

## Article

# Mapping the Main Characteristics of Permafrost on the Basis of a Permafrost-Landscape Map of Yakutia Using GIS

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**Citation:** Shestakova, A.A.; Fedorov, A.N.; Torgovkin, Y.I.; Konstantinov, P.Y.; Vasylyev, N.F.; Kalinicheva, S.V.; Samsonova, V.V.; Hiyama, T.; Iijima, Y.; Park, H.; et al. Mapping the Main Characteristics of Permafrost on the Basis of a Permafrost-Landscape Map of Yakutia Using GIS. *Land* **2021**, *10*, 462. <https://doi.org/10.3390/land10050462>

Academic Editor:  
Jesús Ruiz-Fernández

Received: 30 March 2021  
Accepted: 25 April 2021  
Published: 27 April 2021

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**Abstract:** The purpose of this article was to compile four separate digital thematic maps of temperature and ice content of permafrost, the active layer thickness, and cryogenic processes in Yakutia as a basis for assessing changes to modern climate changes and anthropogenic disturbances. In this work, materials on permafrost were used, serving as the basis for compiling a permafrost landscape map of the Republic of Sakha (Yakutia). The maps were compiled using ArcGIS software, which supports attribute table mapping. The ground temperature and active layer thickness maps reflected landscape zonality and regional differences. Peculiarities of genetic types of Quaternary deposits and climatic conditions reflected the ice content of surface sediments and cryogenic process distribution maps. One of the most common is ground temperatures from  $-2.1$  to  $-4.0$  °C, which were found to occupy about 37.4% of the territory of Yakutia. More than half of the region was found to be occupied by permafrost landscapes with a limited thickness of the active layer up to 1.1 m. Ice-rich permafrost (more than 0.4 in ice content) was found to be typical for about 40% of the territory. Thermokarst is the most hazardous process that occurs in half of Yakutia.

**Keywords:** permafrost landscape; ground temperature; active layer thickness; ice content; cryogenic processes; digital map; GIS model

## 1. Introduction

Permafrost landscapes are highly vulnerable to anthropogenic impacts and climate change due to ice in their substrate [1–3]. Permafrost landscape is a relatively homogeneous natural formation, functioning under the influence of cryogenesis, with certain combinations of permafrost characteristics natural only for it. Permafrost landscapes are an integral part of the earth's landscape sphere, where the upper part of the lithosphere represented by the permafrost [4]. A significant warming trend is observed in the arctic and subarctic regions, with risks of degradation of permafrost [5–7]. The concurrent impact of anthropogenic and climatic factors is most evident here, where the degradation of permafrost landscapes can bring severe societal and economic consequences [8–10]. Furthermore, permafrost changes will directly impact resource exploration and extraction projects con-

centrated in the northern regions [11,12]. Therefore, mapping of permafrost landscapes is essential to identify risk areas with permafrost degradation is necessary [13–16].

At the Institute of Melnikov Permafrost Institute, permafrost landscape maps of Yakutia are compiled at scales 1:2,500,000 [17] and 1:1,500,000 [18], which reflect the distribution of landscapes, the allocation of which, in turn, depends on permafrost. Permafrost landscapes are distinguished by the ice content and temperature of permafrost, the active layer thickness, and the cryogenic processes that occur in them. These maps legend included permafrost characteristics based on the analysis and systematization of properties of landscapes. On the Republic of Sakha (Yakutia), permafrost landscapes map at a scale of 1:1,500,000; 146 types of permafrost landscapes were identified, characterized by various ground temperatures and ice content, the active layer thickness, and cryogenic processes distribution.

The studies of the impact of climate change on permafrost are of particular interest. Changes in permafrost properties [19–21] and their degradation [2,3,22–25] cause the transformation of ecosystems and surrounding landscapes. Anthropogenic landscapes are especially vulnerable to climate change [9,10]. Such changes have a socio-economic response that was reflected in the life of people. In central Yakutia, observations at the Yukechi monitoring site near Yakutsk indicate intense thermokarst activity accompanied by ground subsidence above ice wedges and thaw lakes development [26,27], directly attesting to the warming of the climate. The availability of high-resolution satellite imagery, such as GeoEye, ALOS, and ICONOS, now makes it possible to assess climate change impacts at a larger scale [28].

For a quick assessment of the ongoing cryogenic processes and the assessment of degrading lands, cartographic generalizations needed to clearly show the differentiation of permafrost's main characteristics. These characteristics include the temperature and ice content of permafrost, the active layer thickness, and the spread of cryogenic processes. Knowledge of the spatial differentiation of these characteristics of permafrost will allow researchers of other disciplines to delve into the peculiarities of the natural environment's development in the area of permafrost. The emergence of maps showing the functional features of permafrost landscapes will make it possible to understand better the problems of protection and rational use of the northern regions. It linked with current climate development conditions and activation of cryogenic processes in the permafrost zone [3,27,29,30].

The purpose of this article was to systematize the spatial distribution of modern characteristics of permafrost, temperature and ice content of permafrost, the thickness of the active layer, and cryogenic processes in the territory of Yakutia in the form of separate maps presented here for the first time. These maps compiled using the attributive tables of the permafrost landscape map at a scale of 1:1,500,000 [18]. All this will serve as a basis for assessing changes in permafrost characteristics under climate change and anthropogenic impacts in the future.

## 2. Materials and Methods

The study of permafrost's individual properties—temperature and ice content, the thickness of the seasonally thawed layer, and the spread of cryogenic processes—are decisive in studying permafrost's dynamics and degradation. Their change shows the degree of response of permafrost to climate warming and anthropogenic disturbances. Soil temperature, ice content of sediments, the thickness of the seasonally thawed layer, and cryogenic processes are determined in the field and presented in many literary and stock sources. We used the materials collected for the compilation of the permafrost landscape map of the Yakut ASSR at a scale of 1:2,500,000 [17,31] and a new permafrost landscape map of the Republic of Sakha (Yakutia) at a scale of 1:1,500,000 [18].

The ground temperature was taken when measured at the bottom of the annual fluctuations layer, on average, at a depth of 10–20 m. In the compilation of the above maps, almost all published scientific articles and monographs were used [32–42], as well as

stock materials of the Melnikov Permafrost Institute. All these data were systematized by permafrost landscapes/types of terrain and vegetation groupings and presented in the new map legend [18].

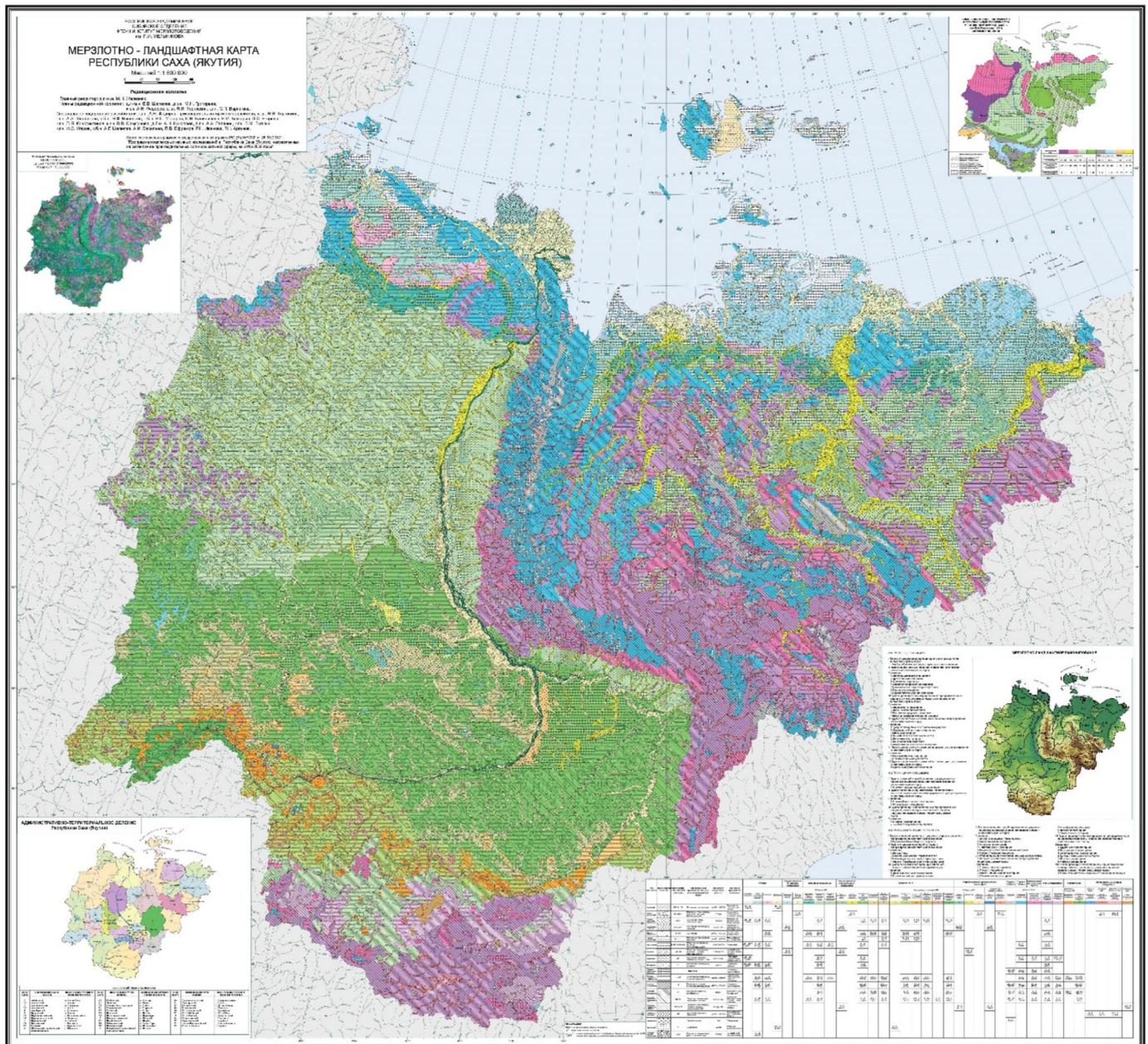
The volumetric ice content of surface sediments was also systematized when compiling the above maps. The data analysis considered the published cryolithological literature [38–41,43–45]. The systematization of ice content carried out according to the stratigraphic-genetic types of surface deposits in landscape zones [17,31]. In the new permafrost landscape map of the Republic of Sakha (Yakutia) at a scale of 1:1,500,000 [18], the volumetric ice content was reflected, and we used these data in this work.

The active layer thickness is the most common characteristic available in permafrost studies and is defined as annual thawing and freeing ground layer in areas underlain by permafrost [46]. The active layer thickness has been reasonably well studied in the landscapes of Yakutia and summarized in maps and monographs [17,31,36,37,47]. The active layer thickness determined during maximum thawing or freezing of soils. If measurements were taken before this period, then the measured values were calculated to the total value. Therefore, they were widely cited in scientific articles and fund materials. The dependence of the active layer on the combination of many natural factors: lithological, climatic, soil-plant, surface moisture, etc., became the basis for applying the landscape method of analysis and generalization of this important characteristic permafrost. For this article, we used the data reflected in the Republic of Sakha (Yakutia)'s permafrost landscapes map at a scale of 1:1,500,000 [18].

Cryogenic processes are closely related to landscapes and permafrost. They are confined to certain permafrost landscapes, genetically determined by cryolithological, climatic, and biological conditions. The spatial patterns of the distribution of individual cryogenic processes have studied in sufficient detail [48–50]. The regularities of the distribution of cryogenic processes in landscapes are well identified [1,51–53]. Their regional features are well described in regional geocryological works [36–38,41,44,54]. In this work, we used previously compiled spatial combinations of cryogenic processes in permafrost landscapes, adopted in our early publications [1,2,20].

On the permafrost landscape map of the Republic of Sakha (Yakutia) at a scale of 1:1,500,000 [18], the ground temperature and the active layer thickness are given in each of the 146 classification units of permafrost landscapes in intervals showing the most characteristic parameters (Figure 1, high-resolution map, see Supplementary S1). For example, in the inter-*alas* type of terrain with an ice complex in a typical tundra with shrub, lichen, and moss vegetation, the ground temperature was found to average  $-9\sim-10$  °C, and the active layer thickness was 0.3–0.5 m. The volumetric ice content and the distribution of cryogenic processes depend on the geological and geomorphological conditions combined on the map into terrain types according to the stratigraphic–genetic complexes of surface sediments. The ice content on the map was given in intervals with a difference of 0.2 fractions of units, low ice up to 0.2, medium ice 0.2–0.4, icy 0.4–0.6, and high ice 0.6–0.8 and more. Cryogenic processes correlated with stratigraphic–genetic complexes that form the types of terrain. Combinations of the main cryogenic processes most typical for the terrain types are given in the map legend.

The permafrost landscapes map compiled on the ArcGIS platform by combining the primary two thematic layers—terrain types and vegetation groups—is the basis for identifying permafrost landscapes [18]. The main characteristics of permafrost—soil temperature, ice content of sediments, the active layer thickness, and cryogenic processes distribution—are closely related to permafrost landscapes. The geocryological database used to compile the map was combined with the merge function's GIS attribute table. The input data in the attribute table were grouped and summarized. In the attributive tables, we put in the average values of the characteristics; for example, instead of the soil temperature of  $-2\sim-4$  °C on the Permafrost landscape map, we laid  $-3$  °C, instead of the thickness of the active layer 1.2–1.4 m–1.3 m, which were then grouped at specific intervals and summarized.

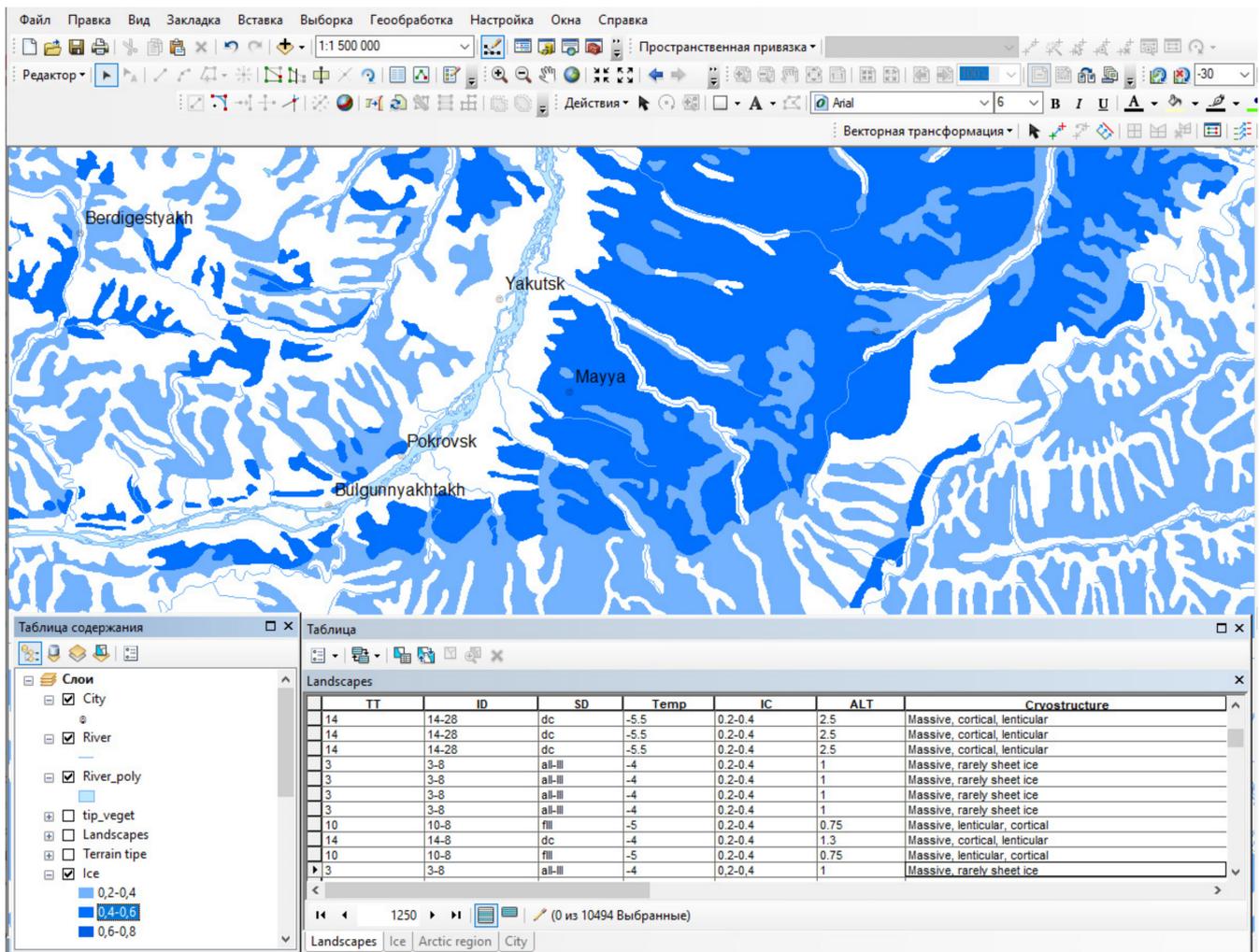


**Figure 1.** Permafrost landscape map of the Republic of Sakha (Yakutia) at a scale of 1:1,500,000 (<http://mpi.ysn.ru/images/mlk20182.pdf> accessed on 1 December 2020).

The general parameters for the compiled maps were as follows: for a map of ground temperature, a step of 1 °C; for a map of the active layer thickness, –0.2 m; ice content of surficial deposits, –0.2 (fraction); and for a map of cryogenic processes, the text legend determined the presence of processes in the contours. When combining two main layers—terrain types and vegetation groups—on the permafrost landscape map [18], the spatial resolution was 0.001 degree. This resolution was also typical for the four thematic maps. We did not use special cartographic generalizations for them.

Map’s data, combined with GIS attribute tables, in which the considered characteristics of permafrost were embedded, served as the primary key to mapping permafrost characteristics. Using ArcGIS software, which supports mapping using an attributive table, we compiled maps of soil temperature, ice content of surface sediments, the active layer thickness, and the distribution of cryogenic processes in Yakutia (Figure 2). These maps made it possible to identify and combine homogeneous territories according

to the considered characteristics of permafrost. This mapping method's main advantage was the rapid mapping of individual geocryological characteristics of great ecological importance for the quick assessment of the permafrost situation in a large region, on the basis of spatial differentiation of permafrost.



**Figure 2.** Fragment of attribute table and its map representation in the ArcGIS environment. Symbols in attribute table: TT—terrain types, ID—combination of terrain type and vegetation group, SD—types of surficial deposits; Temp—ground temperature, IC—ice content, ALT—active layer thickness, Cryostructure—cryogenic structure of surficial deposits.

Uncertainties were found on all four maps. They were primarily associated with the evolution and dynamics of permafrost landscapes. For example, we could not show the temporal variability in the successional stages of vegetation after disturbing the ground temperature and the active layer thickness on the maps. However, such studies showed that the complete disturbance of the vegetation cover led to an increase in ground temperature by 1–1.5 °C and an increase in active layer thickness on 1 m [55,56]. The evolution parameters of permafrost during the current climate warming were also known from 0.5 to 1–2 °C [20,57]. There were fewer such uncertainties in the maps of ice content of surficial sediments and the distribution of cryogenic processes.

### 3. Results

Geocryological data represent the characteristics of landscape invariants with zonal and high-altitude undisturbed primary landscapes. The regularities of the spatial distri-

bution of the soil temperature, the active layer thickness, the content of ground ice, and cryogenic processes are discussed below.

### 3.1. Ground Temperature

Ground temperature is a crucial variable for characterizing permafrost landscape current state and its dynamics and evolution. Increases in ground temperature can trigger or intensify cryogenic processes that strongly affect the stability of landscapes. For example, in forest-free areas of central Yakutia, a ground temperature increase of 0.5–1 °C in the last three decades has caused melting of the top of ice wedges, resulting in widespread thermokarst development [57]. Linear trends of mean annual ground temperature for the 1965–2005 period in Russia’s permafrost zone were generally from 0.01 to 0.04 °C per year [6].

In Yakutia, permafrost temperature monitoring currently conducted within the relatively dense boreholes network covering various landscape types [58–61]. Many of these boreholes were included in the Global Terrestrial Network for Permafrost, an international program designed to detect permafrost changes associated with climate warming [7]. The ground temperature map derived in this study showed average temperatures in different permafrost landscapes, providing representative permafrost temperature information across the region.

A ground temperature map defined 13 classes (Table 1 and Figure 3). The spatial differentiation of ground temperature varied greatly. For example, the area covered by permafrost with high (from 0 to –2.0 °C) temperatures was found to be 13.1% of the territory of Yakutia. They were mainly typical for middle taiga pine and pine–larch forests, less often for larch forests, on terraces of large rivers and plateaus with sandy soils. Ground temperatures from –2.1 to –4.0 °C were found to occupy about 37.4% of the territory. They mainly represented areas with middle taiga larch forests on plateaus and plains with loamy and sandy loam soils. Fragmentarily, they were found in the places of distribution of larch woodlands and open spaces on plateaus and mountains with stony soils. Low ground temperatures from –4.1 to –6 °C were found to occupy 22.7% of the region. They mainly characterized landscapes with open larch forests and open woodlands in the northern taiga and mountain woodlands developed on the Central Siberian plateau, plains, plateaus, and mountains of North-Eastern Siberia and South Yakutia.

**Table 1.** Spatial distribution of ground temperatures.

	Ground Temperature, °C	Area, km <sup>2</sup>	% of Total Area
1	–12.0~–11.1	74,711.3	2.5
2	–11.0~–10.1	52,404.7	1.7
3	–10.0~–9.1	282,639.6	9.3
4	–9.0~–8.1	79,398.5	2.6
5	–8.0~–7.1	95,038.4	3.1
6	–7.0~–6.1	137,867.3	4.5
7	–6.0~–5.1	135,493.0	4.5
8	–5.0~–4.1	545,775.9	18.0
9	–4.0~–3.1	600,003.6	19.8
10	–3.0~–2.1	526,127.6	17.3
11	–2.0~–1.1	213,685.5	7.0
12	–1.0~–0.1	183,155.5	6.0
13	0.0~1.0	107,897.0	3.6
		3,034,197.8	100.0

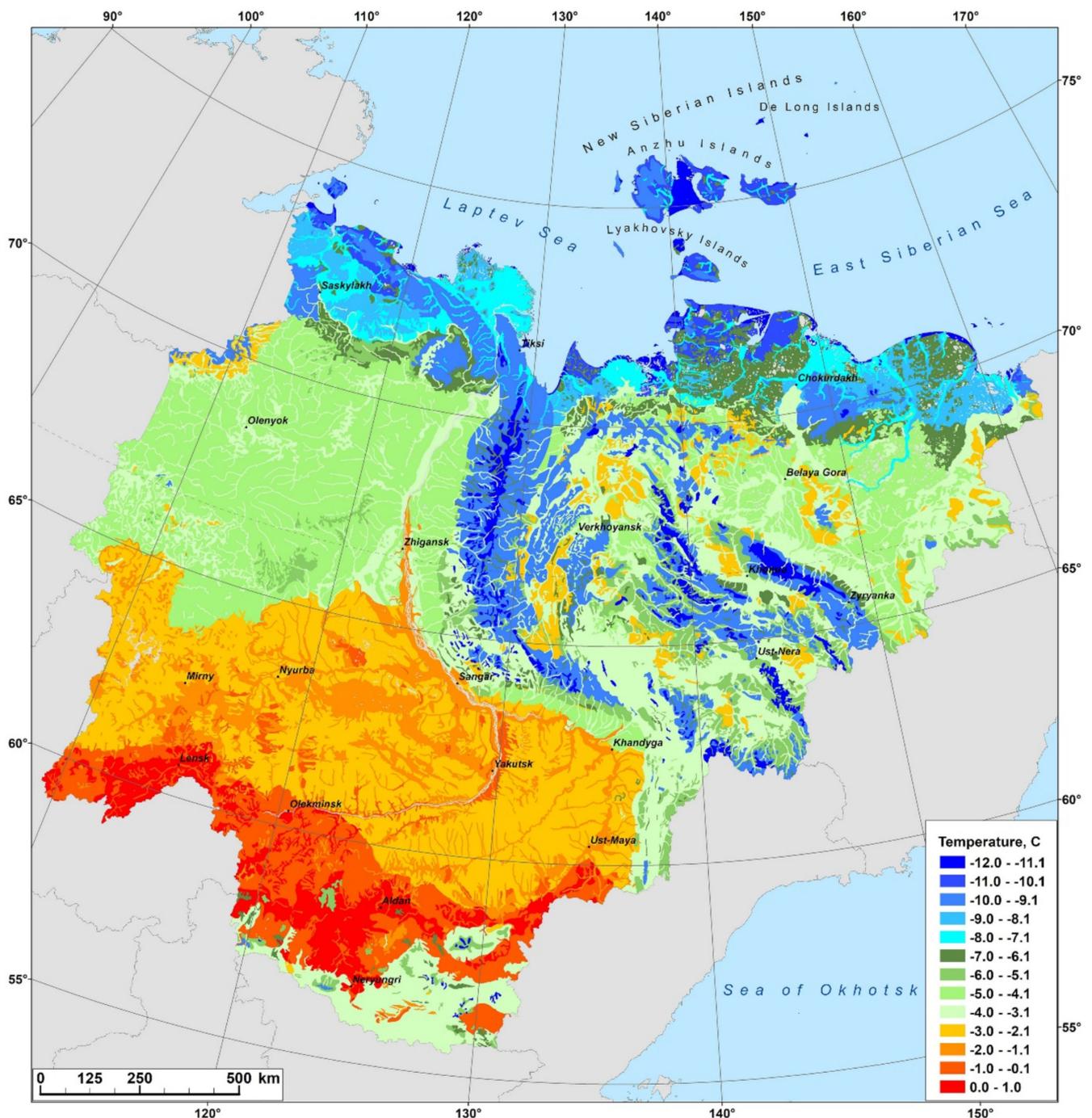


Figure 3. Map of ground temperature at the depth of zero annual amplitude.

Low temperatures below  $-6\text{ }^{\circ}\text{C}$  were found to mainly be typical in the tundra zone, mountain tundra, and desert in mountain structures, occupying about 23.2% of the territory of Yakutia. Landscapes with the seasonally frozen ground ( $T_g > 0\text{ }^{\circ}\text{C}$ ) made up only 3.6% of the region, mainly occupied by pine and pine–larch forests on the plateau in Southwestern and Southern Yakutia. Such a distribution of permafrost temperature indicated the diversity of permafrost landscapes in Yakutia. On the map (see Figure 3, high-resolution map, see Supplementary S2), one can see regional and intraregional landscape differences in ground temperature.

### 3.2. Active Layer Thickness

The active layer is another essential and dynamic parameter of permafrost landscape. In a continuous permafrost zone, the active layer usually reaches the permafrost surface, while in discontinuous and sporadic permafrost zones, this often does not occur. Landscape changes in permafrost regions are closely related to the characteristics of the active layer. An increase or decrease in the active layer's thickness can lead to severe changes in the landscape structure in ice-rich permafrost. The availability of moisture, bio productivity, the development of processes associated with permafrost, and other landscape characteristics primarily depend on the active layer variability.

Yakutian sites included in the circumpolar active layer monitoring (CALM) network [62]. The Melnikov Permafrost Institute has conducted long-term observations over the last 50–60 years to monitor active layer changes specifically [36,37,63]. As is the case elsewhere, active layer thicknesses have generally been increasing in Yakutia. However, no appreciable changes have occurred in central Yakutia's forest-covered areas, as shown by a monitoring study with data starting from the 1980s [61]. This might have been due to increasing forest biomass, which the authors did not consider.

All available data on the active layer thickness were analyzed at 0.2 m intervals using the attribute table, and 14 classes were obtained (Table 2 and Figure 4, high-resolution map, see Supplementary S3). Analysis showed that the thickness of the active layer less than 0.5 m occupied about 5.3% of the territory of Yakutia and was typical for tundra landscapes on the plains. The next step, from 0.51 to 1.10 m, occupied almost half of the region (47.7%), mainly in the subarctic zone—in the northern taiga in the Central Siberian Plateau and the plains of North-East Siberia, as well as in the mountainous landscapes of the North-Eastern Siberia, mainly in mountain deserts and tundra; subalpine shrubs and mountain woodlands with loamy and sandy loam surface deposits; and in swampy areas of river valleys, thermokarst plains, and weakly drained areas of the plateau. The active layer with a thickness of 1.11 to 1.5 m (19.5% of the territory of Yakutia) mainly developed in the middle taiga larch forests of the Central Siberian plateau, the Prilenskoe plateau and Central Yakutia on loamy and sandy loam soils, and in the mountain sparse forests of North-East Siberia and South Yakutia with stony soils.

**Table 2.** Spatial distribution of active layer thickness.

	Active Layer Thickness, m	Area, km <sup>2</sup>	% of Total Area
1	less than 0.30	1516.0	0.1
2	0.30–0.50	156,718.3	5.2
3	0.51–0.70	536,266.7	17.7
4	0.71–0.90	516,875.3	17.0
5	0.91–1.10	393,970.8	13.0
6	1.11–1.30	438,661.3	14.5
7	1.31–1.50	152,772.9	5.0
8	1.51–1.70	367,921.0	12.1
9	1.71–1.90	207,374.1	6.8
10	1.91–2.10	10,560.2	0.4
11	2.11–2.30	19,577.9	0.7
12	2.31–2.50	121,896.8	4.0
13	2.51–3.00	28,671.7	0.9
14	3.01–3.50	81,414.9	2.7
		3,034,197.8	100.0

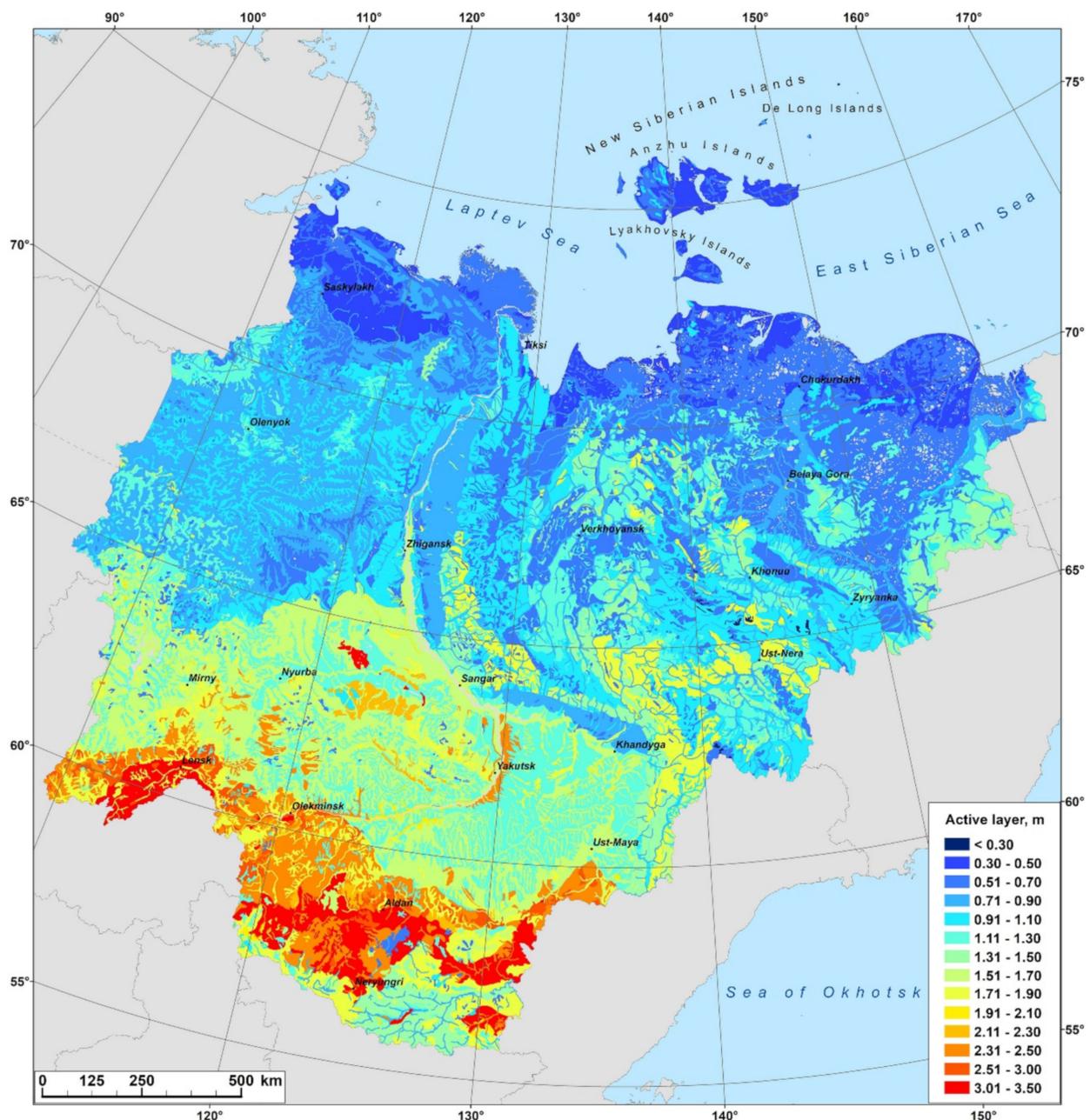


Figure 4. Map of active layer thickness, m.

The interval of the active layer thickness from 1.51 to 2.10 m occupied 19.3% of the territory. It is represented mainly in the middle taiga pine–larch and larch forests with sandy loam and sandy soils in the south part of the Central Siberian Plateau, the Prilenskoe Plateau, and the Central Yakutsk Plain. Territories, with an active layer thickness from 2.11 to 2.5 m, occupying about 4.7% of the total area of Yakutia. They were associated with pine and pine–larch forests on sandy deposits of Central Yakutia and sandy loam and stony soils of the plateau in the South-West and South Yakutia. The thickness of the active layer of more than 2.5 m was typical for 3.6% of the territory of Yakutia, mainly with pine forests on sandy and stony soils in South-West and South Yakutia; in Central Yakutia, they were found in landscapes of cold sandy deserts—tukulans. Almost half of Yakutia’s territory was found to be occupied by permafrost landscapes with a limited thickness of the active layer. Firstly, these are the arctic and subarctic regions, as well as mountainous regions. These landscapes are usually the most vulnerable to human impact and climate change.

### 3.3. Ground Ice Content

Ground ice content correlated with genetic (or stratigraphic–genetic) type of material, bedrock occurrence, topography, and composition of surficial sediments within terrain types (subtypes). With the climate warming presently observed in Yakutia, even a minor surface disturbance can cause seasonal thawing to reach the top of ice wedges in lacustrine and alluvial sediments. This leads to the thawing of permafrost and the development of thermokarst. Thermokarst can develop not only in sediments with massive ice-wedge but with minor ice structures as well. Alluvial, solifluction, and biogenic deposits contain large amounts of ice lenses and layers that can lead to landscape disturbance upon melt.

Mapping shows that sediments with low (<0.2) ice content occupied 33.5% of the territory of Yakutia (Table 3 and Figure 5. high-resolution map, see Supplementary S4), these were mainly high terraces of large rivers, near-watershed and slope well-drained areas, and cold sandy deserts. Sediments with a volumetric ice content of 0.2–0.4 were found to be typical for 26.7% of the total region, and these were mainly floodplains and low terraces of rivers, fluvioglacial plains, and diluvial-colluvial slopes. Relatively high ice content (0.4–0.6) found in 28.0% of the territory occupied by humid landscapes: thermokarst plains, inter-ridge lowlands of alluvial plains, diluvial–solifluction slopes, and moraines. High ice content (0.6–0.8 and more) was found to be typical for 11.8% of the territory occupied mainly by the Yedoma, or ice complex, wetlands (Mari), and glaciers also attributed to it. The high ice content of permafrost was the main reason for the vulnerability of permafrost landscapes to anthropogenic impacts and climate warming. Moreover, the wide distribution of ice-rich permafrost in Yakutia requires a particular and careful attitude to the environment.

**Table 3.** Spatial distribution of ground ice content.

	Active Layer Thickness, m	Area, km <sup>2</sup>	% of Total Area
1	less than 0.2	1,017,649.1	33.5
2	0.2–0.4	809,402.1	26.7
3	0.4–0.6	850,142.4	28.0
4	0.6–0.8	355,488.3	11.7
5	more than 0.8	1516.0	0.1
		3,034,197.8	100.0

### 3.4. Cryogenic Processes

The areal extent, magnitude, and intensity of cryogenic processes are essential indicators for assessing the state of permafrost. Cryogenic processes have always been a significant consideration in permafrost research and engineering. Potential effects of the physical processes related to freezing and thawing of ground material must be investigated in detail before the commencement of any development, such as road and railroad networks, oil and gas pipelines, industrial projects, and land cultivation. Recently, environmental and geotechnical hazards associated with permafrost processes have gained increasing attention in the context of climatic warming.

Observations indicate that thermokarst has intensified in ice-rich permafrost terrain over the last three or four decades and become widespread in unforested and disturbed areas. Our investigations showed very rapid thermokarst development in central Yakutia, with surface subsidence rates of 10–15 cm per year [27,30]. Intense thermokarst development was observed in populated areas of the region, causing severe harm to many rural communities.

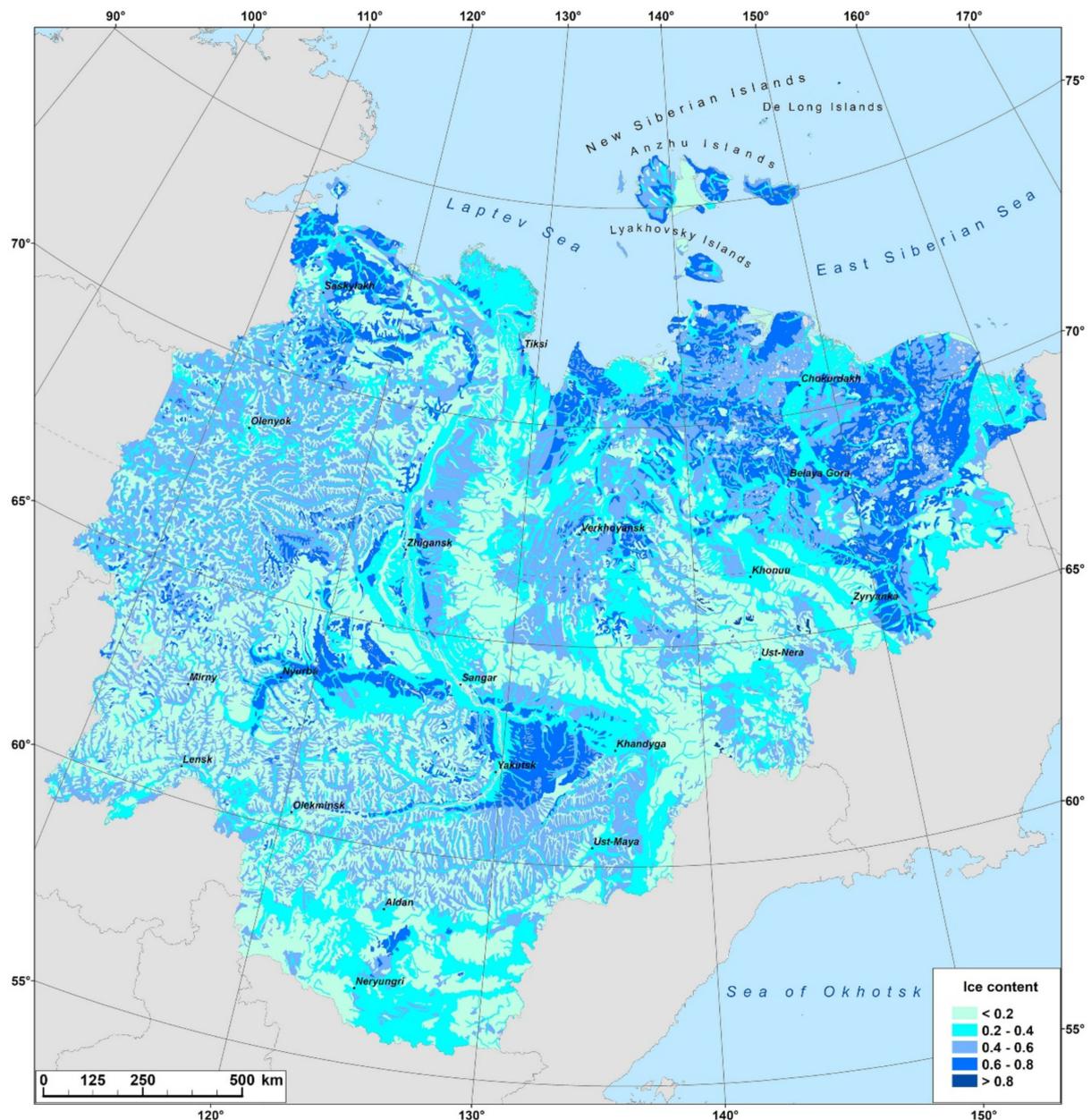
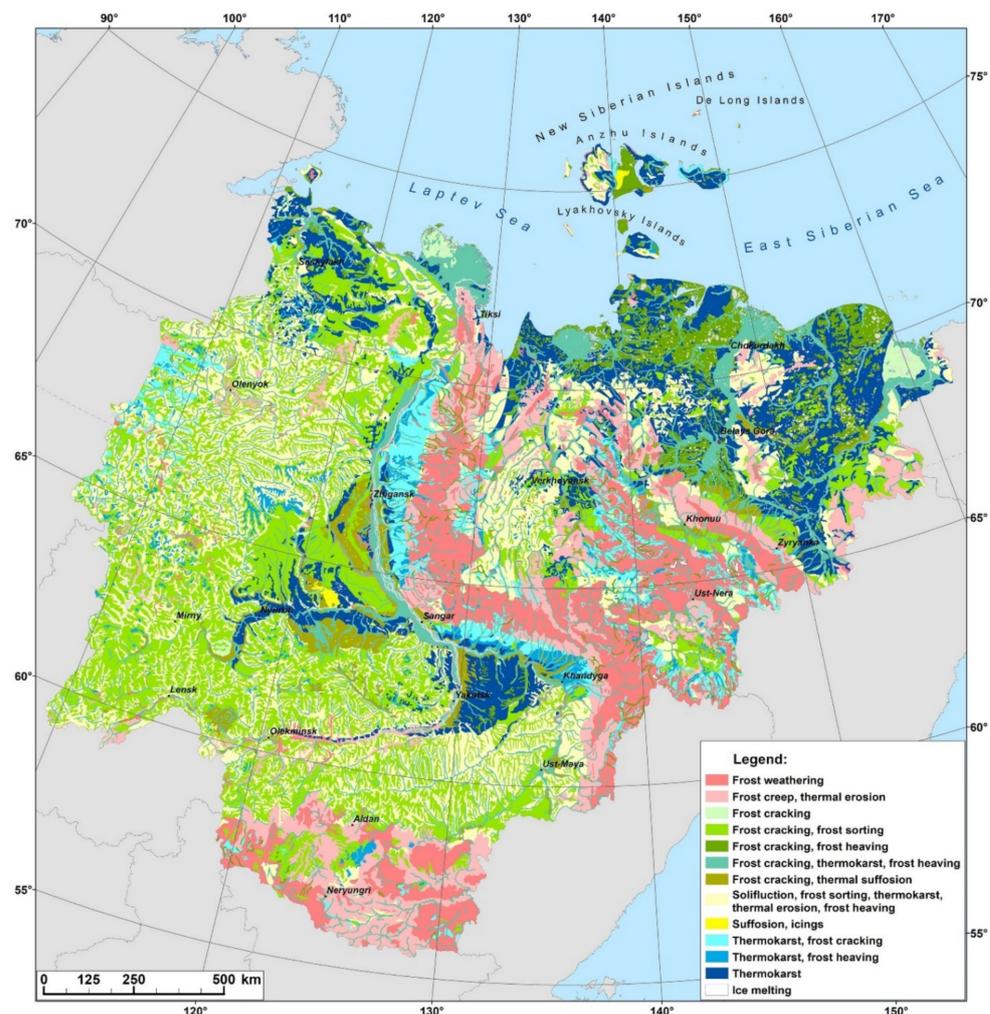


Figure 5. Map of ground ice content (in fraction).

The development of cryogenic processes largely depends on the type of sediment. In permafrost regions with low ice content, frost weathering is the only crucial cryogenic process (Table 4 and Figure 6, high-resolution map, see Supplementary S5). Frost cracking is characteristic of permafrost landscapes with medium ice content of sediments; its combination with heaving is typical of thermokarst depressions and valley landscapes characterized by surface moisture. Frost cracking and heaving in valleys and swampy high terraces of rivers is combined with thermokarst in ice-rich permafrost. Suffosia is characteristic of sandy deposits of high-altitude river terraces. A combination of a whole complex of cryogenic processes—solifluction, frost sorting, thermokarst, thermal erosion, frost heaving—is characteristic of the diluvial solifluction gentle foothills of the slopes of river valleys, plateaus, and mountains. It depends on the permafrost landscape conditions of this complex landscape. Thermokarst develops on highly icy permafrost landscapes, primarily in Yedoma's or on the ice complex. In various permafrost landscapes, heaving in fluvio-glacial plains and weakly drained haze areas and frost cracking in moraines added to thermokarst.

**Table 4.** Spatial distribution of cryogenic processes.

Cryogenic Processes	Area, km <sup>2</sup>	% of Total Area
Frost weathering	329,213.3	10.9
Frost creep, thermal erosion	290,688.4	9.6
Frost cracking	27,360.0	0.9
Frost cracking, frost sorting	631,754.1	20.8
Frost cracking, frost heaving	138,702.7	4.6
Frost cracking, thermokarst, frost heaving	399,152.2	13.2
Frost cracking, thermal suffusion	81,558.5	2.7
Solifluction, frost sorting, thermokarst, thermal erosion, frost heaving	630,634.5	20.8
Suffosion, icings	3439.7	0.1
Thermokarst, frost cracking	114,221.2	3.8
Thermokarst, frost heaving	58,772.4	1.9
Thermokarst	327,184.8	10.8
Ice melting	1516.0	0.1
	3,034,197.8	100.0



**Figure 6.** Map of the distribution of cryogenic processes.

#### 4. Discussion

This article presents the results of studies based on permafrost landscape studies. Landscape methods have long used geocryological map compilation [64,65]. However, direct mapping of permafrost characteristics based on a landscape map has not been previously carried out. We have presented maps of ground temperature, ice content of sediments, the active layer thickness, and distribution of cryogenic processes on the basis of their close relationship with landscapes. We used GIS attribute tables as the primary mapping method, reflecting the relationship between permafrost and landscapes. Each map will inherit landscape differentiation patterns [18], and this is reflected in the mapped objects' discreteness.

The ground temperature map effectively obeys the laws of latitudinal and altitudinal zonation. This map also reflects the intrazonal differences in ground temperature in the tundra, northern taiga, and middle taiga, distinguished by geological–geomorphological and soil–plant features. Early interpretations of maps are not shown for Eastern Siberia [66,67]. Intrazonal differences in ground temperature are shown in the Geocryological Map of the USSR [68], but they are hardly readable due to the map's congestion. Ground temperatures close to the considered map were compiled in Tibet by Zou et al. [69] when compiling the map of permafrost's spatial distribution with the temperature at the top of permafrost on the Tibetan Plateau. The map compiled by Gisnas et al. [70] was also similar in terms of its method of mapping, wherein the spatial distribution of mean annual air temperature was used in the new permafrost map for the Scandinavian Peninsula, as well as in Jorgenson et al.'s [71] mean annual air temperature map, a supporting map for the permafrost map of Alaska. The compiled map shows the ground temperature in controlled conditions, which serve as control values for assessing the impact of climate warming and anthropogenic disturbances. In the future, using the control values of ground temperature, it is possible to estimate the dynamic state of ground temperatures both during evolution and in succession stages. This will make it possible to assess permafrost landscape condition in terms of the risks of permafrost degradation.

The active layer thickness map is in good agreement with the landscape's distributions. The map demonstrates intrazonal differences depending on the geological–geomorphological and soil–plant features. The active layer thickness is a characteristic of permafrost, which is rather difficult to map due to its multifactorial nature. We relied on research in the mapping methodology of Vasiliev [36,37], which depends on the landscape method. Its maps show the leading factors in forming active layer thickness—landscape–climatic zones on the plains and in mountainous regions, and geological–genetic complexes with characteristic soils and vegetation associations. The tabular legend gives the values of the active layer thickness. However, we decided to show the numerical distribution of the active layer thickness in Yakutia, varying from less than 0.3 to 3.5 m. The values of the active layer thickness on the map given for undisturbed landscapes of Yakutia. This map, and the ground temperature map, can serve as a basis for assessing the transformation and degradation of permafrost during climate warming and anthropogenic disturbances.

The ice content map of the surface deposits correlates with the stratigraphic–genetic types of Quaternary sediments. According to the differentiation principles, the ice content map is close to the map of underground ice by Brown et al. [72]. However, the ice content is an essential characteristic influencing permafrost response to climate change and anthropogenic disturbances. Methodologically, the compiled map of ice content is consistent with the principles of collecting the cryolithological map of the USSR on a scale of 1:4,000,000 compiled by Popov et al. [45] (1985) and ground ice map of Alaska compiled by Jorgenson et al. [71]. Areas of maximum ice content are relatively consistent with the Yedoma areas in Eastern Siberia [73]. Ice-rich permafrost with a volumetric ice content of more than 0.4 units with modern climate warming and anthropogenic impact are especially sensitive to disturbances and have a particular risk of degradation.

The distribution of cryogenic processes depends not only on the ice content of permafrost but also on the composition of surface sediments, relief, climate, etc. On this map, we decided to highlight the combinations of the most typical cryogenic processes. In permafrost maps, cryogenic processes usually distinguished by separate symbols [68] or individual processes are shown, such as thermokarst landforms compiled Jorgenson et al. [71]. Our map of the distribution of cryogenic processes is more suitable for the mapping methodology of Tumel and Zotova [53], which showed combinations of main cryogenic processes. It seems to us that the latter approach is most suitable for showing the propagation of cryogenic processes because, in nature, they occur in combination. The compiled map indicates what combinations of cryogenic processes take place in Yakutia. The map of cryogenic processes indirectly shows where the probability of permafrost degradation is highest or lowest during modern climate warming and anthropogenic disturbances.

We believe that our proposed approach for different mapping characteristics of permafrost is practically feasible in terms of the Map of Natural Complexes in the North of Western Siberia [74]. A methodological approach similar to ours was used in mapping the distribution of vegetation in the permafrost zone of the Qinghai–Tibet Plateau [75] is an example of permafrost landscape mapping. The authors set themselves to build a basis for studying vegetation mechanisms in high-altitude areas land surface processes. We believe that such work has prospects in further studying permafrost’s problematic issues in current conditions of climate change and anthropogenic disturbances. Further research in mapping in this direction would help modern methods based on space images interpretation [76].

## 5. Conclusions

On the basis of the permafrost landscape map of the Republic of Sakha (Yakutia) at a scale of 1:1,500,000, we compiled thematic maps involving soil temperature, active layer thickness, ice content, and the spread of cryogenic processes. We drew the following conclusions about permafrost distribution in Yakutia:

1. The spatial differentiation of the permafrost temperature is diverse. The ground temperature was found to be from  $-12$  in the Arctic to  $+1$  °C in the south of Yakutia. One of the most common is ground temperatures from  $-2.1$  to  $-4.0$  °C, which were found to occupy about 37.4% of the territory of Yakutia, being represented mainly by middle taiga larch forests on plateaus and plains with loamy and sandy loam surface deposits. Low temperatures below  $-6$  °C are most typical in the tundra zone on the plains, mountain tundra, and desert in the mountain and occupy about 23.2% of the territory of Yakutia. Landscapes with the seasonally frozen ground ( $T_g > 0$  °C) make up only 3.6% of the region, mainly occupied by pine and pine–larch forests on the plateau in Southwestern and Southern Yakutia.

2. More than half of the territory of Yakutia is occupied by permafrost landscapes with a limited active layer thickness. Areas with an active layer thickness of less than 0.5 m occupy about 5.3% of the territory and are characteristic of tundra landscapes on the plains. The next step, from 0.51 to 1.10 m, occupies almost half of the territory of Yakutia (47.7%), mainly in the subarctic zone—in the northern taiga in the Central Siberian Plateau and the plains of North-Eastern Siberia, as well as in the mountainous landscapes of North-Eastern Siberia, mainly in mountain deserts and tundra, subalpine shrubs, and mountain woodlands with loamy and sandy loam surface deposits, as well as in swampy areas of river valleys, thermokarst plains, and weakly drained areas of the plateau. Territories with an active layer thickness of more than 2.1 m occupy about 8.3% of the total area of Yakutia associated with pine and pine–larch forests on sandy and stony deposits of Central, South-Western, and South Yakutia.

3. Ice-rich permafrost (more than 0.4 in ice content) was found to be typical for about 40% of the territory of Yakutia, of which 11.8% occupies territories with an exceptionally high ice content of more than 0.6, occupied mainly by yedoma or ice complex, or swampy areas (mary). Landscapes with low ice content (less than 0.2) are quite widespread and occupy about 33.5% of the regions. They are typical for high terraces of large rivers,

watersheds and slopes, well-drained areas, and cold sandy deserts in landscape terms. The high ice content of permafrost is the main reason for the vulnerability of permafrost landscapes under anthropogenic impacts and climate warming. Moreover, the wide distribution of icy landscapes in Yakutia requires a particular and careful attitude to the environment.

4. Thermokarst, the most hazardous process, is common in inter-alas and ice-rich terrain. In general, combinations of cryogenic processes with thermokarst occur in half of the territory of Yakutia. The low ice content of permafrost in most study area landscapes suggests a limited development of cryogenic processes.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2073-445X/9/11/453/s1>. Five high-resolution maps (Figures 1 and 3, Figures 4–6) are shown in the Supplementary (S1–S5).

**Author Contributions:** A.A.S., A.N.F., Y.I.T., N.F.V., P.Y.K., S.V.K., V.V.S., T.H., Y.I., H.P., G.I., A.N.G., Conceptualization; A.A.S. and A.N.F.; methodology, A.A.S., A.N.F., Y.I.T., and N.F.V.; investigation, A.A.S., A.N.F., Y.I.T., N.F.V., P.Y.K., S.V.K., V.V.S., T.H., Y.I., H.P., G.I., A.N.G.; writing—original draft preparation: A.A.S., A.N.F., Y.I.T., N.F.V., and P.Y.K.; writing—review & editing, A.A.S., A.N.F., Y.I.T., N.F.V., P.Y.K., S.V.K., V.V.S., T.H., Y.I., H.P., G.I., A.N.G. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by project IX.127.2.3 and IX.127.2.4 (Siberian Branch Russian Academy of Sciences), RFBR grants 18-45-140046 p\_a, 19-29-05151 and HYPE-ERAS project, which is funded by FORMAS (project no. 2019-02332), RFBR (project no. 20-55-71005), JST (grant no. JPMJBF2003) through the Belmont Forum Collaborative Research Action: Resilience in the Rapidly Changing Arctic and Grant for Joint Research Program of the Japan Arctic Research Network Center (FS04) and JSPS KAKENHI (18H03353 and 19H05668).

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Acknowledgments:** We are grateful to the researchers of Melnikov Permafrost Institute of SB RAS, Yakutsk, Russia, for providing long-term investigation data on Siberian Permafrost. We thank editors and anonymous reviewers for their helpful comments that improved the manuscript.

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

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