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Long-term dynamics of the thermal state of technogenic plots in Siberia based on satellite data †

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Abstract: We studied the dynamics of relative anomalies ($\Delta T/T_{bg}$) in the ground cover thermal regime of technogenic territories in Siberia under the conditions of gold mining impact. Impact of gold deposits mining determines the change in the thermal state of the post- technogenic plots for a long time, which is an important feature of ecosystem stability monitoring. We analyzed the spectral characteristics of four technogenic sites that had gold mining quarries of different age. We evaluated the stages of technogenic plots according to the initial level of thermal anomaly, the rate of decrease in thermal anomaly, the time of stabilization recovery processes, and disperse of the residual level of thermal anomaly.

Keywords: technogenic plots; remote sensing; relative thermal anomaly; vegetation cover; soil

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1. Introduction

In the boreal zone all over the world [1], including Siberia, vegetation and soils are disturbed over large areas [2,3]. These disturbances associated both with natural causes, such as forest fires [4–6], and anthropogenic impact [7,8]. The most significant factor is the impact of the industrial/mining complex [3,9,10].

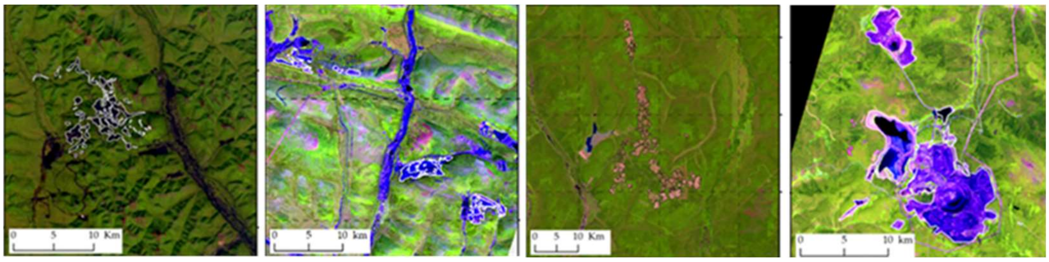
Detailing the characteristics of disturbed plots allows predicting the rate and success of post-technogenic recovery. The vegetation index, proposed by Rouse et al. in 1973, is widely used for monitoring of vegetation state [11,12]. The most famous vegetation index is the Normalized Difference Vegetation Index (NDVI) [13].

However, post-technogenic plots accompanied always by a change in the thermal regime of the surface, caused by a decrease in the surface albedo and a change in the heat-insulating properties of the soil and on-ground vegetation [8,14,15]. Abnormal heating of the surface and upper layers of soil persists for a long time (up to 20–40 years), depending on the degree of disturbance and the type of reclamation [16]. Under these conditions, we suggested remote monitoring vegetation restoration by the long-term losing of temperature anomalies of disturbed plots [17,18].

Currently we investigated temperature anomalies of goal mining plots that had mining quarries of different age. We evaluated the stages of technogenic plots according to the initial level of thermal anomaly, the rate of decrease in thermal anomaly, the time of stabilization recovery processes, and disperse of the residual level of thermal anomaly.

2. Material and Methods

We studied 4 post-technogenic sites located in the taiga zone of Central Siberia, Russia. The identified objects of study are areas of industrial gold mining of different ages (Fig. 1). The plot of Natalka mining plant (NMP) is placed in Magadan Region and is in active stage since 1990. In Irkutsk Region the plot of Verninskoye mining plant (VMP) is in active stage since 2011. The oldest plot of Kuranakh mining plant (KMP) in Republic of Sakha (Yakutia) is in active stage since 1965. The plot of Olimpiada mining plant (OMP) is in active stage since 1990 in Krasnoyarsk Region. Additional information about the studied objects is in the public domain (https://polyus.com/ru/operations/operating_mines/, accessed on 14 October 2022). The peculiarity of selected technogenic plots is that these are rock dumps, where on-ground cover and soil structure are destroyed. Recovery processes (for vegetation cover and soil structure/characteristics) in such plots are much slower than in other post-technogenic areas.



(a) (b) (c) (d)

Figure 1. Area of disturbances from Landsat-8/OLI images of 2015–2020 for technogenic plots of (**a**) NMP (Magadan Region); (**b**) VMP (Irkutsk Region); (**c**) KMP (Republic of Sakha (Yakutia)); (**d**) OMP (Krasnoyarsk Region)

These plots are located in the East Siberian taiga-permafrost forest sub-region. On this territory the main species forming stands are larch (*Larix sibirica*, *L. gmelinii*) and pine (*Pinus sylvestris*), which are covered up to 55% and 18% of the region [6]. The remaining forest-forming species (*Pinus sibirica*, *Abies sibirica*, *Picea obovata*, *Betula* spp., *Populus tremula*) and tundra vegetation make up ~25–27% of the study area [6].

The soil cover is represented by zonal soils (See Table 1) in non-disturbed territories. (soils classified according to World Reference Base (WRB) 2014, https://www.fao.org/3/i3794en/I3794en.pdf, accessed on 14 October 2022). However, technogenic surface formations (*Technosol (TC)*) and anthropogenic transformed types of zonal soils (*Anthrosols (AT)*) are typical for disturbed areas here.

Table 1. Study area characteristics.

Plot	Disturbed Area, 10^3 ha	Start of industrial development of the territory, year	Background Soils (WRB)	Vegetation types
NMP	0.92	1990	Cryosols (CR); Turbic Spodic Follic Cryosols (CR-fo.sd.tu); Entic Podzols (PZ-et)	larch/pine forests with birch and aspen
VMP	1.08	2011	Turbic Cryosols (CR-tu); Turbic Spodic Follic Cryosols (CR-fo.sd.tu); Gleyic Fluvisols (FL-gl)	tundra vegetation and forest tundra
KMP	3.46	1965	Turbic Cryosols (CR-tu); Turbic Spodic Follic Cryosols	larch forests, mountain tundra vegetation

			(CR-fo.sd.tu); Gleyic Cryosols (CR-gl); Gleyic Fluvisols (FL-gl)	
OMP	3.15	1990	Cryosols (CR); Entic Podzols (PZ-et)	pine forests, larch forests and dark coniferous spruce/fir forests

We analyzed long-term dynamics of spectral characteristics and summer temperature fields for each technogenic plot (Fig. 1) from satellite data for 1973–2020. We used images from Landsat 8/OLI/TIRS (Operational Land Imager / Thermal Infrared Sensor), Landsat 7 ETM (Enhanced Thematic Mapper), Landsat 4-5 TM (Thematic Mapper), and Landsat 1 MSS (Multispectral Scanner System) (USGS, https://earthexplorer.usgs.gov/, accessed on 20 July 2022). The spatial resolution is 30 m for data from OLI, and is 100 m for temperature data from TIRS. For each disturbed plot, combinations of channels #5-4-3 for Landsat-4/5/7 and channels #6-5-4 for Landsat-8 were used. Finally, we used data for 1973, 1986, 1990, 2000, 2005, 2010, 2015, and 2020.

Based on standard calibration procedure, we evaluated and averaged the surface temperature (B6, B6/2 channels of λ = 10.4–12.5 μm, Landsat-5,7/TM/ETM and B10 channel of λ = 10.6–11.19 μm, Landsat-8/OLI).

We evaluated temperature fields for selected technogenic plots (Fig. 1,2). Next, we analyzed thermal fields of each plots comparing to temperature of non-disturbed territories (background thermal values) during summer period ($\Delta T/T_{bg}$, °C/°C):

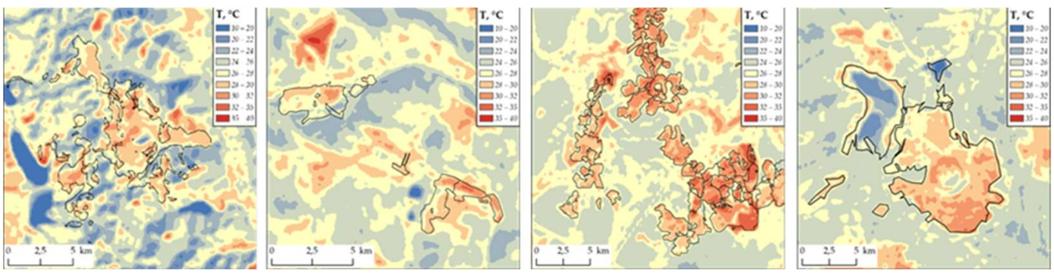
$$\Delta T/T_{bg} = 100\% \times (T_{tg} - T_{bg}) / T_{bg}, \quad (1)$$

where T_{tg} is surface temperature of target (disturbed area), °C, and T_{bg} is surface temperature of background (neighbor non-disturbed territory), °C.

The background temperature was determined from measurements inside the areas closest to the disturbance zone. The background temperature was averaged over 1000–3900 values measured inside polygons with areas of 0.25×10^3–1.0×10^3 ha. Within the disturbed areas, a threshold criterion (T_{tg}<15°C) was additionally used to exclude temperatures in pixels related to technical water bodies present in some disturbed areas (Fig. 2, d) from further averaging. Thermal fields were evaluated for 1990–2020 with 5-year intervals.

3. Results and Discussion

Disturbed areas of technogenic plots are characterized by a significant change in summer thermal regime in comparison to non-disturbed background territory. Long-term temperature anomalies ($\Delta T/T_{bg}$) in disturbed areas were evaluated for 1990–2020 per 5-years intervals (Fig. 2). The average temperature was 10–25% higher in disturbed areas than in non-disturbed background (Fig. 3). The same effect was evaluated for temperature anomalies detected in post-fire plots and in technogenic plots of coal mining [16].



(a) (b) (c) (d)

Figure 2. Temperature field for technogenic plots of (**a**) NMP (Magadan Region); (**b**) VMP (Irkutsk Region); (**c**) KMP (Republic of Sakha (Yakutia)); (**d**) OMP (Krasnoyarsk Region)

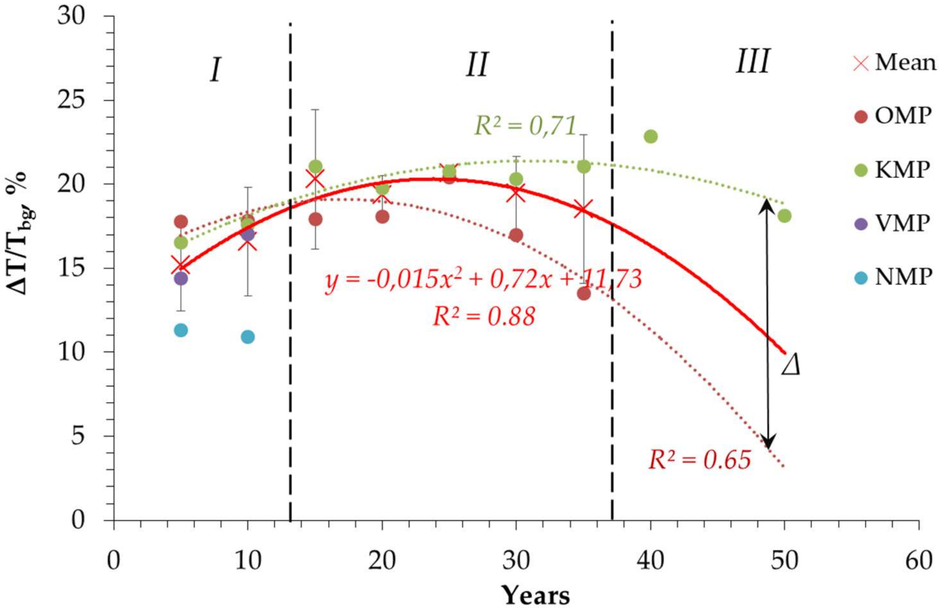


Figure 3. Thermal anomalies in disturbed areas of selected technogenic plots: (×) average for all areas; (OMP) Olimpiada, (KMP) Kuranakh, (VMP) Verninskoye, (NMP) Natalka; initial stage of technogenic impact (I), the stage of technogenic activity (II), and post-technogenic recovery stage (III) have been marked out.

According to thermal anomaly values ($\Delta T/T_{bg}$), we marked out (Fig. 3) three stages of technogenic plots functioning during 50 years. These are initial stage of technogenic impact (I) during the first 10–12 years, the stage of technogenic activity (II) during the next 35 years, and post-technogenic recovery stage (III), which starts at 35–40 years.

During the stage I, the formation of a technogenic territory started. Therefore, the increase in the values of the thermal anomaly is determined by the increase in the area of disturbance.

In the stage II, there is a long-term technogenic impact, which effects significantly on ground cover and soils of disturbed areas. Under this conditions, the values of the thermal anomaly ($\Delta T/T_{bg}$) are smoothed out, and the dispersion tends to a minimal value, which indicates the same state for all variants of studied objects in this stage. However, this stage is unique for technogenic objects of open pit gold mining. Identified objects of study are areas of industrial gold mining where on-ground cover and soil structure have been destroyed completely as the result of initial technogenic impact and further technogenic activity. Under such conditions, restoration of soil and vegetation cover is very difficult and the start of the recovery process is delayed for 35–40 years.

By the time of the stage III, post-technogenic recovery begins by reducing the technogenic impact. At this stage, it is expected to reduce the thermal anomaly to 7–10% above background norm. Previously, we showed that the stage III is typical for other variants of disturbed areas with a long-term restoration process, such as post-technogenic plots and post-fire plots as well [16–18]. However, in post-fire areas, recovery processes are recorded immediately after a fire [7]. The same is true under the conditions of minor technogenic impacts or after the reclamation of disturbed areas [18].

We found that the initial level of thermal anomaly varies in the range of 10–30% with an average value of ~15%. The highest level of the initial anomaly was recorded for the OMP plot ($\Delta T/T_{bg}$ ~ 30%). The smallest anomaly was recorded for NMP plot ($\Delta T/T_{bg}$ ~10%). The anomaly leveling process probably stabilized at a level of $\Delta T/T_{bg}$ ~ 16–20% during the stage II.

Thus, all that time (20–40 years) thermal anomalies affect both the state of vegetation [2,19] and the microbial community [14,15]. Further, it is possible to predict the processes associated with this effect, which may be most significant in the permafrost zone of Siberia, where additional heating of the soil profile determines the annual dynamics of the permafrost level, as the most important factor in the existence of northern ecosystems [16].

4. Conclusions

The considered plots of gold mining are a unique case of technogenic disturbance, in which there is a long-term (up to 40–50 years) absence of recovery processes. Thus, the efficiency of such processes is significantly lower in comparison with post-technogenic areas of coal mining and post-fire areas, where a significant recovery of the thermal anomaly ($\Delta T/T_{bg}$) is observed already during the first 20 years.

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Data Availability Statement: Publicly available datasets were analyzed in this study. These data can be found here: http://pro-vega.ru/maps/ (accessed on 27 July 2022) and https://worldview.earthdata.nasa.gov/ (accessed on 27 July 2022).

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