Antropogenic Impacts on the Thermal Condition of Permafrost in Central Yakutia

P N Skryabin¹, S P Varlamov¹
¹ Melnikov Permafrost Institute SB RAS, Yakutsk, Russia

E-mail: svarlamov@mpi.ysn.ru

Abstract. The results of long-term geothermal investigations in disturbed landscapes along the railway, water line and gas pipeline are presented. Human-induced changes in the ground thermal state are analyzed. The study has shown significant increases in mean annual temperature of the upper permafrost layers, as well as in seasonal thaw depth in the inter- alas type of terrain after the removal of trees, ground surface stripping and post-fire clearing. Quantitative estimates are given for the dynamics of mean annual ground temperatures on cuts and burns in relation to vegetation succession.

1. Introduction
The thermal condition of the ground is the most important factor controlling the stability of geotechnical systems in permafrost terrain. Studies were carried out using the method of landscape thermophysics based on experimental observations.

Assessing the evolution of near-surface permafrost under the influence of climate change and human activities is currently a problem of high priority. The permafrost temperature regime in disturbed areas has been a focus of research by the Melnikov Permafrost Institute for many years [1-15].

In Central Yakutia, construction of pipelines, roads, railways, and power transmission lines is expanding which is inevitably accompanied by disturbance to the environment. Anthropogenic impacts of varying type and magnitude (tree removal, fires, surface stripping, etc.) significantly alter permafrost conditions, including the thermal state of soils, and can trigger adverse surface processes. Noting certain achievements of these long-term geocryological works for the implementation of measures for the rational use of natural resources, the need to expand research to assess the spatiotemporal response of the upper horizons of the cryolithozone to anthropogenic impacts is relevant and timely.

2. Observation network and methodology
Since 1987, observational studies have been conducted along the northern section of the Tommot–Yakutsk Railway to quantitatively assess the spatiotemporal changes in the thermal state of permafrost due to anthropogenic impacts [16-21].

The geothermal monitoring network covers over 90 sites affected by various disturbances, including stripping of the surface vegetation and organic mat (8 sites), removal of trees (40 sites), fires (23 sites), tree removal in burned areas (11 sites), plowing (2 sites) and railway embankments (26 sites). The length of observations varies and is one year, 5-10, 15-25 and 30 years. A large number of monitoring sites were established during 1987-1990, 1993-1995 and 2007-2009 as part of permafrost research programs in support of major transportation projects.
The basis for long-term studies of the thermal regime of soils, the parameters of which change in the daily, seasonal, and annual cycle, were based on landscape, stationary and monitoring methods. They demanded a landscape typification of natural complexes, the organization of experimental sites and a system of observations on them. Experimental sites and thermometric wells were organized in various landscape conditions and covered almost all typical natural complexes of the region [22-23].

3. Results and Discussion
Experimental observations provide data needed to assess the effects of anthropogenic disturbances on the ground thermal regime in dominant landscapes. For such assessment to be done, it is necessary to estimate the limits of changes determined by the interacting controls, including geobotanical (vegetation type, density and growth) and cryolithological (lithology, active-layer moisture content, permafrost ice content) factors.

In 2005, monitoring observations were established at an ice-rich permafrost site on the railway right-of-way where ice-rich soils and ice wedges occur at depths of only 0.6-1.2 and 1.8-2.3 m from the surface, respectively. The soils are classified as IV and V thaw-susceptibility class. Trees and surface vegetation were removed in the central part of the site. The peripheral area with tree removal presented an analog of a right-of-way (Fig. 1).

![Figure 1. Revegetation stages at the experimental site.](image)

In warm winters with higher than normal snow precipitation, the active layer did not freeze back down to the permafrost table, indicating decreased thermal stability of the soils at the disturbed site (Fig. 2).

![Figure 2. Ground temperature dynamics at the experimental site.](image)
The greatest changes in the ground thermal regime due to removal of surface vegetation were observed at sites representing the inter- alas terrain type. Increases in \( t_0 \) and \( \xi \) were 1.5-2 °C and 0.5-1.8 m, respectively. Thermokarst development resulting in polygonal landforms has initiated at disturbed sites, threatening the structural integrity of linear structures.

Forest vegetation is removed to cut lines for geotechnical investigations, power transmission lines, railroads, roads and pipelines. Clearing is done mainly during the winter, with the surface covers left nearly intact. It is well known that forest vegetation affects the ground thermal regime by shading the surface and changing snow depth and water regime. The cooling effect of a forest stand during summertime depends on tree crown density, as well as on type and thickness of surface vegetation. Increases in incoming solar radiation, surface radiation balance and ground heat flux in cleared areas lead to warmer permafrost temperatures compared to the forest sites.

Where good management practices are not implemented, tree stand removal (selective, gradual or clear cutting) can lead to extensive deforestation and permafrost changes. Monitoring observations allow to document changes in mean annual ground temperature for different harvest methods. In sand ridge terrain, clear cutting of a thin, young pine stand (10-30 years of age) did not cause any significant changes in the ground thermal regime. In inter- alas terrain, selective cutting in a larch–pine stand (C-187/89) at the birch–shrub stage (10-20 years) resulted in a 0.3-0.6°C decrease in \( t_0 \). Gradual cutting in larch forest (C-56/87) at the herb (3-8 years) and birch–shrub stages (10-20 years) increased \( t_0 \) by 0.5-1.2°C. At a clear-cut site (C-190/89) at the stage of birch–larch young forest (thicket) 10-30 years in age, \( t_0 \) decreased on average by 1°C (Fig. 3).

![Figure 3](image_url)

**Figure 3.** Changes in mean annual ground temperature at 10 m depth in larch forest (B-57/87), and on selective cut (B-187/89), gradual cut (B-56/87) and clear cut (B-190/89) in inter- alas terrain type, Tommot–Nizhny Bestyakh Railway route.

Selective, gradual and clear cutting caused an increase in \( t_0 \) by 0.1-1.5°C and in \( \xi \) by 0.1-1.9 m (Table).
Table 1. Ground thermal parameters in cut sites.

| Terrain type | Soil texture      | Undisturbed conditions | Cut sites |
|--------------|-------------------|------------------------|-----------|
|              | $W_\xi$, %        | $\xi$, m               | $t_0$, °C | $\xi$, m | $t_0$, °C |
| Low terrace  | Sand, silty sand  | 7-29                   | 1.1-3.0 | -0.4…-3.5 | 1.2-3.5 | -0.1 to -3.0 |
| Sand ridge   | Sand              | 3-14                   | 1.8-2.7 | -0.2…-1.5 | 2.2-3.5 | 0.0 to -0.4 |
| Inter-ridge depression | Peat, sand, silty sand | 5-820 | 0.5-2.1 | -0.4…-4.4 | 0.7-4.0 | -0.3 to -2.9 |
| Inter-alas   | Silty sand, silt  | 10-25                  | 1.2-2.0 | -1.1…-5.1 | 1.5-2.8 | -0.5 to -4.1 |
| Interfluve   | Silty sand, silt  | 13-26                  | 1.0-1.5 | -1.1…-1.8 | 1.2-1.5 | -0.9 to -2.1 |

Note: “warm” and “cold” varieties of the natural complexes are considered.

The study results indicate that ground warming and active-layer deepening associated with forest cutting are greatest at sites located in inter-ridge depression and inter-alas terrain and smallest in sand-ridge terrain.

Analysis of meteorological conditions with the highest and lowest wildfire activity has shown that large fires occur if weather in the first three months of the thaw season is warm and dry, while low fire activity is observed if the first two months of the fire season are cold and wet.

Fires cause changes in $t_0$ and $\xi$ as a result of destruction of the insulating surface vegetation, reduced surface albedo, and increased soil moisture due to the loss of transpiration. In the interfluve terrain type, the thermal effects of fire were studied on two old burns with recovering larch and birch stands (C-8/95 and C-11/95). Here, an increase in $\xi$ of 0.3-0.4 m and in $t_0$ of 0.4-0.7°C was observed.

Forest cutting in burned areas is a common type of anthropogenic disturbance. In the sand-ridge terrain unit, clear and selective cutting of pine trees on old burns located on a sand ridge and an upland crest resulted in a 0.3-0.5°C increase in $t_0$ and in formation of suprapermafrost taliks (C-8/87, C-59/87). Selective cutting in 1992 and a fire in 2002 on a gentle slope covered with pine and larch forest caused an increase in $t_0$ by 0.2°C and in $\xi$ by 0.5 m over 10 years (C-130/88). Selective cutting and surface fire in 1997 on a mixed pine and larch stand on a gently sloping upland surface increased $t_0$ by 0.2°C and $\xi$ by 0.6 m 15 years later (C-167/89). Significant deepening of the active layer was caused by increased volumes of meltwater in the last two years.

In low-terrace and inter-alas terrain, fires and forest cutting led to an increase in $t_0$ by 0.3-0.8°C and in $\xi$ by 0.4-0.8 m after first three years. Fifteen years later, $t_0$ decreased by 0.5-0.7°C with vegetation recovery. In inter-alas terrain with ice wedges occurring close to the surface, deep seasonal thawing resulted in the formation of residual thaw layers and the development of thermokarst with attendant polygonal features.

In inter-alas terrain, a site for thermal observations is located near the Taas Tumus – Yakutsk gas pipeline. In the summer of 2002, a fire burned most of the birch–larch stand. The burned trees were clearcut next winter for domestic use. Compaction of the snow cover during cutting and hauling reduced its insulating effect and caused a 0.3°C lowering of mean annual ground temperature at 15 m depth one year later. The depth of seasonal thaw in silty clays with increased moisture content increased by 0.5 m on the burn (C-2/03) compared to the control site (C-1/03). By the end of winter 2005 with deep snow cover, a seasonally frozen layer 2.2 m in thickness has formed. Below this upper frozen layer was a talik extending to the permafrost table at 3.2 m. However, the talik refroze during the winters of 2010-2012 with low snow, formed again in the winters of 2013-2016, froze completely in the winters of 2017-2018 and formed again in the warm winter of 2019 (Fig. 4). The depth of thaw on the burn increased by 2 m after 8 years following the disturbance, while the mean annual ground temperature at 10 m depth increased by 2.7°C (Fig. 5). Thaw subsidence of 0.07 m and development of incipient polygonal topography have been observed, which can affect the pipeline stability.
Figure 4. Thaw depth changes in the birch–larch forest and on the cut burn in inter-alas terrain, Taas Tumus–Yakutsk gas pipeline route. The blue line shows the base of the seasonally frozen layer.

Figure 5. Variations in mean annual ground temperature at 10 m depth in the birch–larch forest (B-1/03) and on the cut burn (B-2/03) in inter-alas terrain, Taas Tumus–Yakutsk gas pipeline route.
Changes in the ground thermal regime depends on the stage of vegetation succession following disturbance. Permafrost degradation and increased active-layer depths due to fires are most dangerous in inter- alas terrain where ice-rich deposits occur near the surface. Here, the development of adverse cryogenic processes can pose a threat for stability of engineering structures.

4. Conclusions
The following conclusions can be made from long-term observations:

- Removal of the insulating surface cover in the inter-ridge depression and inter- alas terrain types resulted in an increase in mean annual ground temperature at 10 m depth by 1.5 to 2.0 °C and in active-layer thickness by 1.4 to 1.6 times.
- Cutting of tree stands in the sand-ridge and inter- alas terrain units caused an increase in T₀ by 0.2-0.8 °C and in ξ by 0.3-0.6 m. Tree removal in burned areas in the sand-ridge and inter- alas terrain units increased T₀ by 0.3-0.8 °C and ξ by 1.2-1.6 times.
- An increase in T₀ by 0.2-2.0 °C and in ξ by 0.3-1.5 times was observed during the first 5-7 years after disturbances. Vegetation regrowth at succession stages 2 and 3 led to decreases in T₀ by 0.5-1.0 °C and in ξ by 0.2-0.3 m.
- Long-term thermal observations indicate higher permafrost resilience in sand-ridge terrain. Inter-alas terrain with shallow depths to ground ice is more sensitive to anthropogenic disturbances which initiate adverse processes threatening the structural integrity of linear infrastructure.
- The results of the study can be extrapolated to similar anthropogenic landscapes and used for modeling human-induced changes in the ground thermal regime.

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