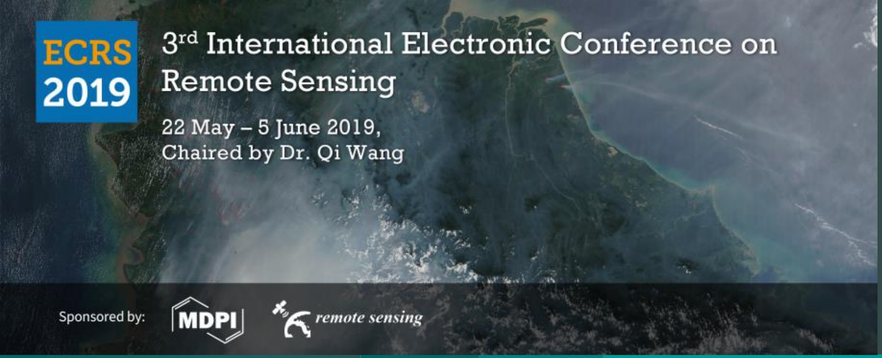

Post-fire effect modeling for the permafrost zone in Central Siberia on the basis of remote sensing data

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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. More than 10% of entire larch forests were damaged by wildfire during the last 15 years. Post-fire effect determines long-term dynamics of the seasonal thawed layer.

Current research analyzed 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 background temperature 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 profile 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.

Actuality

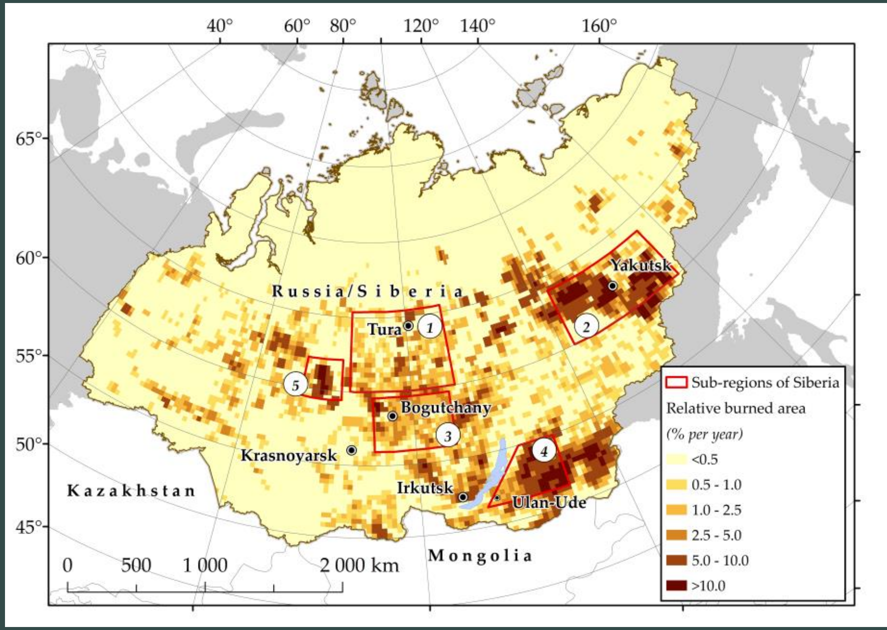
Wildfire impact is the main factor, which affected strongly on the state of boreal ecosystems of Siberia. The postfire changes in the vegetation cover in the larch forests of Central Siberia form conditions for significant changes in thermal balance. These changes can affect the further dynamics of the seasonally thawed layer.

Significant and long-term post-fire effects are well-documented in the permafrost zone of Siberia (*Kharuk et al., 2005; Anisimova, Sherstiukov, 2016; Ponomarev, Ponomareva, 2018; Knorre et al., 2019*). Topical problems, such as changes in the distribution and degradation of seasonally thawed layer of permafrost soils, variations of temperature and water regimes, and other changes caused by the disturbances of the vegetation cover have been discussed in many studies (*Anisimova and Sherstiukov, 2016; Brown et al., 2016; Bezkorovaynaya et al., 2017*). Postfire changes in the thermal balance can result in the disturbance of the "transitional layer", which protects the upper horizons of permafrost (*Desyatkin et al., 2017*).

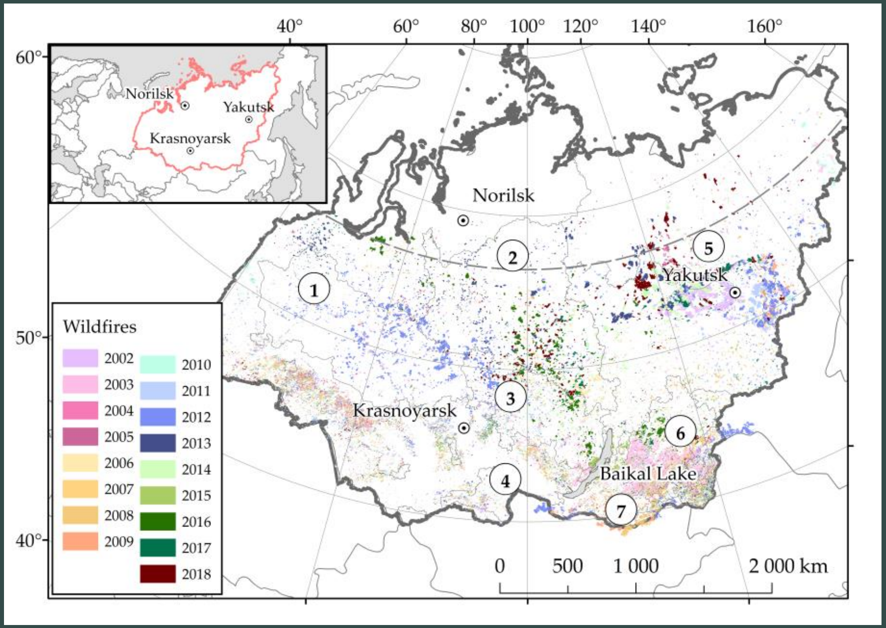
Given the vast nature of the geographical area to be managed, satellite techniques are the primary means for wildfire monitoring in most part of the boreal forest zone of Russia.

<u>The main aims are</u> (i) to perform a quantitative analysis of thermal anomalies in fire-damaged areas of the permafrost zone of Siberia at various 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.

Fire impact / relative burned area



Relative burned area (RBA) per year, %
1 – Evenkia, 2 – Yakutia,
3 – Angara river basin, 4 – Trans-Bailkal,
5 – Western Siberia area

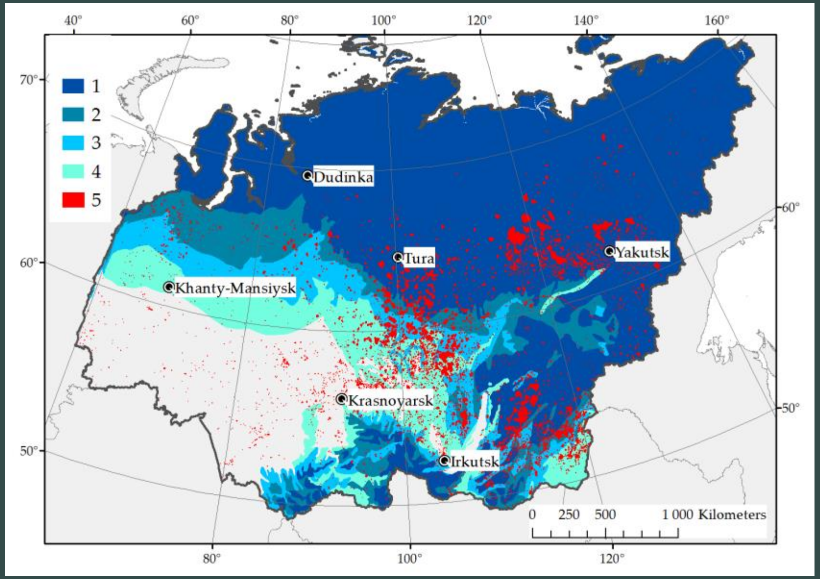


Long-term (2002-2018) data on
wildfires in Siberian forests

Relative burned area per year is in range of **0.1%** — **14.5%** in different parts of Siberia.
Average RBA for Siberia is **1.19**%. For comparison RBA is **0.56**% for the forests of Western Canada (*deGroot et al., 2013*).

Area of interest

Examples of post-fire changes in soil and vegetation cover

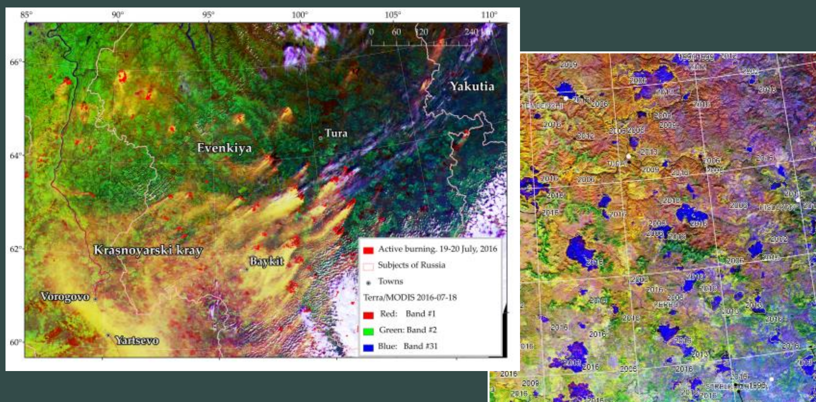


Types of permafrost: 1 – continuous (90 – 100%); 2 – discontinuous (50 – 90%); 3 – sporadic (10 – 50%); 4 – isolated patches (0 – 10%);
5 – burned area in 2016 – 2018

The study area included the central regions of Evenkia, covering the territory from 62° to 66° N and from 96° to 107° E. This region belongs to the Central Siberian flat-mountainous taiga region of the taiga forest vegetation 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 (*Brown et al., 2002*).

Remote sensing data pre-processing

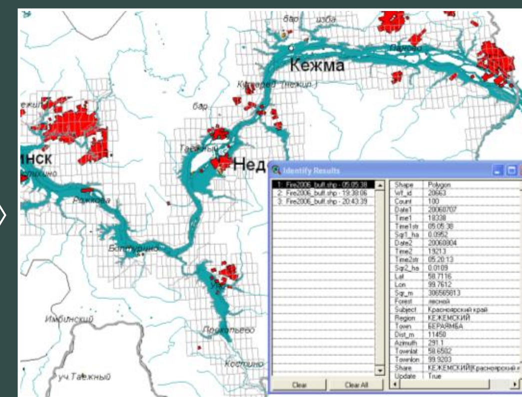
A Raw satellite data



Active burning and post-fire pattern of territory.
Terra/MODIS

B Pre-processing

C Wildfires database in GIS



Database time: 1996–2019;
Data volume: ~$\mathbf{2{\times}10^6}$ records;
Data format: polygonal GIS-layers, and joint attribute data for each record

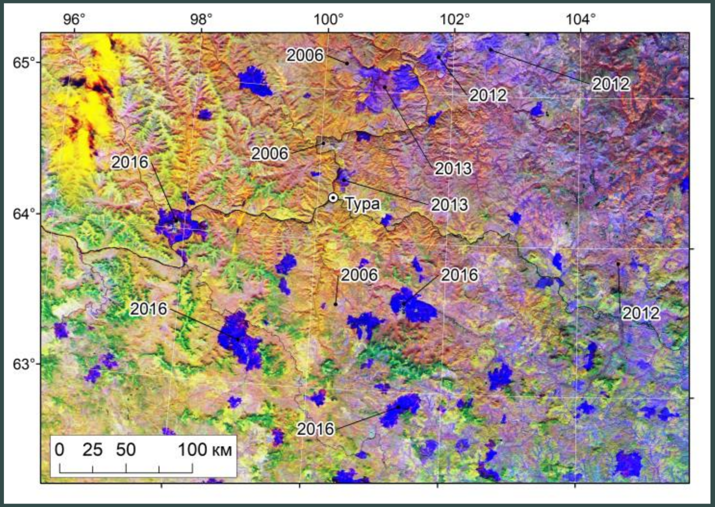
D Data analysis, post-fire effects investigating

Terra/MODIS

Landsat-8/OLI

Sentinel-2

The data was used



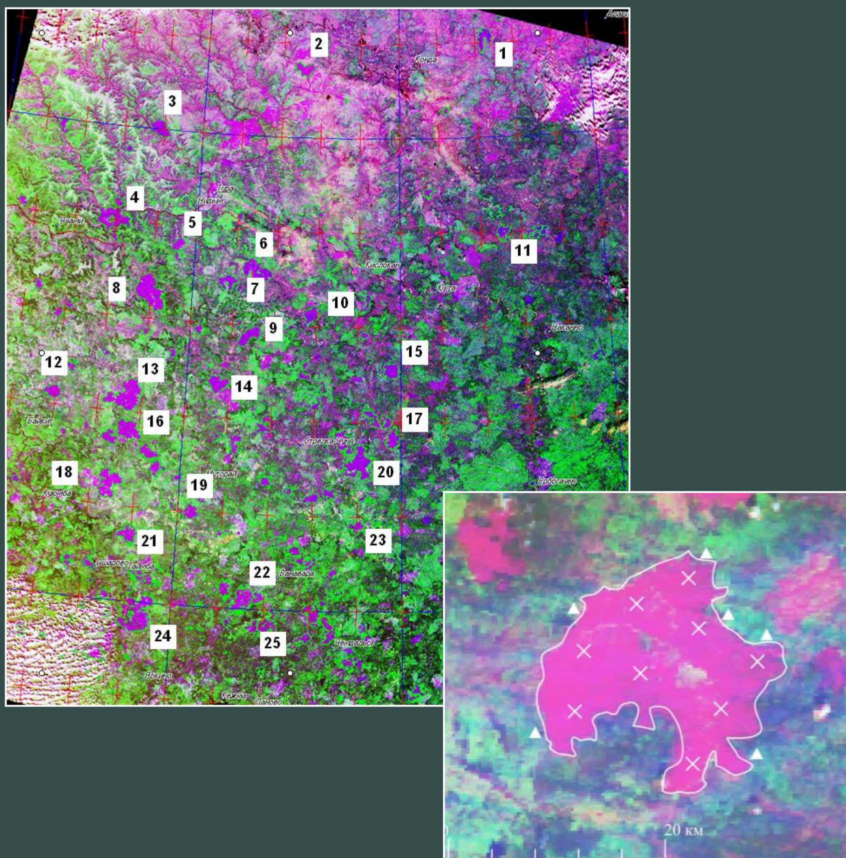
1) Retrospective multispectral materials of Terra and Aqua / MODIS for the period 2006–2018, as well as information on wildfires in the format of geo-information polygonal layer (*Ponomarev, Shvetsov, 2015*) were used to post-fire plots selecting

2) High resolution imagery (15–30 m) of Landsat/ETM/OLI (Enhanced Thematic Mapper/ Operational Land Imager) and Sentilel-2 for wildfire geometry precise estimating

3) Multispectral data from Terra/Aqua and the retrospective imagery were very useful for such studies because they allow evaluate long-term changes both in the "vegetation" channels of the spectrum and in the thermal range.

The parameters at 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).

Methods



Test post-pyrogenic sites on the multispectral image of Terra / MODIS; Selection of points for measurement of temperature/NDVI.

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.

Dates of fires were controlled using the attribute information of the wildfire databank.

The averaged data on albedo, NDVI and temperature was collected for the post-pyrogenic sites and was analized jointly with averaged values obtained for non-disturbed sites.

Across the entire set of initial data,
a 10 days- averaging was performed taking into account the recovery succession stages
(1st, 5th, 10th year after the burning).

Results / Wildfires impact

On-ground cover pattern after burning / Measurement of amount of on-ground cover after burning

Wildfires impact on vegetation of area of interest during the last 22 years of satellite monitoring

Parameter	Numbers of wildfires	S, MHa	Relative burn area (γ), %
For 1996-2018	7614	12.74	10.90
Per year	346	0.58	0.51
SD (σ)	98	0.19	0.18

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

Vegatation cover

Post-fire plots in larch trees shrub-green moss. Evenkia region, Siberia.
Photo by Irina N. Bezkorovaynaya (Siberian Federal University)

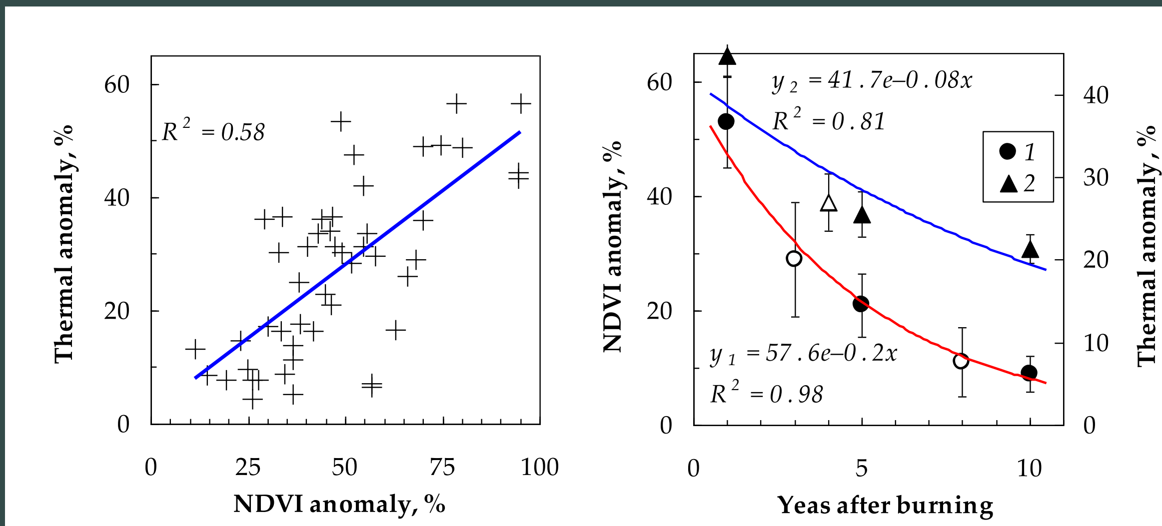
Comparison of spectral characteristics for disturbed and undisturbed areas allows assessing the fire impact and the dynamics of post-fire succession. This procedure based on the calibrated values on the surface albedo (%), invariant vegetation index (Normalized Difference Vegetation Index, NDVI), and temperature (°C).

On the postfire sites aged 1 year, the value of NDVI is 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 the dynamical restoration of the vegetation cover. The mean deviation from control values did not exceed 9% with a significant dispersion of $\sigma = 5\%$.

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 (*Kharuk et al., 2005; Knorre et al., 2019; Bezkorovaynaya et al., 2017*).

Dynamics of thermal and vegetation anomalies



Long-term dynamics of

1) Dynamics of NDVI index anomalies averaged for June – August

2) Averaged thermal anomalies

Thermal anomalies *vs* NDVI anomaly

The maxima of temperature abnormality are staying significant more than 10–15 years after a wildfire.
For burned larch forest of Central Siberia such maxima was fixed in range of 7.0 ± 1.5°C during mid-summer.
The rate of loss of thermal anomalies was 2.5 times lower than the rate of NDVI restoration (the coefficients of exponential approximation are –0.08 and –0.2, respectively).

Seasonal thawing layer depth

Numerical Simulation of the Thawing Depth

The thawing depth of the permafrost layer was estimated by quantitative methods depending on the thermal field abnormalities of the studied sites. The dynamic parameters of heat energy in soils were calculated using partial differential thermal conductivity equation (Arzhanov et al., 2007; Vinogradov et al., 2015):

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\frac{\partial^2 T}{\partial x^2},$$

with Stefan boundary conditions of phase transitions on the boundary of layers

$$\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x=x_{12}} - \lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{x=x_{12}} = lu\rho \frac{\partial x_{12}}{\partial t},$$

where ρ is the rock density (kg/m^3), c is specific heat capacity (J/(kg °C)), T is the temperature of the thawing layer (T_1) and permafrost layer (T_2), 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), l is specific heat of fusion (J/kg), u is the volumetric water content of soil (%), and x_{12} is the depth of boundary layer of permafrost and thawing horizons (m).

The Stefan solution for the depth of seasonal thawing layer (x) has the following form (Arzhanov et al., 2007):

$$x = \sqrt{\frac{2\lambda_f (T_s - T_f)\tau}{lu\rho}}, \quad (1)$$

where T_s is the surface temperature, T_f is the initial temperature in freezing point, λ_f is the thermal con-

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Variety of the thaw depth of the permafrost layer (Z) was estimated depending on the thermal anomaly at the surface.
Numerical modeling was based on the Stefan solution of the heat conduction equation in partial derivatives for the depth of the seasonal thawing layer.

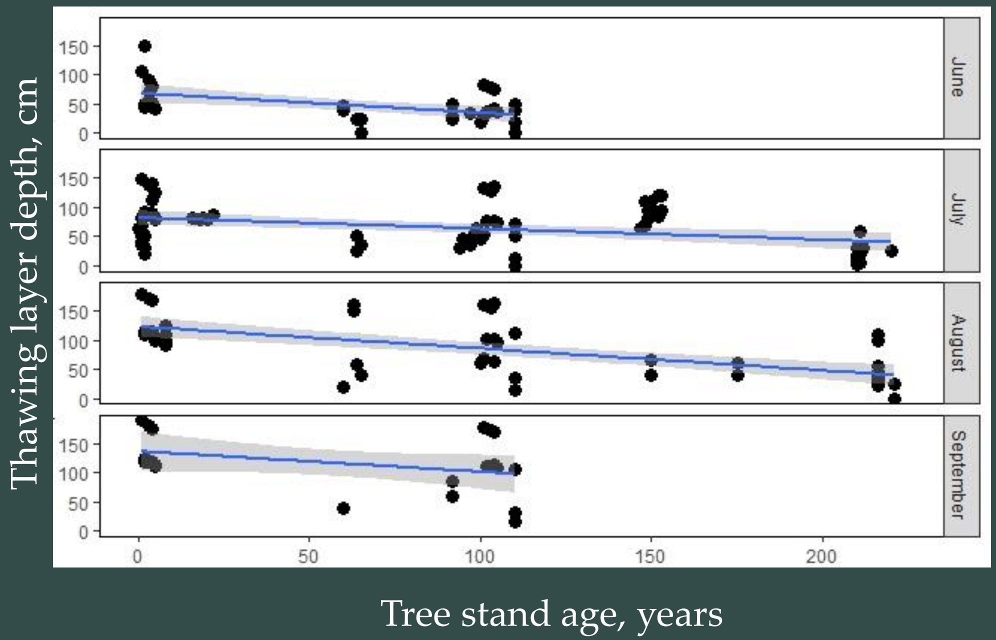
$$x = \sqrt{\frac{2\lambda_f (T_s - T_f)\tau}{l \cdot u \cdot \rho}}$$

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 (%)

The variation of the seasonal thawing layer depth was determined as the ratio $Z = \Delta x / x_{backgranund}$

Ponomarev E.I., Ponomareva T.V. (2018) The Effect of Postfire Temperature Anomalies on Seasonal Soil Thawing in the Permafrost Zone of Central Siberia Evaluated Using Remote Data// Contemporary Problems of Ecology. 2018. Vol. 11. # 4. P. 420–427. doi: 10.1134/S1995425518040066.

Estimation of thawing layer depth

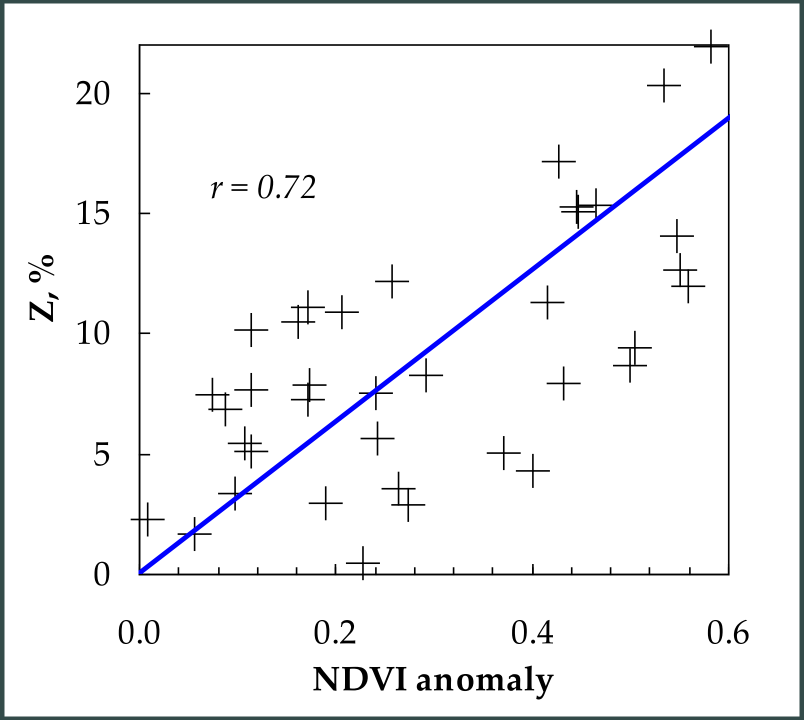


Available literature data on active layer depth for different ages of tree stand

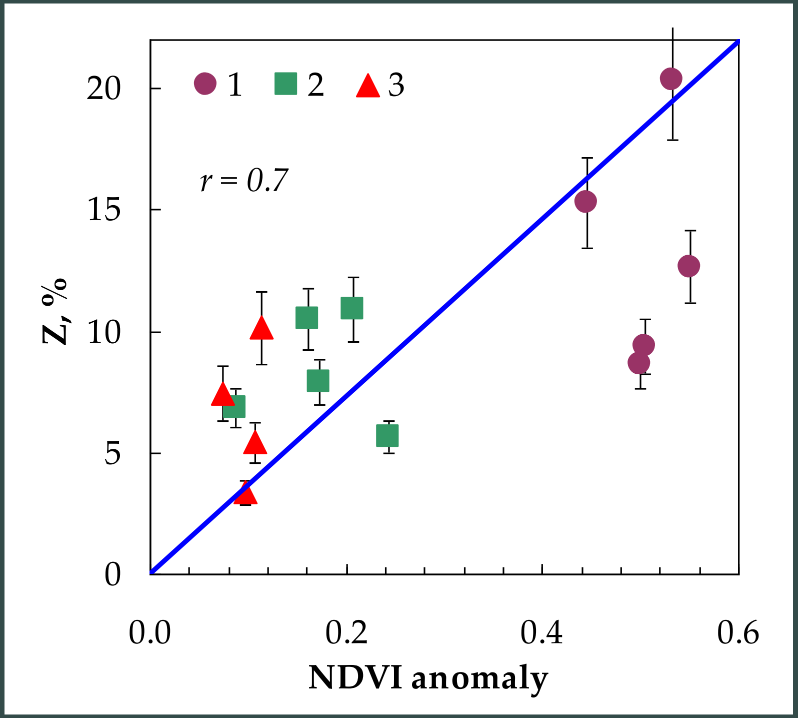
Under the condition of abnormal heating of significant areas, the thawing depth is 10–20% higher than the mean normal value. The depth of seasonally thawing layer of permafrost could vary significantly during the season (*Knorre et al., 2019*). It was confirmed by results of numerical modeling of the depth of the seasonal thawing layer (*Ponomarev, Ponomareva, 2018).*

Estimation of thawing layer depth

Numerical modeling result on abnormal thawing after wildfire impact on vegetation cover



Increment of the thawing layer depth
vs NDVI anomaly.
Correlation of r=0.72



Thawing layer depth anomaly during vegetation recovery process

1 – one year after burning,
2 – 5 years after burning,
3 –10 years after burning.

Conclusion

Changes in thermal regime of postfire areas in Central Siberian are accompanied by an abnormal increase in average temperatures of the soil surface by ΔT = **7.2 ±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 depend 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 10 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 stable functioning of permafrost ecosystems.

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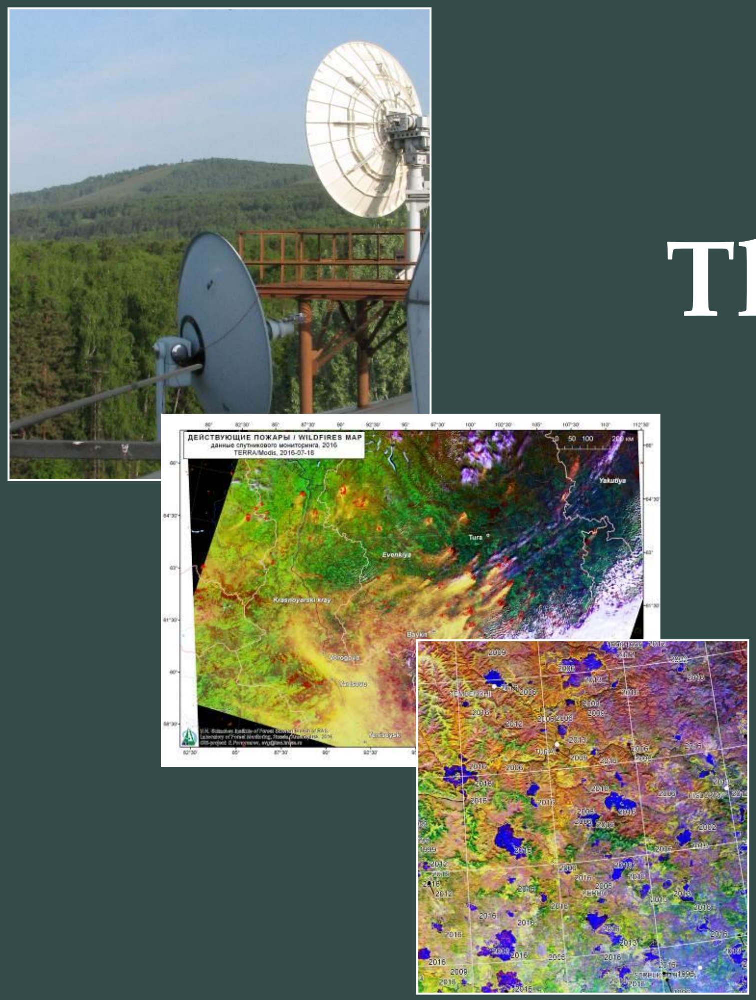

Thank you!

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