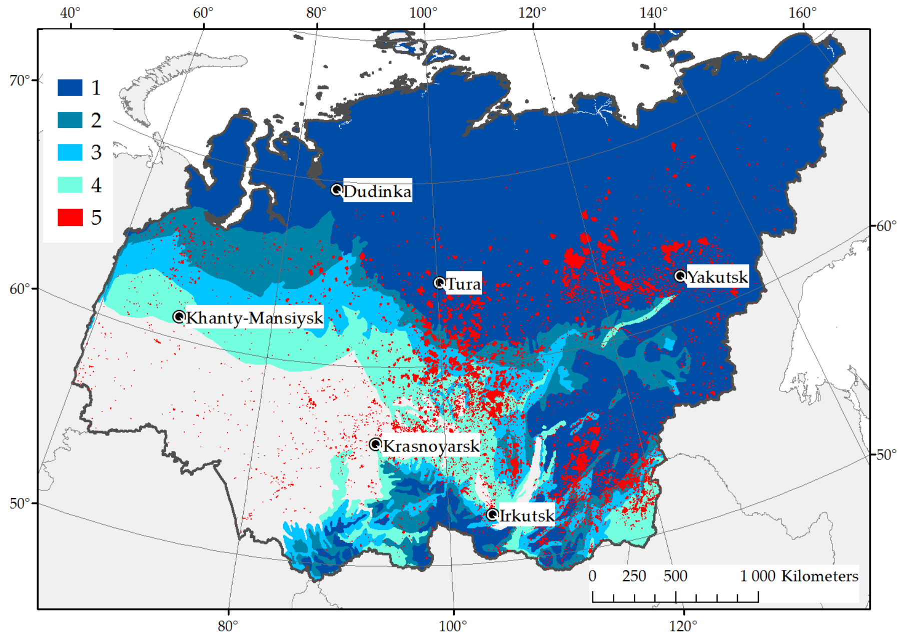


Figure 1. Study area in Central Siberia. Types of permafrost: 1 – continuous (90 – 100% of territory); 2 – discontinuous (50 – 90%); 3 – sporadic (10 – 50%); 4 – isolated patches (0 – 10%); 5 – remote sensing monitoring data on burned area in 2016 – 2018.

2.2. Materials and method

Retrospective multispectral materials of Terra and Aqua / MODIS for the period 2006–2018, as well as information on wildfires in the format of geo-information polygonal layer [10] were used to post-fire plots selecting. High resolution imagery (15–30 m) of Landsat/ETM/OLI (Enhanced Thematic Mapper/ Operational Land Imager) and Sentilel-2 were used for wildfire geometry precise estimating. Multispectral data from Terra/Aqua and the retrospective imagery allows evaluate long-term changes using both the "vegetation" channels of the spectrum and the thermal range. The characteristics of the postfire area were determined by analyzing of spectral features in the range of λ_1 = 0.620–0.670 μm, λ_2 = 0.841–0.876 μm (product MOD09GQ), and in thermal band of λ_3 =

10.780–11.280 μm (product MOD11A1)/(L2G и L3 https://lpdaac.usgs.gov/dataset_discovery/modis) [11,12].

Temperature, albedo and Normalized Difference Vegetation Index (NDVI) dynamics were investigated in total for 50 post-fire plots under different stages of succession (1, 2, 5 and 10 years after burning) in comparison with non-disturbed vegetation cover sites under the same natural conditions. Across the entire set of initial data, a 10-days averaging was performed taking into account the recovery succession stages. Dates of fires and post-fire stages were controlled using the attribute information of the wildfire databank [10].

Variety of the thaw depth of the permafrost layer (Z) was estimated depending on the thermal anomaly at the surface and vegetation recovery stage. Numerical modeling was based on the Stefan solution of the heat conduction equation for the depth of the seasonal thawing layer [4,13,14]:

$$Z = \sqrt{\frac{2\lambda_f (T_s - T_f)\tau}{l \cdot u \cdot \rho}}, \quad (1)$$

where ρ is the density (kg/m^3), T is the temperature of the surface (T_s) and the temperature of permafrost layer (T_f), x is the depth of the layer (m), λ is the thermal conductivity coefficient (W/(m °C)) for the thawing layer (λ_1) and permafrost layer (λ_2), τ is the duration of heating, l is specific heat of fusion (J/kg), u is the volumetric water content of soil (%).

3. Results and discussion

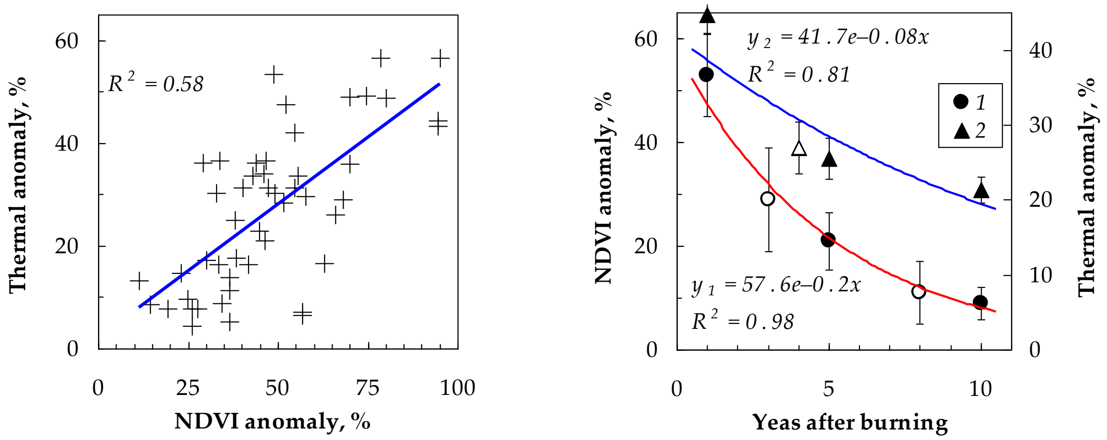
Over the study area, fires were recorded on a total area of 12.743 MHa during 22 years of available instrumental observations. It is more than $\gamma > 12.0\%$ of forested area, relative burned area (RBA) was 0.51±0.18% per year. Average RBA for Siberia is 1.19% [15]. For comparison, RBA is 0.56% for the forests of Western Canada [16]. Significant "accumulative" effect from fires provokes large-scale anomalies of vegetation cover and thermal balance (Table 1).

Table 1. The averaged characteristics of post-pyrogenic sites in the mid-summer (maxima of thermal anomaly)

Time after burning, years	Anomalies of NDVI, %	Range of temperature maxima, °C	Anomalies of temperature, %
1	53.5±10.7	6.5–7.2	40–50
5	21.0±7.8	3.8–4.9	27–32
10	9.0±5.0	3.4–4.6	15–20

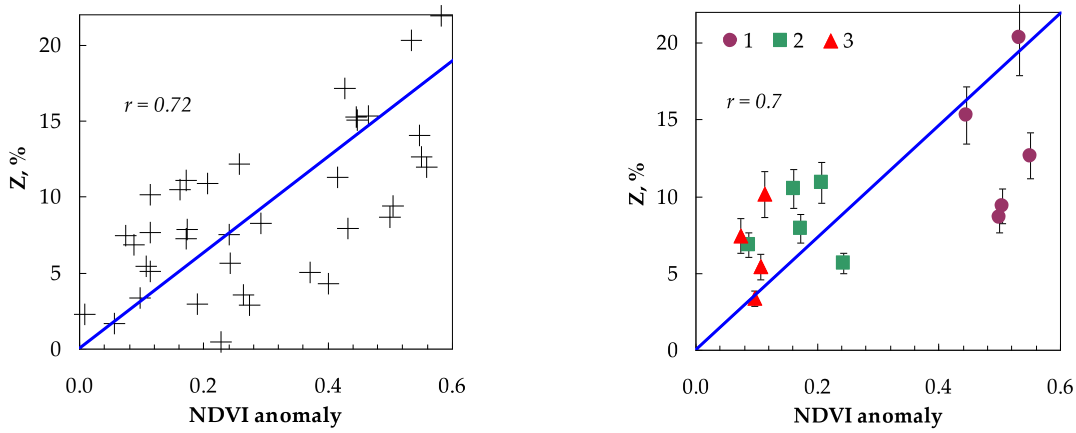
On the postfire sites aged 1 year, the value of NDVI was typically of 50 ± 8% comparing to the non disturbed plots. The deviation of NDVI (21 ± 7%) abnormality was 2 times lower of the control values on the postfire sites aged 5 years. Fire sites with an age of 10 years do not differ significantly from the control in terms of NDVI, which is caused by success restoration of on-ground vegetation cover. The mean deviation from control values did not exceed 9% with a significant dispersion of σ = 5%. Anomalies in vegetation cover are lost during the next 5–7 years after fire. However, the process of tree stands restoring is much longer up to 50 years [5,7,17].

For the same plots vegetation anomalies correlates with data on mid-summer thermal anomalies as well (Fig. 2, a). The maxima of temperature abnormality are staying significant more than 10–15 years after a wildfire (Table 1, Fig. 2). Absolute temperature maxima were fixed in range of 7.0 ± 1.5°C during mid-summer for plots of burnt larch forest of Central Siberia. This is 20–40% higher than the temperature of undisturbed sites. The rate of loss of thermal anomalies was 2.5 times lower than the rate of vegetation restoration according to NDVI. The coefficients of exponential approximation are –0.08 and –0.2, respectively (Fig 2, b).



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

Figure 2. Experimental data on NDVI and temperature for post-fire plots relative to non-disturbed territories: (**a**) Thermal anomalies *vs* NDVI anomaly; (**b**) Long-term dynamics of NDVI index anomalies averaged for June – August (1) and averaged thermal anomalies (2).



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

Figure 3. Numerical modeling result on abnormal thaw depth after wildfire impact on vegetation cover: (**a**) Increment of the thawing layer depth *vs* NDVI anomaly. Correlation of r=0.72; (**b**) Thawing layer depth anomaly during vegetation recovery: 1 – one year after burning, 2 – 5 years after burning, 3 –10 years after burning.

Numeric simulation and field measurements [5,7,18] fix the average statistical norm of seasonal thawing of active soil layer at 0.6–2.0 m under the conditions similar to the region of interest. As shown by the results of numerical simulation, the excess heat flux on the surface causes an increase in depth thawing (Z) on average by 10–20% (Fig. 3) relative to the average statistical norm. Thawing of the soil profile is possible for an additional 0.5 m in depth under the conditions of stable anticyclone that is usually observed over central part of Siberia during summer for up to 20–30 days [19] and an excessive insolation of the surface. Despite the fact that the maximum of the thermal anomaly is fixed in the middle of summer (Table 1), the maximum of thawing depth should be expected in August. The delay in temperature dynamics with depth of soil profile should be taking into account [20].

The results of satellite monitoring [4] and a number of ground-based experiments [7] allow us to state the long-term (15–25 years) effects of thermal anomalies on the post-fire sites of the permafrost zone. On post-fire plots the NDVI values are restored 3 to 5 years after the fire. But surface temperature anomalies still can be considered as statistically significant during 10–15 years after burning. The low rate of vanishing of the thermal anomaly makes it possible to consider this factor of long-term influence on the state of the soil and the permafrost as one of the most significant. A similar effect was observed, in particular, in Alaska [6]. The obtained results are also consistent with the data for Russian forests [3,21]. This should be taken into account when assessing the state of the forests, tree mortality or monitoring of regeneration processes in the forests of the permafrost zone using satellite methods [22]. Temperature fields restored using the satellite data can be considered as the basis for monitoring the condition of forests of the permafrost zone of Siberia.

Considering the predicted climate changes, toughening of fire regimes and increased fire activity in the forests of the permafrost zone [15,19,23,24], the integral effect of post-fire thermal anomalies will strengthen and is likely to grow increasingly.

4. Conclusions

Changes in thermal regime of postfire areas in Central Siberian are accompanied by an abnormal increase in average temperatures of the soil surface by $\Delta T = 7.2 \pm 1.3$°C. This is 20–40% higher than the temperature of undisturbed sites. The NDVI values are restored 3 to 5 years after the fire. The rate is depending on the regeneration of the vegetation cover. The partial regeneration of vegetation covers does not compensate the changes, which lead to long-term temperature abnormalities. The thermal balance of postfire sites with disturbed vegetation cover remain affected for more than 15 years.

It was found that the abnormal temperatures on a significant area of the permafrost zone can result in a seasonal increase in the thawing depth of the soil by 10–20% when compared with the mean normal value.

Vast postfire disturbances (currently up to 25% of total forested area per the last two decades) of the vegetation cover in the northern regions of Siberia have a significant effect on the temperature regime of the "ground cover"– "soil"–"permafrost layer" boundary layer. A more detailed study of post-fire effects is important for predicting the response of boreal ecosystems to the fire impact, which currently tends to increase.

The low rate of the thermal anomaly lost, at least in the first 10 years after the fire, makes it possible to consider this factor of long-term influence on the state of the seasonal thawed soil layer as one of the most significant. This technique and remote sensing data could be used for determining the stability of permafrost ecosystems.

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

Abbreviations

The following abbreviations are used in this manuscript:

MODIS: Moderate Resolution Imaging Spectroradiometer
NDVI: Normalized Difference Vegetation Index
RBA: Relative Burned Area
ETM: Enhanced Thematic Mapper
OLI: Operational Land Imager

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