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

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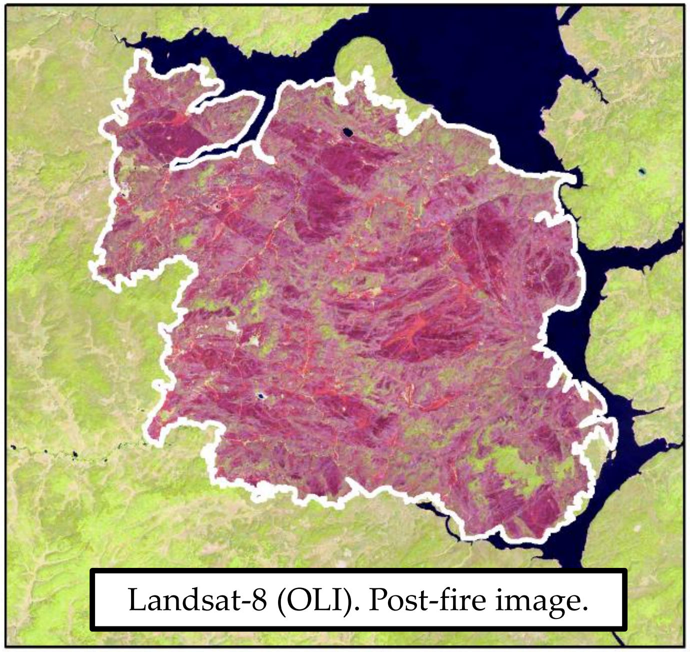
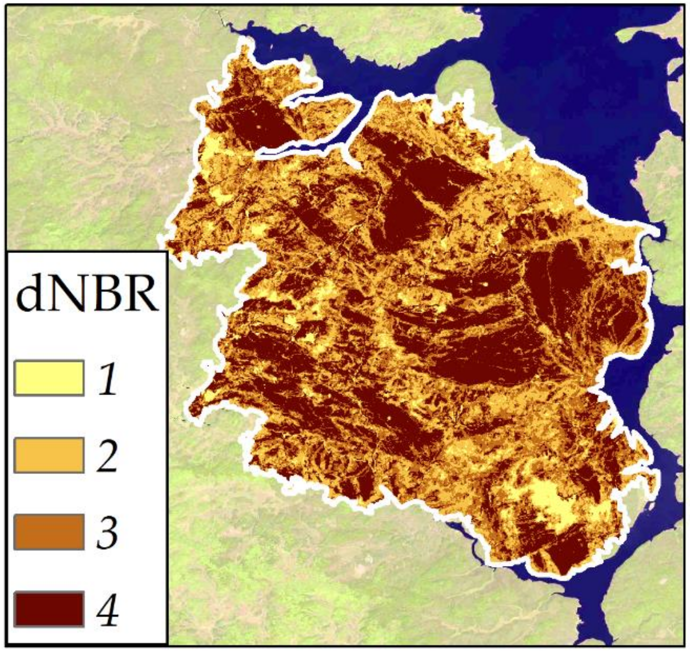
Objective

The main objective is to identify the connection between the degree of fire impact and the dynamics of restoration processes using remote methods and spectral indices, taking into account the features characteristic of various stands of Siberia.

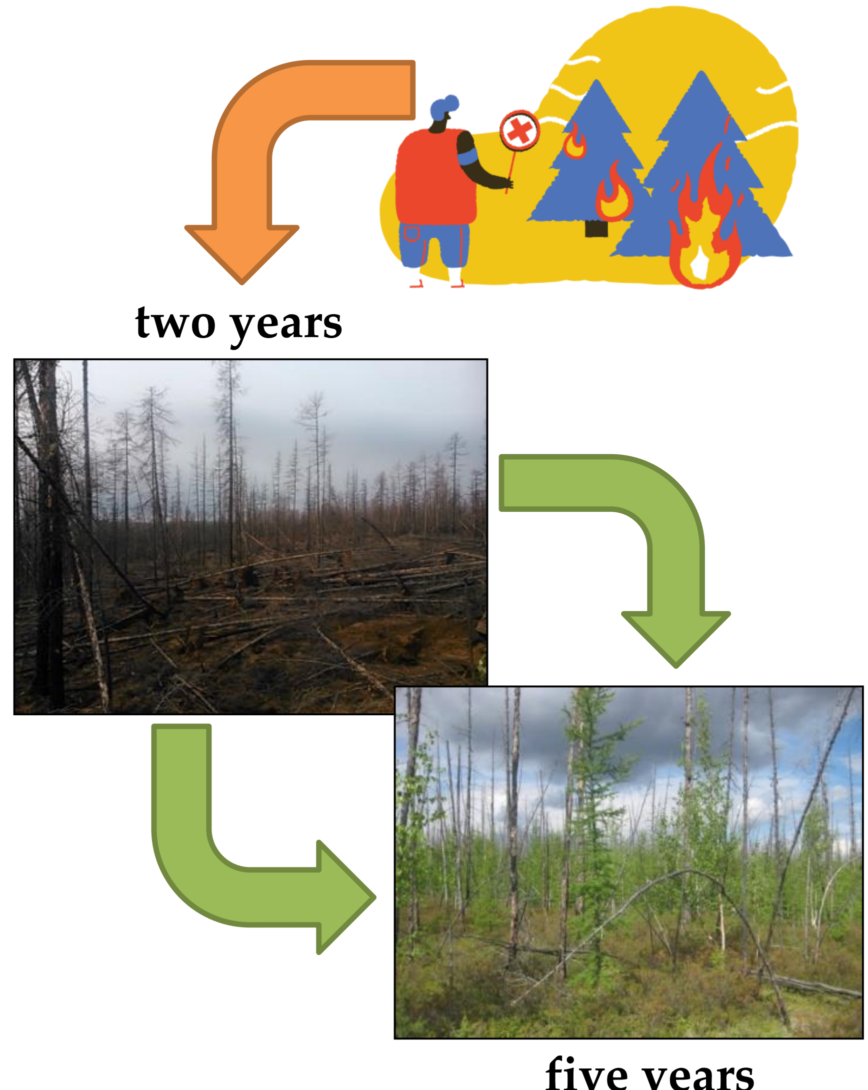




preprocessing

Abstract

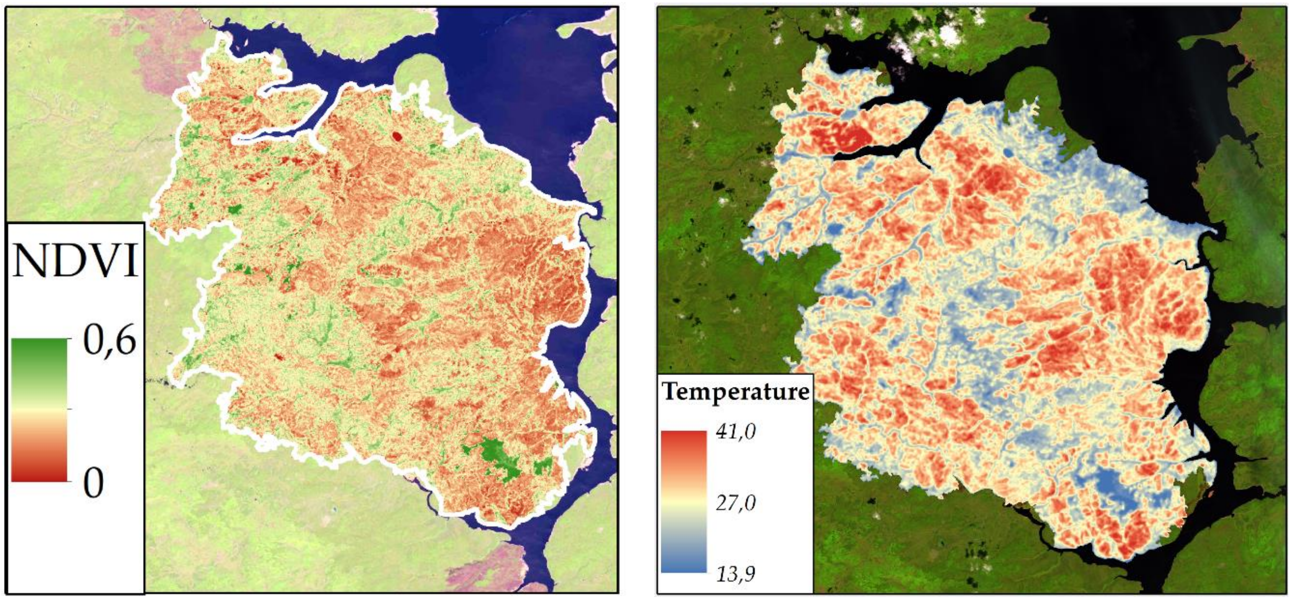
Violation of the soil and vegetation cover is the cause of changes in the thermal regimes of local areas. Such changes together can have a significant impact on the state and dynamics of ecosystems, soil, permafrost layers *[Knorre et. al. 2019, Ponomarev et. al. 2020]*. The use of data from thermal channels increases the observation period of the recovery period of damaged areas. Due to overgrowth, vegetation characteristics are lost, while thermal characteristics are preserved.



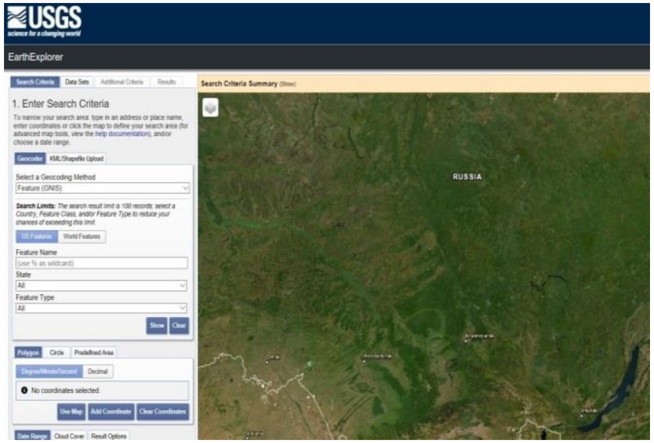
* Photo by I. Bezkorovaynaya

Abstract

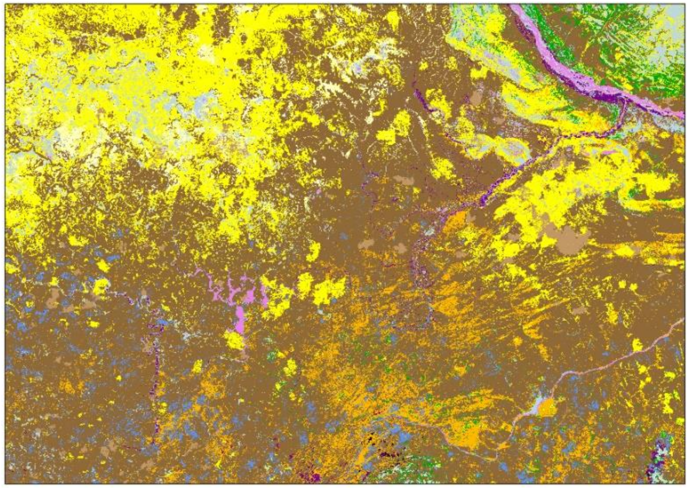
The degree of damage of the covers thermal measurement can be monitored for a long time using the most common spectral index dNBR.



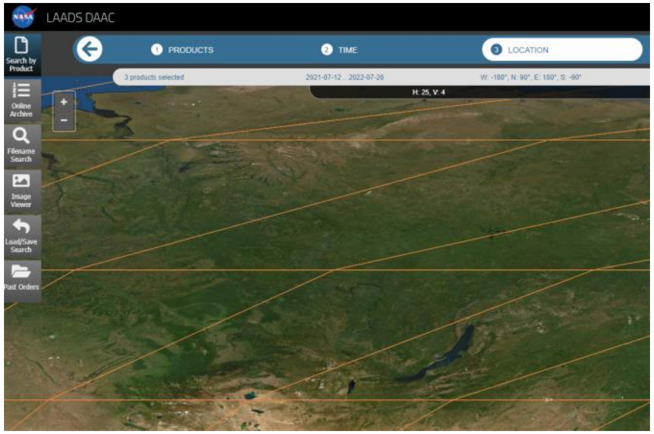
Initial data base



Satellite images of medium spatial resolution *Landsat–8/OLI/TIRS* (Operational Land Imager / Thermal Infrared Sensor) were used. They were obtained from open catalogues of the US Geological Survey (https://earthexplorer.usgs.gov/).



An example of a Siberian stand map based on the Vega-Pro satellite system (Lupyan E.A., ICI RAS, Moscow, 2022).



In addition to this, the data of temperature and vegetation index NDVI from the open catalogue of the NASA Modis database were used in the work (https://ladsweb.modaps.eosdis.nasa.gov).

Methods

Identification of damaged areas with varying degrees of violations was carried out according to the following formulas:

$$\boldsymbol{NBR} = \frac{(NIR - SWIR)}{(NIR + SWIR)} \quad (1)$$

- *NIR* - Near Infrared (λ=0,845—0,885 µm)
- *SWIR* - Short Wavelength Infrared (λ= 2,100—2,300 µm)

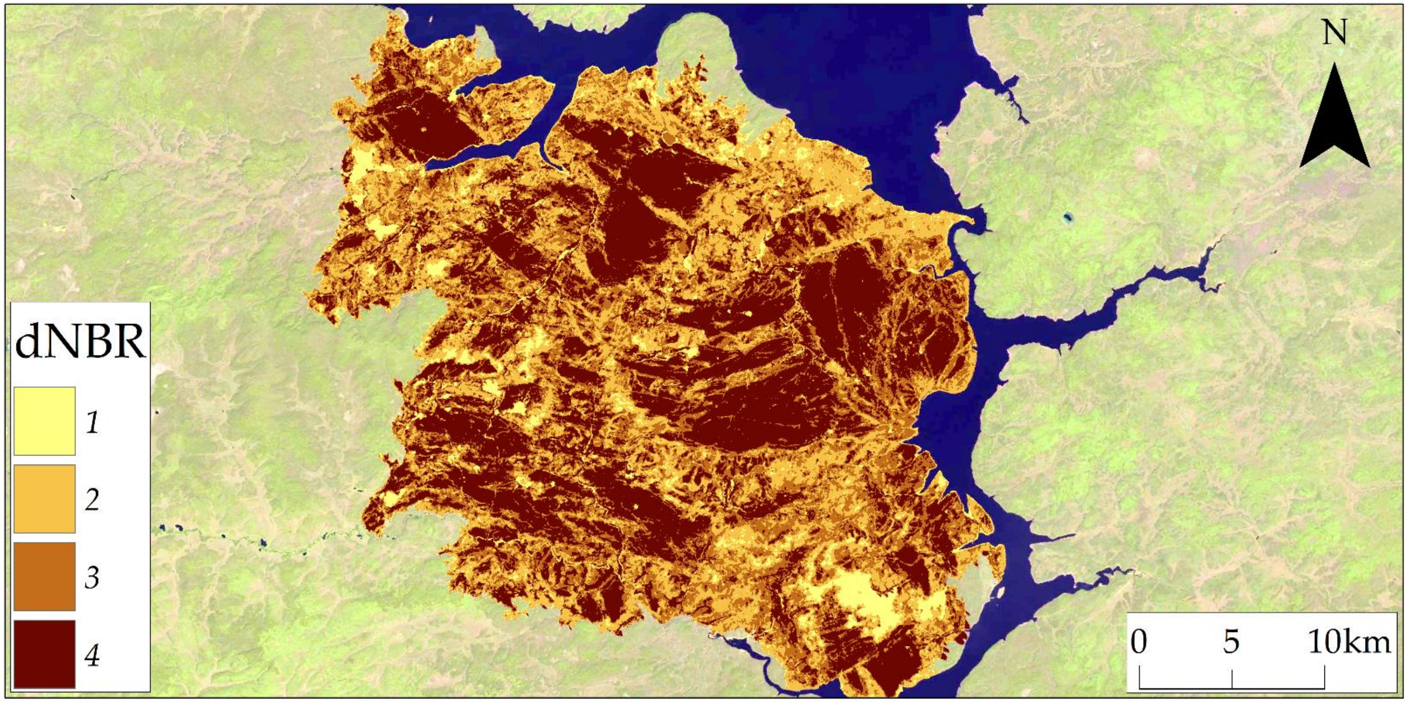
- In Landsat 4-7, *NBR* = (Band 4 – Band 7) / (Band 4 + Band 7).
- In Landsat 8-9, *NBR* = (Band 5 – Band 7) / (Band 5 + Band 7).

$$\boldsymbol{dNBR} = NBR_{pre-fire} - NBR_{post-fire} \quad (2)$$

- $NBR_{prefire}$ - *pre-fire image*
- $NBR_{postfire}$ - *post-fire image*

Table 1. Thresholds of the *dNBR* to classify fire severity and level of fire impact on vegetation cover according to [*dos Santos et. al. 2020, Key, C.H. et.al. 2021*].

Degree of Fire Impact	Class Number	*dNBR* Range	Fire Severity
Low (***LI***)	1	< 0.099	Nonburned vegetation
	2	0.101 . . . 0.439	Low severity
Moderate (***MI***)	3	0.440 . . . 659	Moderate severity
High (***HI***)	4	> 0.660	High severity



Methods

Analysis of the amplitude of deviations of the values of the damaged areas from the background (%) for $\Delta T/T_{bg}$ and $\Delta NDVI/NDVI_{bg}$, was carried out during the growing season according to the following formulas :

$$\Delta T/T_{bg} = 100 \cdot (T_{\mathrm{tg}} - T_{bg})/T_{bg} \quad (3)$$

- $T_{background}$ – thermal field for background vegetation
- T_{target} – thermal field of damaged areas

$$\Delta NDVI/NDVI_{bg} = 100 \cdot (\alpha_{\mathrm{tg}} - \alpha_{bg})/\alpha_{bg} \quad (4)$$

- $NDVI_{background}$ – vegetation index for background vegetation
- $NDVI_{target}$ – vegetation index of damaged areas

Results

Post-fire damage

The proportion of severe fires varied according to the transition from dominant larch stands (33.2% of the area burned) to pine stands (12.6%) and dark coniferous stands (up to 26.4%) on average. The proportion of severe fires was 2.0–2.5 times lower under conditions of vegetation types, dominated in the north (65 + N) of boreal forests of Siberia (18.6%, 14.7%, and 4.2%, in Pinus pumila, larch sparse, and tundra, respectively).

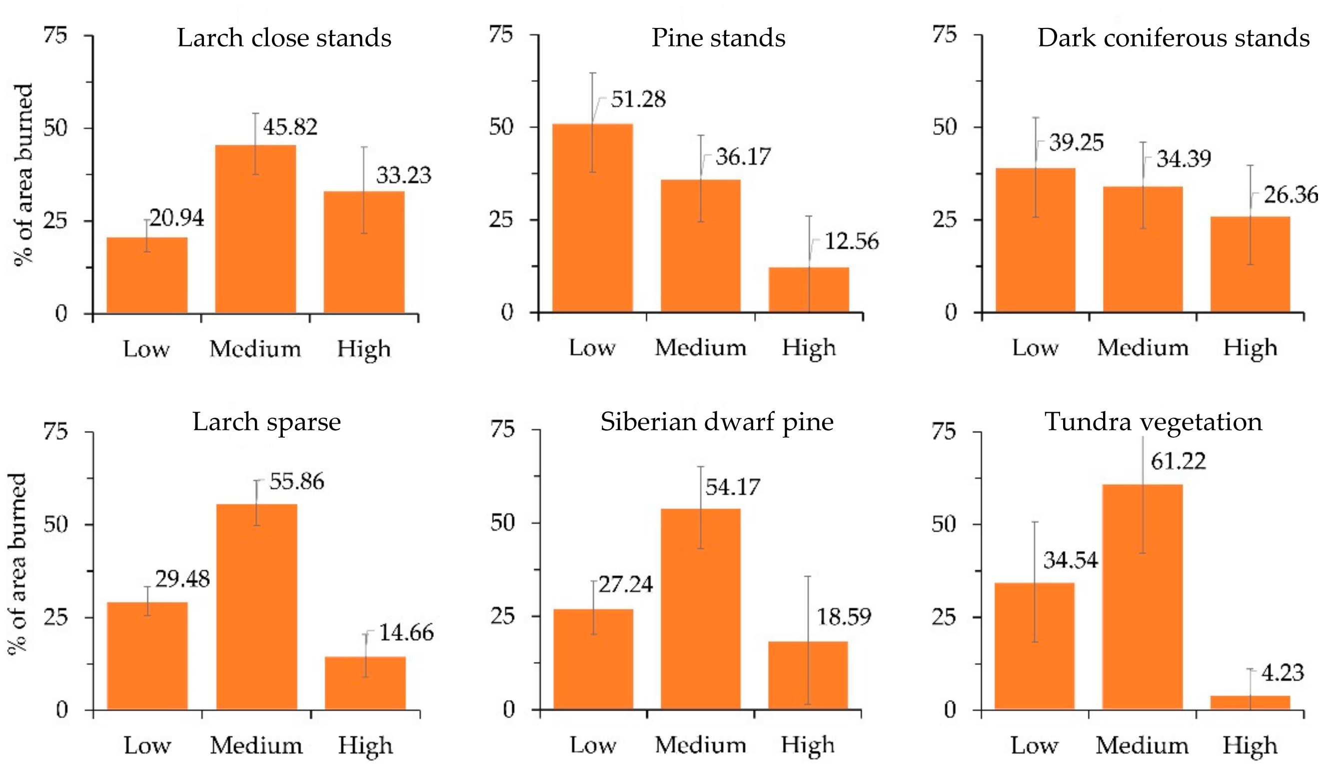


Fig. 1 - Severity/fire impacts (low, moderate, high) depending on dominant tree tands and types of vegetation

Results

Dark coniferous stand (Fir (*Abies sibirica*))

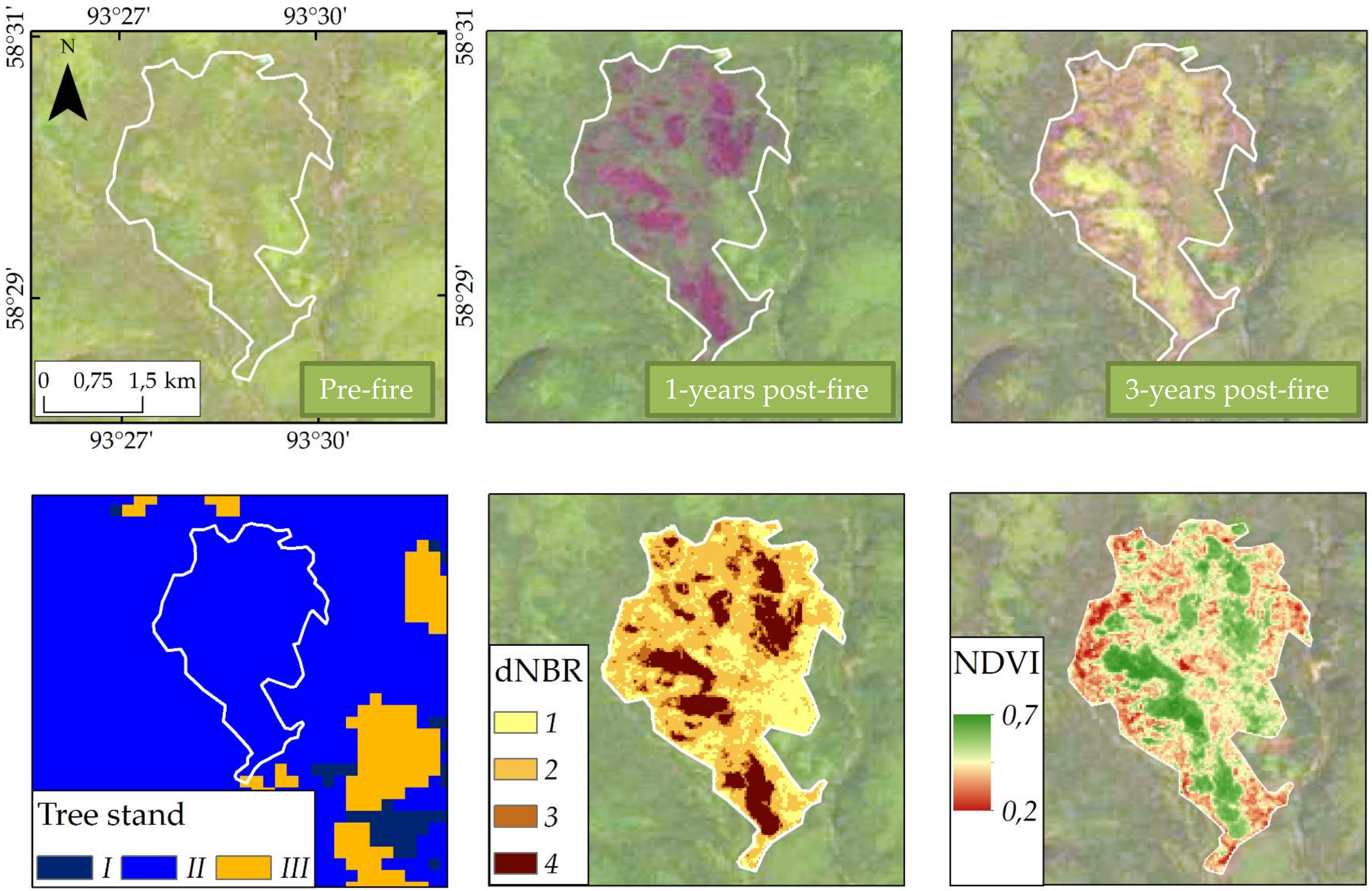


Fig. 2 – Calculated *dNBR* & *NDVI* indicators for dark coniferous stands **(Fir (*Abies sibirica*))**: (I – Other stand, II-Fir (*Abies sibirica*), III-Pine (*Pinus sylvestris*); *1*-Nonburned vegetation, *2*-Low severity, *3*-Moderate severity, *4*-High severity).

Results

Dark coniferous stand (Spurce (*Picea obovata*))

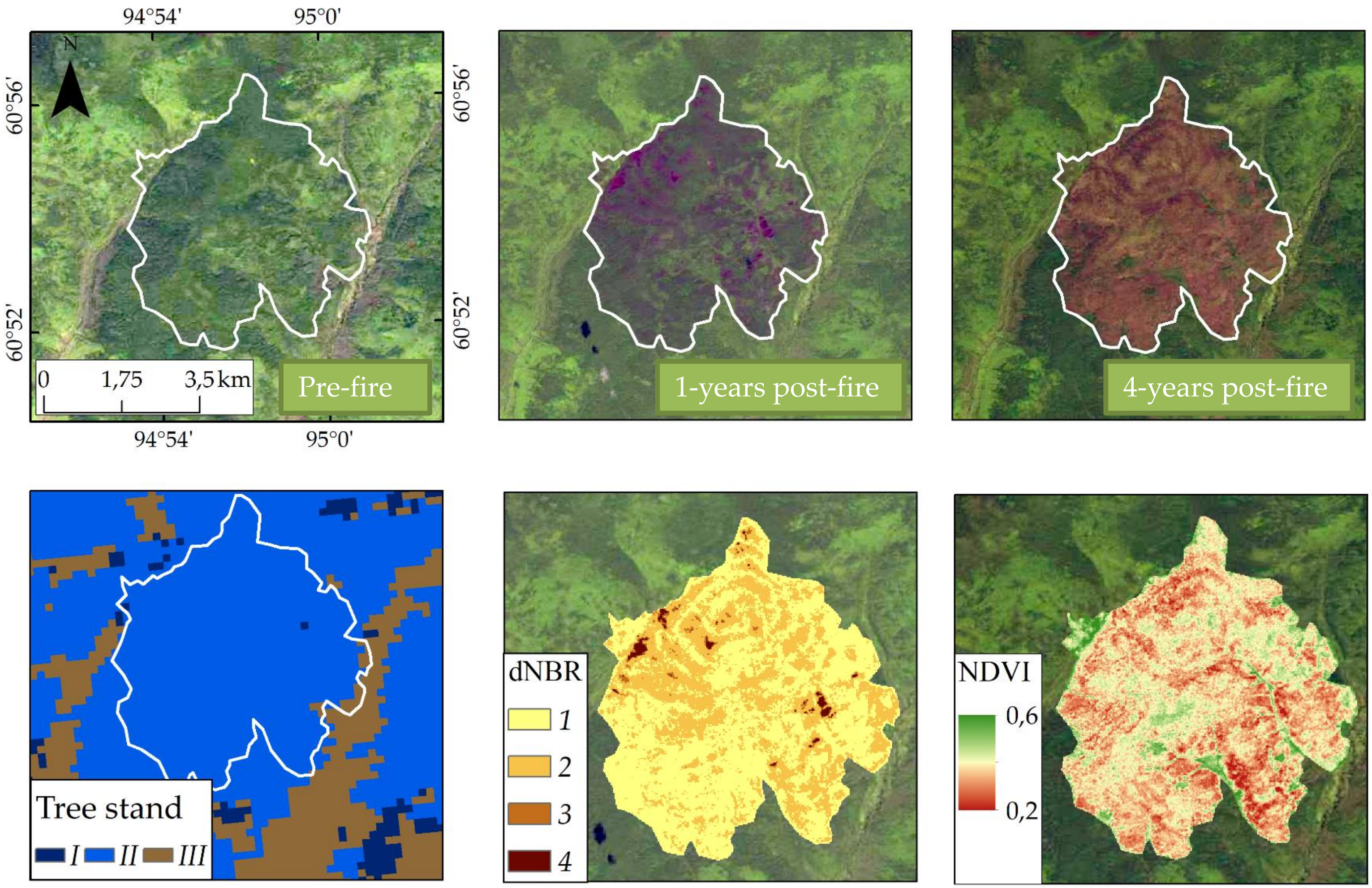


Fig. 3 – Calculated *dNBR* & *NDVI* indicators for dark coniferous stands **(Spurce (*Picea obovata*)):** (I – Other stand, II – Spurce (*Picea obovata*), III-Larch (*Larix sibirica*); *1*-Nonburned vegetation, *2*-Low severity, *3*-Moderate severity, *4*-High severity).

Results

Light coniferous stand (Pine (*Pinus sylvestris*))

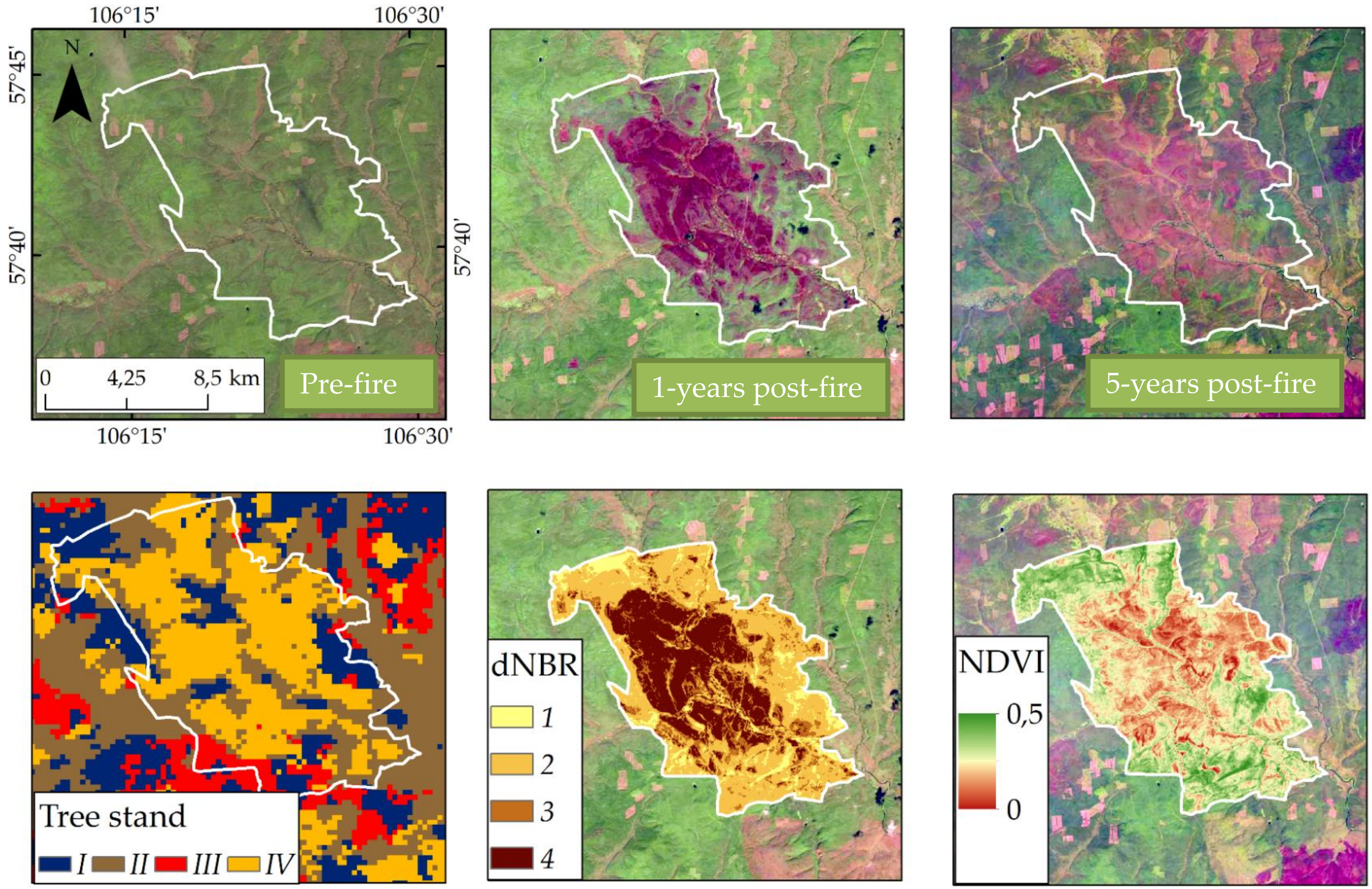


Fig. 4 – Calculated *dNBR* & *NDVI* indicators for light coniferous stand**(Pine (*Pinus sylvestris*)):** (I – Other stand, II-Larch (*Larix sibirica*), III-Cedar Sibirica (*Pinus sibirica*), IV-Pine (*Pinus sylvestris*); *1*-Nonburned vegetation, *2*-Low severity, *3*-Moderate severity, *4*-High severity).

Results

Light coniferous stand (Sparse larch stands)

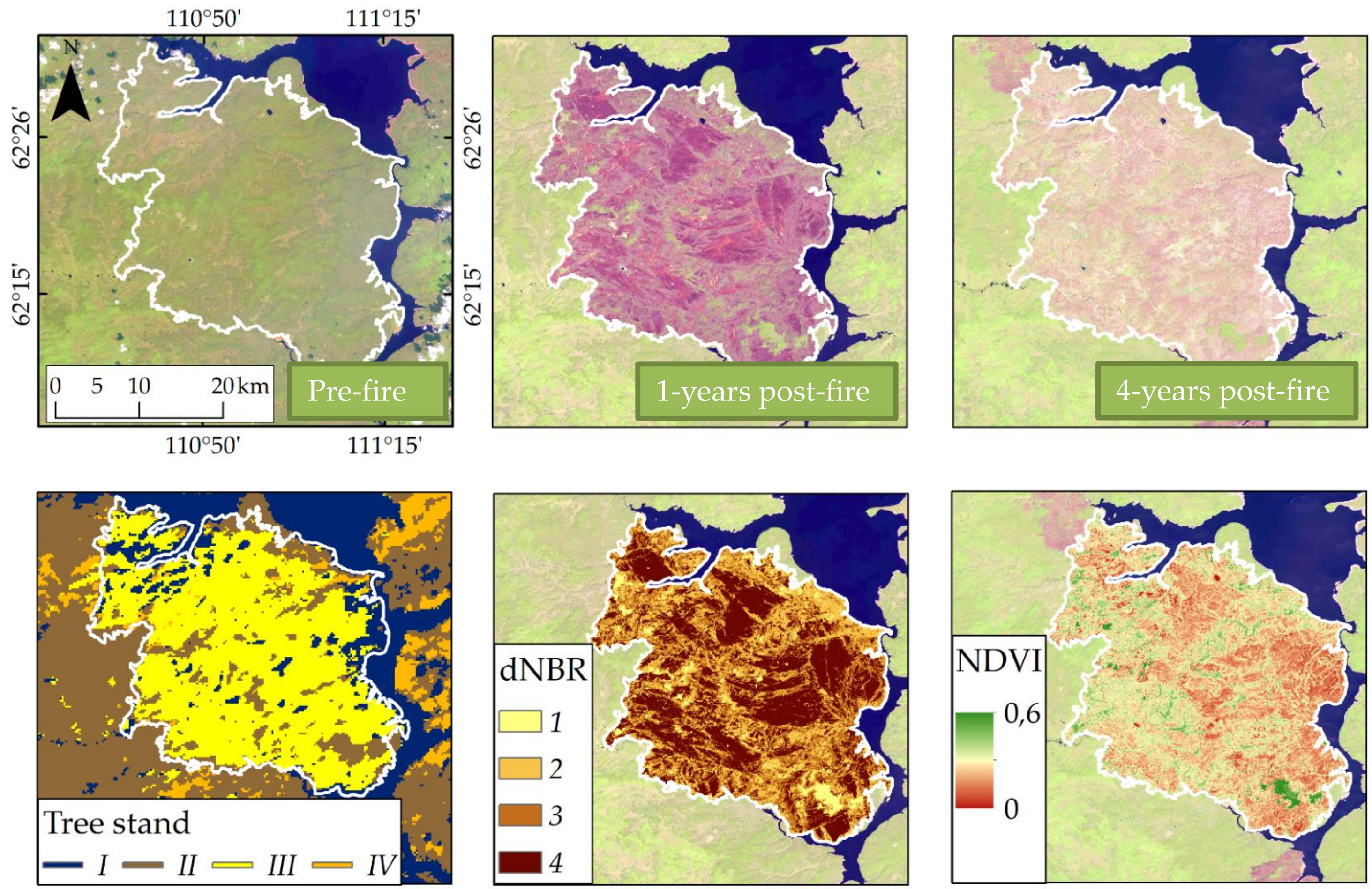


Fig. 5 – Calculated *dNBR* & *NDVI* indicators for light coniferous stand **(Sparse larch stands):** (I – Other stand, II-Larch (*Larix sibirica*), III-Sparse larch stands, IV-Pine (*Pinus sylvestris*); *1*-Nonburned vegetation, *2*-Low severity, *3*-Moderate severity, *4*-High severity).

Results

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 dominated 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

In larch forests, up to 80% of the total area of post-fire sites is attributed to moderate (>45% of the total area) and to high level (33%) of the 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 α=0.05).

Results

Table 3. Post-fire temperature anomalies $\Delta T / T_{bg}$.

Year	Larch (*Larix sibirica*)				Pine (*Pinus sylvestris*)			
	LI	*MI*	*HI*	*Average value*	*LI*	*MI*	*HI*	*Average value*
1	10,2	26,4	34,9	27,6	8,1	22,3	40,9	19,9
2	8,5	17,3	21,8	17,4	6,4	18,3	30,2	15,3
3	8,9	16,5	21,3	16,5	4,4	12,9	21,3	10,6
4	9,0	15,1	18,0	15,0	4,9	13,0	20,0	10,6
5	7,5	12,3	14,0	12,0	5,9	12,9	18,9	10,7
Year	**Spurce (*Picea obovata*)**				**Fir (*Abies sibirica*)**			
	LI	*MI*	*HI*	*Average value*	*LI*	*MI*	*HI*	*Average value*
1	6,0	19,1	25,4	6,6	6,2	16,2	19,4	9,2
2	5,0	14,0	17,6	5,1	5,3	17,1	17,4	7,4
3	3,8	10,5	12,5	4,1	5,6	17,9	19,5	8,0
4	3,7	9,3	12,1	3,9	-	-	-	-
5	3,9	8,6	9,7	4,0	-	-	-	-

Results

Table 4. Post-fire anomalies of the vegetation index $^{\Delta NDVI}/_{NDVI_{bg}}$.

Year	Larch (*Larix sibirica*)				Pine (*Pinus sylvestris*)			
	LI	*MI*	*HI*	*Average value*	*LI*	*MI*	*HI*	*Average value*
1	41,6	98,7	100	97,6	24,68	62,34	92,21	49,35
2	29,1	61,5	88,3	64,7	29,00	57,00	74,90	45,00
3	23,0	42,2	45,2	40,0	26,34	39,59	49,17	34,44
4	18,3	38,2	41,5	35,1	24,17	35,83	45,83	32,50
5	23,7	45,6	44,7	40,4	14,18	15,67	15,67	14,93
Year	**Spurce (*Picea obovata*)**				**Fir (*Abies sibirica*)**			
	LI	*MI*	*HI*	*Average value*	*LI*	*MI*	*HI*	*Average value*
1	29,7	71,3	63,9	30,8	17,4	39,3	49,9	23,8
2	30,4	55,3	43,9	31,9	3,0	11,3	18,3	1,8
3	35,9	52,0	39,0	37,6	4,9	3,6	1,6	2,4
4	19,5	26,5	20,5	19,7	-	-	-	-
5	14,2	14,7	6,1	14,2	-	-	-	-

Results

5-year dynamics of anomalies $\Delta T/T_{bg}$ and $\Delta NDVI/NDVI_{bg}$

Values of temperature anomalies (ΔT/Tbg, %) are determined by initial level of fire impact and by the type of tree stand (Fig. 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 (Fig. 2a). The initial level of ΔT/Tbg was ~35% for post-fire plots in Larch forests, and was 25% and 20%, respectively for plots of Spruce and Fir.

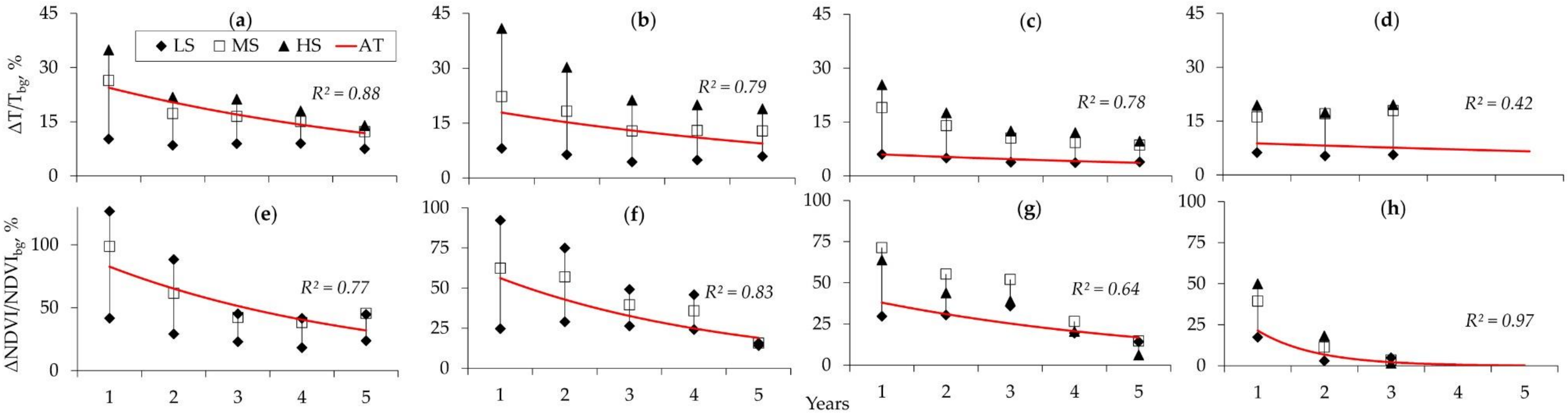


Fig. 6. 5-year dynamics of $\Delta T/T_{bg}$ (**a–d**) and $\Delta NDVI/NDVI_{bg}$ (**e–f**) anomalies in post-fire plots in dominant tree stands: (**a, e**) Larch (*Larix sibirica*), (**b, f**) Scots pine (*Pinus sylvestris*), (**c, g**) Spruce (*Abies sibirica*), (**d, h**) Fir (*Picea obovata*). LS is a low degree of severity in terms of dNBR, MS is a moderate degree of severity, HS is a high degree of severity, AT is an exponential approximation of the averaged values.

Results

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 (Fig 6. 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 (Fig. 6, AT for a, b versus c, d).

Relatively high recovery rate was recorded for the ΔNDVI/NDVIbg anomalies during the first 3 years after fire impact. Further, the values are stabilized at a level of at least 5–15% understatement the background, depending on the dominant tree stands (Fig. 2e–h). We found high level of ΔNDVI/NDVIbg anomaly (~40–45%) in Larch forests after 5 years of post-fire recovery, because of significant disturbance of the ground cover. For other considered tree stands, the level of residual ΔNDVI/NDVIbg 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.

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 dominated 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. High recovery rate was recorded for the $\Delta NDVI/NDVI_{bg}$ anomalies during the first 3 years after fire impact, and finally the values stabilized at 5–15% understatement of the background.
- Thus for success remote control of recovery, 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.

Literature

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