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Article

# Permafrost-Landscape Map of the Republic of Sakha (Yakutia) on a Scale 1:1,500,000

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**Abstract:** The history of permafrost landscape map compilation is related to the study of ecological problems with permafrost. Permafrost-landscape studies are now widely used in geocryological mapping. Permafrost-landscape classifications and mapping are necessary for studying the trends in development of the natural environment in northern and high-altitude permafrost regions. The cryogenic factor in the permafrost zone plays a leading role in the differentiation of landscapes, so it must be considered during classification construction. In this study, a map's special content was developed using publications about Yakutian nature, archive sources from academic institutes, the interpretation of satellite images, and special field studies. Overlays of 20 types of terrain, identified by geological and geomorphological features, and 36 types of plant groupings, allowed the systematization of permafrost temperature and active layer thickness in 145 landscape units with relatively homogeneous permafrost-landscape conditions in the Sakha (Yakutia) Republic. This map serves as a basis for applied thematic maps related to the assessment and forecast of permafrost changes during climate warming and anthropogenic impacts.

**Keywords:** permafrost; landscape; mapping; Yakutia; ground temperature; active layer thickness

## 1. Introduction

The history of the compilation of permafrost landscape maps is connected with the study of ecological problems of permafrost. Since the 1970s in the USA, studies have been conducted to assess the stability of the surface, which were accompanied by the compilation of maps based on the study of landscapes and permafrost [1–3]. Landscape maps played a significant role in these studies. Permafrost-landscape studies were carried out in the 1970s in the USSR [4] during the development of the largest oil and gas fields in the north of Western Siberia. These works became the foundation for permafrost-landscape mapping, based on the early studies of landscape indications of permafrost [5–7]. Permafrost landscape studies are now widely used in geocryological mapping for studying the dynamics and evolution of permafrost, including the problems caused by current climate warming [8–13].

Permafrost is particularly sensitive to changes in the environment. Anthropogenic impacts and climate change cause significant transformations. However, these transformations depend not only on the properties of permafrost but also on landscape conditions. The need for more qualitative modeling of the permafrost response to current climate warming and anthropogenic impacts requires the use of more informative maps that synthesize factors affecting the environment. Differentiation of vegetation cover and its dynamics due to disturbance, soil, surface water runoff conditions, snow cover, and microclimatic features play a significant role in changing permafrost conditions.

The creation of a better basis for predicting and simulating changes in permafrost is necessary to elucidate the trends in the development of the natural environment in northern and highly mountainous regions that are currently experiencing the greatest pressures of modern climate warming [14–19].

The permafrost zone in Eastern Siberia, which includes the Republic of Sakha (Yakutia), has been well studied in geocryological terms. In connection with the development of the mining industry and the construction of the Berkakit-Yakutsk railway, the oil and gas pipelines in the Far East, and regional-level infrastructure, a purposeful study of the natural environment in this region was conducted. In addition, studies were completed on many international projects aimed at assessing the dynamics of the natural environment of the permafrost under the influence of modern climate change [19,20].

The mapping of the permafrost-landscape in Eastern Siberia has a fairly wide representation [21–23] and a method of permafrost-landscape scale mapping has been developed [24]. The catalog of permafrost landscapes of Yakutia [25] and the Permafrost-Landscape Map of the Yakut ASSR on 1:2,500,000 scales [26] synthesize the conducted studies. This map was compiled using conventional cartographic methods in paper form and published under the Gosgeodezia USSR. When compiling the map, almost all available stock, literary, and cartographic materials on the permafrost and landscape conditions of Yakutia until 1988 were used.

A large amount of information and methodological material, which appeared after the release of this map, allowed for the improvement of the methodology for the compilation of permafrost-landscape maps. The wide use of space imagery improved the mapping process. The emergence of geographic information system (GIS) technologies somewhat simplified the classification process of permafrost landscapes by layer-by-layer imposition; these also simplified the interpretation of maps including attributive tables and generated a series of thematic maps for better perception of the permafrost landscape situation [27–30]. GIS interpretations based on the permafrost-landscape map of the Yakut Autonomous Soviet Socialist Republic [26] confirmed the correctness of the classification units of cryogenic landscapes that we previously applied [31–33].

In connection with a significant change in the information and methodological base, alongside the need to compile a basis for studying the dynamics and stability of the permafrost of Yakutia given the conditions of modern climate change, we aimed to update the previously compiled permafrost-landscape map of the Yakut ASSR scale 1:2,500,000 [26]. The main purpose of mapping on a scale of 1:1,500,000 was to improve the existing spatial model of the landscapes to determine environmental development during this climate warming period and anthropogenic impacts. Thus, we wanted to depict the main patterns of differentiation of ice content and permafrost temperature, the active layer thickness, and cryogenic processes in natural landscape, according to the new data and methodological decisions.

The vast territory in the region is a combination of both latitudinal-zonal and high-altitude landscapes, such as cryogenic formations with powerful ice wedges and frosty rock mountains. The landscapes of Yakutia are diverse: forest-steppe landscapes called "charans", alases with bulgunnyakhs (pingos), polygonal-structural rock formations, icing and glaciers, sand deserts called "tukulans", and "kisilyahs", which are stone remains on the peaks and slopes of low mountains. The permafrost is equally diverse, which, when combined with landscape analysis, enabled the identification on the map of 143 different combinations of permafrost landscapes.

## 2. Materials and Methods

### *2.1. Basic Principles of Differentiating Permafrost Landscapes*

The object of this study was a relatively homogeneous territorial formation, where geological, climatological, soil, and geobotanical components are closely interconnected. Within the permafrost zone, their main characteristics—temperature, ice content, seasonally thawed, and seasonally frozen layers—are the elements that determine the permafrost landscape. The cryogenic factor in the permafrost zone plays a leading role in the differentiation of landscapes, so it was necessary to consider during classification constructions [24].

### *2.2. Basic Units of Mapping*

Based on our goals and objectives, scale mapping (1:1,500,000) and the volume of available factual material, the primary units we selected were types of terrain types and landscapes, which correctly show the distribution of ice content, temperature, and active layer thickness of the permafrost [24].

### *2.3. Types of Terrain*

Natural formations formed by certain genetic (or stratigraphic-genetic) complex deposits (alluvial, lacustrine-alluvial, fluvioglacial, eluvial, etc.); they are sometimes part of, or combinations of, certain locations in the environment with naturally forming components of structural units. We identified and displayed 20 types of terrain on the permafrost-landscape map on a scale of 1:1,500,000 in the Republic of Sakha (Yakutia).

### *2.4. Types of Landscapes*

Bioclimatic complexes, which are similar in morphological structure and proceeding physiographic processes, were characterized by a certain ratio of heat and moisture, and the corresponding types of soils and vegetation (tundra, taiga, mountain tundra, mountain-taiga, and others).

### *2.5. Permafrost-Landscape Zoning*

Zoning is the allocation of large regional complexes with a relatively homogeneous combination of typological permafrost landscapes: countries, provinces and regions. The main categories of their allocation included territorial integrity, genetic unity, and individuality in space. We conducted zoning at the level of permafrost-landscape provinces and a total of 54 provinces were allocated.

### *2.6. Mapping*

In developing the special content of a map, we used published material on the nature of Yakutia; stock sources of the Permafrost a of the Siberian Branch of the Russian Academy of Science (SB RAS), the Institute of Biological Problems of the Cryolithozone of the SB RAS, and the Institute of Geography of the SB RAS; and the materials of space surveys and special field studies. The following cartographic generalizations served as the basis for mapping the map: the geological map of the Yakut ASSR on a scale of 1:1,500,000 [34], the soil map of Yakutia on the scale of 1:5,000,000 [35], vegetation map of Yakutia on a scale of 1:5,000,000 [36], and map of quaternary formations of the Russian Federation on a scale of 1:2,500,000 [37].

Generalizing and summarizing works for various regions of Yakutia [38–51] played an essential role in compiling the map. The technique used was tested by us in permafrost-landscape studies along the Amur-Yakutsk railway [21] and in South [52], and Western Yakutia [49].

The main legend is provided in a table form, where cryogenic components are determined by the synthesis of the geological-geomorphological (cryolithological) and bio hydroclimatic factors: the temperature of permafrost and active layer (seasonally thawed and seasonally frozen) thickness.

The systematization of provinces was produced according to the scheme: Country, Provincial Group, or Province. For the convenience of systematizing the natural conditions of the province within the country, the provinces were grouped together, for example, the north taiga provinces with a continuous distribution of permafrost, or the province with a prevalence of mountain-tundra natural complexes of continuous distribution of permafrost, etc.

At the mapping stage, the task of cartographically displaying permafrost landscapes as a conjugate system of interconnected components was solved using a spatial model based on ArcGIS 10.1 (ESRI (Environmental Systems Research Institute), Redlands, CA, USA). A special role was assigned to the compilation work, a choice of different methods for imaging and design to provide better visibility. Please note that the types of landscapes are reflected in color, and the types of terrain are hatched. As a geographical basis, a digital topographic map of the Russian Federation on a scale of 1:1,000,000 was adopted.

Types of terrain were classified on the basis of an analysis of the genetic types of Quaternary sediments taken from the map of quaternary deposits of the Russian Federation on a scale of 1:2,500,000 [37]. Types of landscapes (plant communities, 35 in total), the second layer maps, were allocated on the basis of vegetation maps of Russia on a 1:5,000,000 scale [53] and Landsat imagery.

The next operation was the overlay of the selected two layers: terrain types and plant associations. In total, 145 combinations were obtained by merging these two layers. For comparison, in the previously compiled permafrost-landscape map of the Yakut ASSR [26], only 77 such combinations were identified. The types of terrain on the map are shown by hatching and signs, and plant associations are represented in various colors. The colors were chosen to highlight the plains and mountainous landscapes. In this respect, the color gradations of the previously compiled map provided significant assistance. To distinguish the boundary between continuous and discontinuous (sporadic) permafrost zones, a cartographic interpretation of the January radiation temperature of the surface of the cosmic image of Moderate Resolution Imaging Spectroradiometer (MODIS) was used.

The allocation of permafrost-landscape provinces in the three physiographic countries (Middle Siberia, North-Eastern Siberia, and Southern Siberia mountains), represented on the territory of the Republic of Sakha (Yakutia), was not especially updated by us, since the principles of their identification had not changed. The differentiation of permafrost-landscape provinces is provided in a separate map.

Maps on a scale of 1:10,000,000, including the administrative map of the Republic of Sakha (Yakutia), the map "Zoning of distribution and regional features of the permafrost" [54], and the map of the permafrost-landscape regionalization at the provincial level and the satellite imagery mosaic map comprise the main map.

## 3. Results

The permafrost-landscape map of the Republic of Sakha (Yakutia) on a scale of 1:1,500,000 (Figure 1) was compiled at the Melnikov Permafrost Institute SB RAS, Yakutsk, Russia, in 2017 in the framework of Program II of the Yakut complex expedition (2010–2020). A full-scale PDF file can be downloaded from the website of the Melnikov Permafrost Institute SB RAS [55].

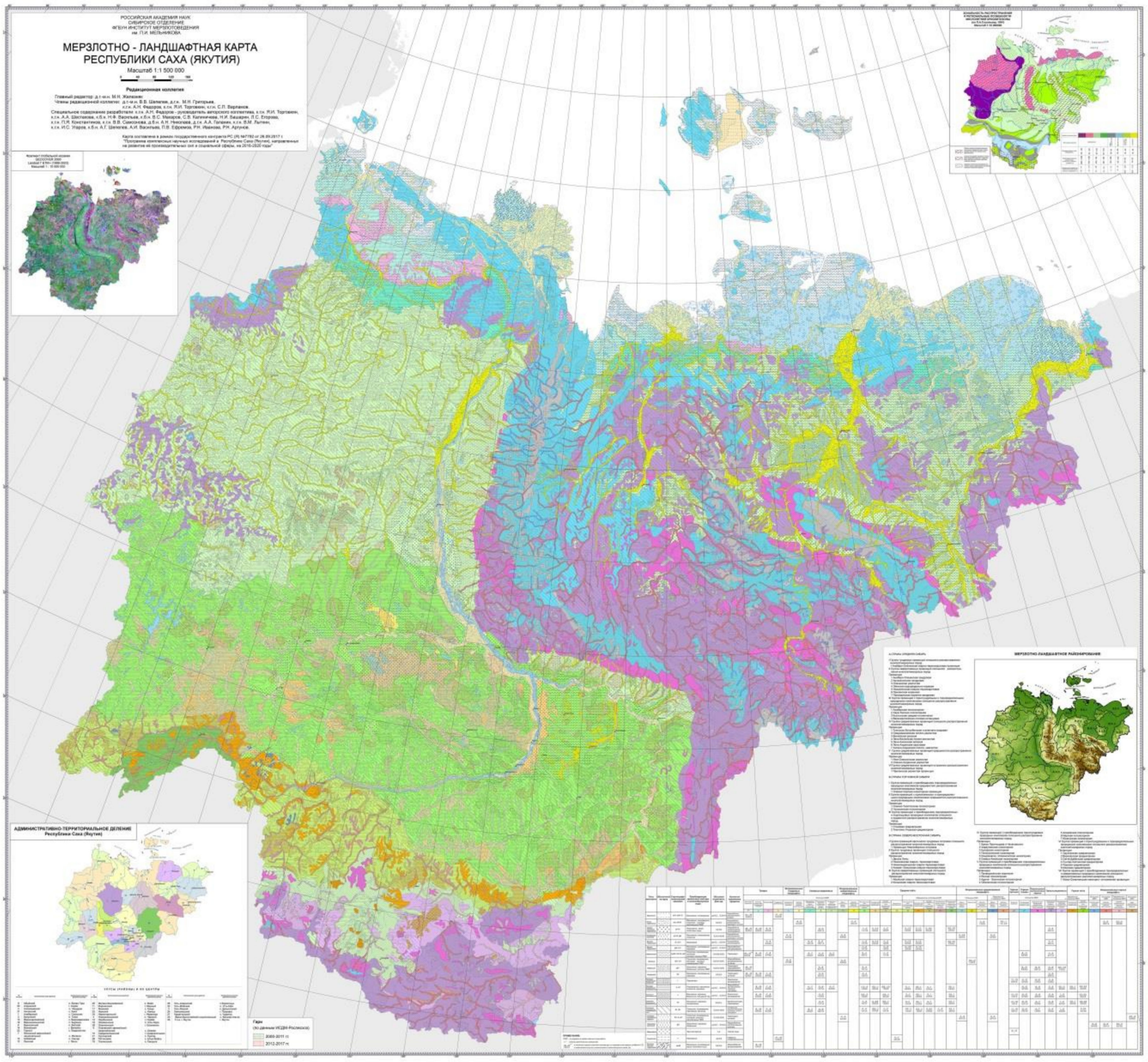



**Figure 1.** Permafrost-landscape map of the Republic of Sakha (Yakutia) on a scale of 1:1,500,000.

To show the permafrost content on the map, we used a combination of two types of units, identified on the basis of a geological-geomorphological map indicating the cryolithological and bio hydroclimatic features of permafrost landscapes, controlling the temperature of the soils and the thickness of the active layer. In landscape classifications, they represent the types of terrain and types of landscapes [56].

### 3.1. Terrain Type

We identified and display only 20 types of terrain on a permafrost-landscape map of a scale of 1:1,500,000 in the Republic of Sakha (Yakutia) (Table 1). Terrain types are mainly correlated with geological-geomorphological and cryolithological features of landscapes. Compared with the previously compiled map of the permafrost landscapes of Yakutia [26], the list of terrain types has changed somewhat. The slope type of terrain is subdivided into colluvial, diluvial-colluvial, and diluvial-solifluction according to the genetic types of slope deposits. This details the content of terrain types by cryolithological features and cryogenic processes, which is important for permafrost landscapes.

**Table 1.** Terrain types distribution in Yakutia.

| No. | Terrain Type | Stratigraphic-Genetic Complex | Prevailing Cryogenic Textures and Trapped Ice | Volumetric Ice Content, Fraction | Basic Cryogenic Processes | Distribution, % from Total Area |
|---|---|---|---|---|---|---|
| 1 | Marshes | mH, mH1–2 | Massive, lenticular | up to 0.2, rarely 0.2–0.4 | Frost cracking, heaving | 0.4 |
| 2 | Low terrace | aH, aIII-H | Massive, lenticular, layered; Holocene ice wedges | 0.2–0.4 | Frost cracking, thermokarst, heaving | 12.9 |
| 3 | Mid terrace | aII-III | Massive; rarely massive ice | 0.2–0.4 | Frost cracking, thermosuffu sion | 2.7 |
| 4 | Inter-ridge-lowland | aII-III, bH | Massive, lenticular, layered | 0.2–0.4 (0.6) | Frost cracking, thermokarst, heaving | 0.2 |
| 5 | High terrace | aI, aI-II | Massive | up to 0.2, rarely 0.2–0.4 | Frost cracking | 0.4 |
| 6 | Old terrace | lpH, LH | Massive, crust-like, lenticular | up to 0.2, rarely 0.2–0.4 | Frost cracking | 0.1 |
| 7 | Inter-alas | LedIII, laII-III, aIII | Layered, lenticular, reticular; Pleistocene ice wedges | 0.4–0.6 (0.8) | Thermokarst | 10.8 |
| 8 | Alas | lpH, LH | Layered, lenticular, reticular; Holocene ice wedges | 0.2–0.4 (0.6) | Frost cracking, heaving | 3.6 |
| 9 | Moraine | gIII | Massive, cortical, basal; ice wedges | 0.2–0.4 (0.6) | Thermokarst | 3.7 |
| 10 | Outwash | fIII | Massive, lenticular, cortical | 0.2–0.4 | Thermokarst, heaving | 1.0 |
| 11 | Rock-ridge | r | Crack-like ice | - | Cryogenic/frost weathering | 0.8 |
| 12 | Eluvial | e, ed | Lenticular, massive, layered, crust-like | up to 0.2, rarely 0.2–0.4 | Frost cracking, frost sorting | 20.6 |
| 13 | Colluvial | c | Massive, cortical, basal | up to 0.2, rarely 0.2–0.4 | Cryogenic/frost weathering | 9.9 |
| 14 | Diluvial colluvial | dc | Massive, crust-like, lenticular | 0.2–0.4 | Cryogenic creep, thermoerosion | 9.5 |
| 15 | Diluvial solufluc-tion | ds, dp | Layered, lenticular, massive, reticular | 0.2–0.4 (0.6) | Solifluction, frost sorting, thermokarst, thermoero-sion, heaving | 20.6 |
| 16 | Non-drained boggy terrain | bH, e, ed | Layered, lenticular, reticular; Holocene ice wedges | 0.4–0.6 (0.8) | Thermokarst, heaving | 0.9 |
| 17 | Glacial-valley | gIII | Massive, crust-like, basal | up to 0.2, rarely 0.2–0.4 | Frost cracking, heaving | 0.7 |
| 18 | Glacier | - | Glacier ice | 1.0 | Thawing ice | 0.05 |
| 19 | Tukulan | v | Massive | up to 0.2 | Thermosuffu-sion, icing | 0.1 |
| 20 | Valley-sea terrace | amIII | Massive, lenticular; rarely massive ice | 0.2–0.4 | Frost cracking | 0.5 |
| | | | Water bodies | | | 0.4 |

The inter-alas type of terrain, reflecting the areas with ice-rich sediments with ice wedges on the map, also includes the high terraces of mountain rivers, which were shown separately on the previous map. The glacial and fluvioglacial complexes on the plains and mountains were combined into moraine and outwash types of terrain. The sand-ridge-type terrain of medium-elevated terraces complexes with alluvial-marine sediments in the delta-marine terraced type of terrain were singled out. On the top sections of the mountain ranges, the rock-ridge type of terrain is separately identified.

The spatial distribution of terrain types is uneven. The most widespread are eluvial and diluvial-solifluction (20.6%), low terrace (12.9%), inter-alas (10.8%), colluvial (9.9%), and diluvial-colluvial (9.5%) terrain types. Types of terrain such as marshes, inter-ridge-lowland, high and old terraces, glacier, and tukulan are spread over an area less than 0.5% of the area of Yakutia.

Types of landscapes have a clear differentiation in terms of climatic parameters [25] corresponding to the well-known unit biome (Table 2). However, in this map, we used vegetation groups in types of landscapes that affect the temperature of permafrost. This applies to pine and pine-larch forests, moistened larch forests with ernik, etc.

**Table 2.** Characteristics of Yakutian means types of landscapes [25].

| Type of Landscapes | Landscape Subtype | Perma-Frost Type | AT Sum, °C | +T Duration | MAAT var, °C | $T_{Jan}$ var, °C | $T_{Jul}$ var, °C | Phyto-Mass, c/ha |
|---|---|---|---|---|---|---|---|---|
| Tun-dra | Arctic | Conti-nuous | – | 80–100 | −13.5 ÷ −15.5 | −29.5 ÷ −35 | 2–4 | 20–130 |
| | Typical | Conti-nuous | – | 100–120 | −12.5 ÷ −15.5 | −30.5 ÷ −38 | 4.5–11.5 | 75–330 |
| | South | Conti-nuous | 400–650 | 110–130 | −11.5 ÷ −14 | −33 ÷ −35.5 | 11–12 | 155–400 |
| Taiga | Northern woodland (taiga) | Conti-nuous | 650–1200 | 120–140 | −11 ÷ −17 | −37.5 ÷ −50 | 12–16 | 400–1000 |
| | Middle taiga | Conti-nuous | 1200–1600 | 140–160 | −7.5 ÷ −11.5 | −32.5 ÷ −45.5 | 16–19 | 1200–1500 |
| | | Disconti-nuous | 1400–1600 | 150–160 | −6.5 ÷ −9.0 | −33.5 ÷ −40.5 | 17.5–18.5 | 1500–2000 |
| | | Sporadic | 1400–1600 | 160–165 | −5.5 ÷ −6.5 | −30 ÷ −32 | 17.5–18 | 2000–3000 |
| Mountain desert | – | Conti-nuous | – | 90–100 | −13.5 ÷ −14.5 | −30 ÷ −30.5 | 2.5–4.5 | <50 |
| Moun tain tundra | – | Conti-nuous | – | 90–105 | −12 | −28 ÷ −29 | 6.5–9.5 | appr. 70 |
| Sub-alpine shrub | – | Conti-nuous | 450–700 | 110–125 | −12 ÷ −14 | −31 ÷ −37.5 | 11–13 | 330–720 |
| Moun tain sparse wood land | – | Conti-nuous | 560–1100 | 115–140 | −11.5 ÷ −17 | −36 ÷ −50 | 12–15.5 | appr. 1000 |
| | – | Disconti-nuous | 800–1100 | 125–150 | −7.5 ÷ −11 | −28 ÷ −40 | 14.5–15.5 | appr. 1000 |
| Moun tain taiga | – | Sporadic | 1150–1300 | 150–160 | −6 ÷ −9.5 | −28 ÷ −36.5 | 16–17.5 | appr. 1600 |

Notes: AT sum—Sum of active temperatures (more than 10 °C/day); +T duration—Number of days with more than 0 °C; MAAT, °C—Mean annual air temperature variations, °C; $T_{Jan}$—Mean temperature of January variations, °C; $T_{Jul}$—Mean temperature of July variations, °C Phytomass, c/ha—Phytomass reserves, centners per hectare.

Tundra is subdivided into arctic (1), typical (2), and southern tundra (3) landscape subtypes, with herbaceous-gramineous, moss-lichen, shrub associations, and sparse vegetation on marshes dominating (4). Intrazonal tundra landscapes are subdivided into low-centered polygonal tundra (5) and a complex of tundra valley vegetation (6).

Northern taiga consists of pre-tundra larch sparse woodland (7), larch sparse woodlands (8), and larchwood swamps (9). It is characterized by a low shrub, lichen, and moss cover. Intrazonal northern taiga landscapes consist of bogged larch sparse woodlands (10) and a complex of northern taiga valley vegetation (11).

The middle taiga on the continuous permafrost zone is characterized by the predominance of larch forests (12), pine (13), and pine-larch forests (14). They are characterized by low shrub and low shrub/lichen-moss coverings. Sparse vegetation of the Tukulans is also distinguished here (15).

The middle taiga on discontinuous and sporadic permafrost includes larch (16), pine (17), pine-larch (18), and pine-larch with cedar and spruce (20) forests. They are characterized by low shrub and low shrubby/lichen/moss covers. Larch sparse woodland (19) is also characteristic in the swampy areas. Intrazonal mid-taiga landscapes on continuous permafrost form bogged larch sparse woodlands (21), alas meadows (22), and valley vegetation (23), and in discontinuous and sporadic permafrost zone, bogged larch sparse woodlands (24) and valley vegetation (25).

Mountain deserts are represented by epilithic lichens (26), mountain tundra by lichen and low shrub/moss tundra (27), subalpine shrub by cedar elfin wood in combination with alder and birch fruticose (28), mountain sparse woodlands by larch sparse woodlands in the continuous permafrost zone (29), and larch woodlands in the discontinuous permafrost (30), and mountain taiga is characterized by pine (31) and pine-larch (32) forests. Intrazonal mountain landscapes include valley mountain-tundra (33), mountain sparse woodland (34), and mountain bogged taiga (35), bog and larch sparse woodland in upland (36).

The spatial distribution of plant groups is also uneven (Table 3). The most widespread are Larch sparse woodland low shrub/lichen/moss in the northern taiga (17.9%), Larch sparse woodland low shrub/lichen and moss in mountain sparse woodland (15.9%), Larch sparse woodland low shrub and low moss in the middle taiga (15.4%), Lichen and low shrub/moss mountain tundra (9.2%), and complex northern taiga valley vegetation (4.9%). A total of 15 plant groups represent 1 to 2.7% of the total land cover each and 15 represent less than 1% each.

*3.2. Permafrost Landscape Characteristics*

A new classification unit, the "natural complex", obtained by superimposing two layers, enabled systematizing the permafrost component of the landscape (Figure 2). Using the table legend along with the map, it was possible to obtain the following information about the permafrost landscapes of Yakutia.

The inter-alas terrain type with ice-rich deposits (with volumetric ice content of 0.4–0.6 and up to 0.8) is widely encountered in the continuous of permafrost zone. The tundra average ground temperatures are from −10 to −12 °C in the arctic tundra, from −8 to −10 °C in a typical, and from −7 to −8 °C in shrub tundra. The active layer thickness is 0.2–0.4, 0.3–0.5, and 0.4–0.6, respectively. Northern woodlands ground temperatures vary from –6 to –7 °C in pre-tundra to from –4 to –6 °C in typical larch sparse woodlands. The active layer thickness varies from 0.5−0.7 to 0.6–0.8 m, respectively. Middle taiga ground temperatures increase significantly ranging from −2 to −4 °C in larch and from −1 to −3 °C in pine-larch forests, with active layer thickness of 1–1.3 m and 1.4–1.8 m, respectively. In fragments of the inter-alas type of terrain in mountain tundra, the temperature of the ground is from −8 to −11 °C, active layer thickness is 0.5–0.8 m, and in mountain sparse woodland, these values are from −4 to −8 °C and 0.7–1.2 m [55], respectively.

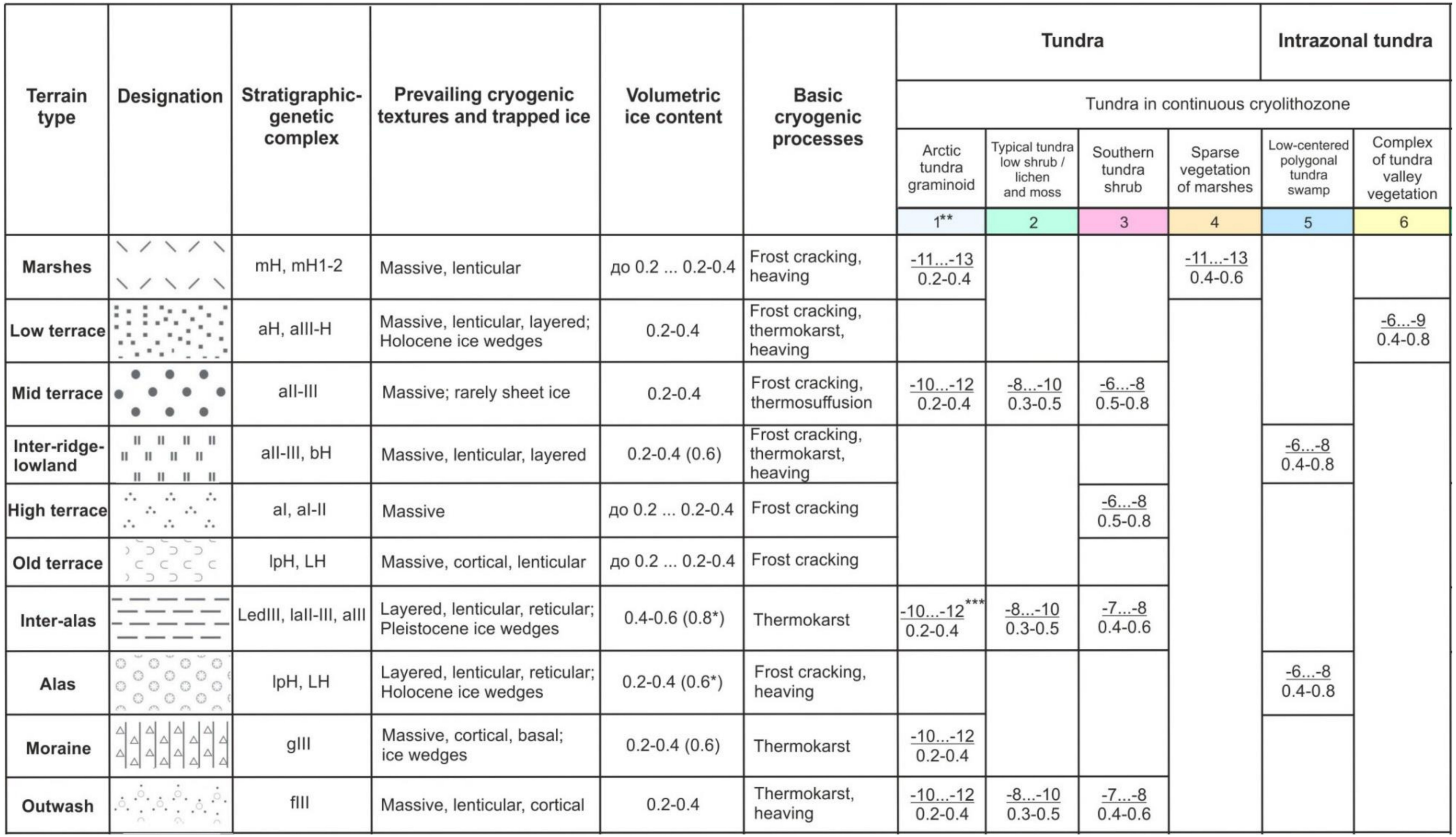
Slope diluvial-colluvial terrain, with a volumetric ice content of 0.2–0.4, is found widely in Yakutia. In northern woodlands, the ground temperature is from −6 to −7 °C in the pre-tundra and from −3 to −5 °C in larch sparse woodlands, and the active layer thickness is 0.6–1 and 1.2–1.4 m, respectively. Middle taiga, with a continuous permafrost ground temperature, is from −1 to −3 °C in larch, from −0.5 to −1 °C in pine-larch forests, and from 0 to −0.5 °C in pine forests, with active layer thickness 1.2–1.7, 1.8–2.2, and 2–3 m, respectively. In middle taiga with discontinuous and sporadic permafrost, negative temperatures are typical for larch forests (from 0 to −1 °C; 1.5–3 m), and for pine forests the soil temperatures are usually from 0.5 to 1 °C with freezing layer thickness of 2–3 m. In pine-larch forests, the temperature of soils is from 0 to +1 °C and freezing layer thickness is 2–3 m. The conditions of development of mountain landscapes are characterized by the following patterns of temperature changes in the soil and freezing layer thickness: from −to −13 °C/1–1.5 m in mountain desert, from −8 to −11 °C/0.5–1.5 m in mountain tundra, from −4 to −7 °C/2–3 m in subalpine bushes, from −2 to −6 °C/1.5–2.5 m in larch woodlands, from −1 to −2 °C/2–3 m in larch forests, and from 0.2 to 0.5 °C/3–4 m in pine-larch forests [55].

**Table 3.** Vegetation unit distribution in Yakutia.

| Type of Landscape | Map Index No. | Vegetation Unit | Distribution, % of Total Area |
|---|---|---|---|
| Tundra in continuous permafrost zone | 1 | Arctic tundra graminoid | 2.2 |
| | 2 | Typical tundra low shrub/lichen and moss | 2.7 |
| | 3 | Southern tundra shrub | 0.6 |
| | 4 | Sparse vegetation of marshes | 0.2 |
| Intrazonal tundra | 5 | Low-centered polygonal tundra swamp | 2.1 |
| | 6 | Complex of tundra valley vegetation | 2.5 |
| Northern taiga in continuous permafrost zone | 7 | Pre-tundra larch sparse woodland low shrub/lichen/moss | 1.2 |
| | 8 | Larch sparse woodland low shrub/lichen/moss | 17.9 |
| | 9 | Larchwood swamp moss | 0.3 |
| Intrazonal northern taiga | 10 | Bogged larch sparse woodlands | 2.0 |
| | 11 | Complex of northern taiga valley vegetation | 4.9 |
| Middle taiga in continuous permafrost zone | 12 | Larch forest low shrub and low shrub/moss | 15.4 |
| | 13 | Pine forest low shrub/lichen | 0.7 |
| | 14 | Pine-Larch forest low shrub/lichen/moss | 2.5 |
| | 15 | Sparse vegetation of sand | 0.1 |
| Middle taiga discontinuous and sporadic permafrost zone | 16 | Larch forest low shrub and low shrub/moss | 2.5 |
| | 17 | Pine forest low shrub/lichen | 0.9 |
| | 18 | Pine-Larch forest low shrub/lichen/moss | 1.0 |
| | 19 | Larch sparse woodland sedge/low shrub/moss with yernik | 0.2 |
| | 20 | Pine-Larch forest with Cedar and Spruce low shrub and low shrub/moss | 0.5 |
| Intrazonal middle taiga in continuous permafrost zone | 21 | Mari and Larch sparse woodland moss | 0.3 |
| | 22 | Alas meadow | 0.1 |
| | 23 | Complex of middle taiga valley vegetation | 2.7 |
| Intrazonal middle taiga in discontinuous and sporadic permafrost zone | 24 | Mari and Larch sparse woodland moss | 0.03 |
| | 25 | Complex of middle taiga valley vegetation | 0.5 |
| Mountain desert in continuous permafrost zone | 26 | Epilithic lichen | 1.9 |
| Mountain tundra in continuous permafrost zone | 27 | Lichen and low shrub/moss mountain tundra | 9.2 |
| Subalpine shrub in continuous permafrost zone | 28 | Cedar elfin wood in combination with alder and birch fruticose | 2.6 |
| Mountain sparse woodland in continuous permafrost zone | 29 | Larch sparse woodland low shrub/lichen and moss | 15.9 |
| Mountain sparse woodland in discontinuous and sporadic permafrost zone | 30 | Larch sparse woodland low shrub/moss | 1.4 |

**Table 3.** *Cont*.

| Type of Landscape | Map Index No. | Vegetation Unit | Distribution, % of Total Area |
|---|---|---|---|
| Mountain taiga in discontinuous and sporadic permafrost zone | 31<br>32 | Pine forest low shrub/lichen<br>Pine-Larch forest low shrub/lichen/moss | 0.03<br>1.5 |
| Intrazonal mountain valley tundra in continuous permafrost zone | 33 | Complex of mountain tundra valley vegetation | 0.2 |
| Intrazonal mountain sparse woodland in continuous permafrost zone | 34 | Complex of mountain woodland valley vegetation | 2.3 |
| Intrazonal mountain valley sparse woodland in discontinuous and sporadic permafrost zone | 35 | Complex of mountain woodland and forest valley vegetation | 0.2 |
| Upland intrazonal sparse woodland in continuous permafrost zone | 36 | Bog and Larch sparse woodland moss | 0.1 |
| Water bodies | - | - | 0.4 |



| Terrain type | Designation | Stratigraphic-genetic complex | Prevailing cryogenic textures and trapped ice | Volumetric ice content | Basic cryogenic processes | Tundra | | | | Intrazonal tundra | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Tundra in continuous cryolithozone | | | | | |
| | | | | | | Arctic tundra graminoid | Typical tundra low shrub / lichen and moss | Southern tundra shrub | Sparse vegetation of marshes | Low-centered polygonal tundra swamp | Complex of tundra valley vegetation |
| | | | | | | 1** | 2 | 3 | 4 | 5 | 6 |
| Marshes | | mH, mH1-2 | Massive, lenticular | до 0.2 ... 0.2-0.4 | Frost cracking, heaving | -11...-13<br>0.2-0.4 | | | -11...-13<br>0.4-0.6 | | |
| Low terrace | | aH, aIII-H | Massive, lenticular, layered; Holocene ice wedges | 0.2-0.4 | Frost cracking, thermokarst, heaving | | | | | | -6...-9<br>0.4-0.8 |
| Mid terrace | | aII-III | Massive; rarely sheet ice | 0.2-0.4 | Frost cracking, thermosuffusion | -10...-12<br>0.2-0.4 | -8...-10<br>0.3-0.5 | -6...-8<br>0.5-0.8 | | | |
| Inter-ridge-lowland | | aII-III, bH | Massive, lenticular, layered | 0.2-0.4 (0.6) | Frost cracking, thermokarst, heaving | | | | | -6...-8<br>0.4-0.8 | |
| High terrace | | aI, aI-II | Massive | до 0.2 ... 0.2-0.4 | Frost cracking | | | -6...-8<br>0.5-0.8 | | | |
| Old terrace | | lpH, LH | Massive, cortical, lenticular | до 0.2 ... 0.2-0.4 | Frost cracking | | | | | | |
| Inter-alas | | LedIII, laII-III, aIII | Layered, lenticular, reticular; Pleistocene ice wedges | 0.4-0.6 (0.8*) | Thermokarst | -10...-12***<br>0.2-0.4 | -8...-10<br>0.3-0.5 | -7...-8<br>0.4-0.6 | | | |
| Alas | | lpH, LH | Layered, lenticular, reticular; Holocene ice wedges | 0.2-0.4 (0.6*) | Frost cracking, heaving | | | | | -6...-8<br>0.4-0.8 | |
| Moraine | | gIII | Massive, cortical, basal; ice wedges | 0.2-0.4 (0.6) | Thermokarst | -10...-12<br>0.2-0.4 | | | | | |
| Outwash | | fIII | Massive, lenticular, cortical | 0.2-0.4 | Thermokarst, heaving | -10...-12<br>0.2-0.4 | -8...-10<br>0.3-0.5 | -7...-8<br>0.4-0.6 | | | |

Notes: *in tundra and northern taiga landscapes; **index of vegetation units; ***in numerator – mean annual temperature of the ground, °C; in denominator–active layer thickness, m.

**Figure 2.** Fragment of legend of permafrost-landscape map of Sakha (Yakut) Republic in original form.

The inter-ridge lowland type of terrain (volumetric ice content 0.2–0.4, in places up to 0.6) occurs quite commonly throughout Yakutia, with intrazonal landscapes developed within. On the tundra, typical tundra-marsh and low centered polygons are characterized with ground temperature from −6 to −9 °C and active layer thickness from 0.4 to 0.8 m; in northern taiga larch sparse woodland these values are from −3 to −6 °C and 0.6–0.8 m, respectively; in middle taiga the bogged larch woodland is from 0 to −3.5 °C and 0.5–2 m, respectively; and in mountain areas in the larch sparse woodlands, these values are from −3 to −5 °C and 0.8–1.2 m, respectively [55].

The table-legend provides the soil temperatures and active and freezing layer thickness for each of the 145 types of combinations of natural complexes that occur in Yakutia. General regularities occur in the latitudinal-zonal landscapes of the most severe ground temperatures. The lowest active layer thickness is in Arctic tundra landscapes from −10 to −13 °C and from 0.2 to 0.4 m thicknesses, which is natural given the cold climate. In northern sparse woodland, the ground temperature of different types of terrain changes from −4 to −7 °C with active layer thickness from 0.5 to 1 m.

In middle taiga with continuous permafrost, the ground temperature varies from −0.5 to −4 °C, the active layer thickness can reach 2.5 m in larch forests, which is the most common in this type of landscape. In the pine forests, soil temperature increases up to 0 ÷ −0.5 °C and active layer thickness varies from 2 to 4 m. Since the late 2000s, permafrost landscapes have been unstable in connection with climate warming and anthropogenic influence, which can cause the negative development of cryogenic processes.

Middle taiga in discontinuous and sporadic permafrost shows positive ground temperatures up to +1.5 °C typical for seasonally frozen landscapes with pine forests with an admixture of spruce and cedar. The lowest soil temperatures of up to from −1 to −1.5 °C and active layer thickness up to 2–3 m develop in larch forests.

At intrazonal landscapes in the tundra and northern sparse woodlands, there is a slight increase in soil temperature in comparison with the upland landscapes. In the middle taiga with discontinuous and sporadic permafrost, on the contrary, there is a decrease in ground temperature.

Mountain landscapes show a clear increase in ground temperature from the mountain deserts that occupy the top of the mountain ranges to the mountain taiga in upland from −13 °C to positive values. In conditions of mountain sparse woodlands and mountain taiga, temperature inversions are typical when valley and near-bottom slopes have more cold permafrost conditions than those located higher up the slope [47]. Such areas are usually characterized by the development of boggy sparse woodlands.

The most widespread are natural complexes (Figure 2): eluvial terrain type with larch sparse woodland (6.9% of total area), diluvial-solufluction terrain type with larch sparse woodland low shrub/lichen/moss in northern taiga in continuous permafrost (5.9%), diluvial-solufluction terrain type with larch forest low shrub, and low shrub/moss in middle taiga in continuous permafrost (5.0%). Seven combination of terrain types and vegetation group occupy from 3 to 5%, 19 from 1 to 3%, and 114 occupy up to 1%. Even though many units occupy small areas, they reflect the full range of characteristics of permafrost landscapes.

## 4. Discussion

Maps represent a compilation of geographical studies and reflect the level of knowledge at the time of their compilation. Almost no map remains current forever, but they can offer starting points for the creation of future maps. The information base is constantly updated, scientific tasks are changing, techniques and methods of mapping are updated. As all this is happening constantly, all cartographic generalizations strive to reflect the actual current state of natural and social conditions.

The permafrost-landscape classifications adopted in this study create a basis for assessing the stability of permafrost landscapes with climate change and anthropogenic impacts. To do this, we reflected the ice content of sediments, soil temperature, and active (freezing) layer thickness on the map with the help of landscape classifications.

Preparation of small-scale maps involves the synthesis of various data to depict the permafrost conditions of the huge territory of Northern Eurasia [47,54,56–58]. In the past, the generalization of the results of investigations by several generations of Russian permafrost scientists were reflected in a geocryological map of the USSR on a scale of 1:2,500,000 [57]. The release of a series of small-scale maps made it possible to reveal the general patterns of permafrost differentiation, and primarily the distribution and thickness of permafrost, as well as the soil temperature.

The map of seasonal thawing of the soils of Eastern Yakutia on a scale of 1:2,500,000 [48] was the first cryogenic-landscape map in Yakutia. The principles of mapping that are included played an important role in the compilation of permafrost-landscape maps in Yakutia. Vasiliev [48] summarized a huge amount of actual data on active layer thickness by imposing engineering geological and geobotanical layers, which was an effective solution.

The permafrost-landscape map of the Yakut ASSR on a 1:2,500,000 scale involved work by many authors [26]. A total of 21 types of terrain, 26 types (subtypes) of landscapes, and 54 permafrost-landscape provinces were identified. In the explanatory note of the map [25], a catalog of landscapes and characteristics of the permafrost landscapes of Yakutia was provided. This map is already historical, and our new map introduces new methodological and classification solutions. Therefore, on a new map with a scale of 1:1,500,000, the slopes are differentiated into colluvial, diluvial-colluvial, and deluvial-solifluction. The moraine, outwash, and inter-alas areas are not divided into flat and mountainous landscapes. In the types (subtypes) of landscapes, the main plant groupings that significantly affect permafrost conditions are listed. Thus, we identified pre-tundra larch forests, pine and pine-larch forests, and bogged larch woodlands. However, the general principle of mapping a single criterion for identifying landscapes in flat and mountainous areas has not changed.

The map in question is based on the principles of construction, and thus differs from the previously compiled "Map of the natural complexes of the North of Western Siberia" [58]. However, a methodically correct decision was taken by the authors to show features of regional landscape differentiation, which allocated several sea terraces.

Of the other maps, we are most impressed by the compilation of a new permafrost spread map of the Tibet Plateau [59] using the new MODIS land surface temperature method. The discreteness of permafrost, which is important, is shown here. Mapping the distribution of vegetation cover in the permafrost zone of the Qinghai-Tibet Plateau [60] is a real example of cryogenic-landscape mapping. We were tasked with forming the basis for the study of vegetation mechanisms in the land surface processes of high-altitude areas. Thus, we conclude that we are tackling almost the same tasks. We will use all these successful methodological developments in our future cartographic projects.

The current rate of change in permafrost conditions and the transformation of permafrost landscapes require new solutions to minimize negative processes and help the population and socio-economic conditions adapt to changes. Qualitative modeling is of particular importance at the moment: more reliable basic knowledge and the availability of a variety of cartographic models are necessary here, including permafrost-landscape maps.

## 5. Conclusions

Based on the developed methodology and legend; the use of Landsat, MODIS, and a specialized database with more than 800 geocryological observation points, including separate geothermal boreholes, the Permafrost-Landscape Map of the Republic of Sakha (Yakutia), 1:1,500,000 was compiled in ArcGIS. On the completed map, 20 types of terrain and 36 plant associations are identified, with the addition of 143 units, which are characterized by relatively homogeneous permafrost-landscape conditions. A regionalization of Yakutia was completed, with the allocation of 54 units with a relatively unified combination of natural conditions at the level of permafrost-landscape provinces. This allowed us to highlight the diversity of permafrost landscapes with specific natural conditions.

Of the total area, analysis of the map showed that tundra landscapes occupy 10.3%, northern taiga 26.4%, middle taiga 27.5%, mountain deserts 1.9%, mountain tundra 9.4%, subalpine shrubs

2.6%, mountain sparse woodlands 20.3%, and mountain taiga 1.5% of the total territory of Yakutia. In general, plain permafrost landscapes occupy about 64.2% and mountainous areas about 35.4%, with 0.4% occupied by water bodies. Ice-rich permafrost landscapes—inter-alas terrain type, vulnerable to climate warming and anthropogenic influences—are spread over 10.8% of the territory of Yakutia. The identification of spatial patterns will allow a differentiated approach for the assessment of permafrost landscapes of Yakutia for the purposes of rational use and nature protection.

This study provides a new interpretation of the differentiation of permafrost for a region as large as Yakutia. The use of a combination of two factors—geocryological and landscape—in the classification of the object to be mapped will allow us to consider the regularities of the structure of the natural environment in more detail.

The compiled map showing the differentiation of modern permafrost landscapes of Yakutia can be the basis for further research on the environment protection in terms of climate and permafrost changes. The map can serve as an initial base for compiling of thematic geocryological maps necessary for solving environmental and economic problems of the Sakha (Yakutia) Republic at the present stage and in the future.

**Supplementary Materials:** Permafrost-landscape map of the Republic of Sakha (Yakutia) is available online http://mpi.ysn.ru/images/mlk20182.pdf.

**Author Contributions:** A.N.F., M.N.Z. and V.V.S. proposed the topic, conceived and designed the study. N.F.V., Y.I.T., A.A.S., S.S.K., N.I.B., V.S.M. and L.S.E. did cartographic work. A.N.F., S.P.V., M.N.Z., V.V.S., P.Y.K., I.S.U., P.V.E., R.N.A., V.V.S., A.G.S., A.I.V., R.N.I., A.A.G., V.M.L., G.P.K. and V.V.K. carried out landscape and permafrost data analysis and systematization. All authors collaborated with the corresponding author in the preparation of the manuscript.

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## References

1. Webber, P.J.; Walker, D.A. Vegetation and landscape analysis at Prudhoe Bay, Alaska: A vegetation map of the Tundra Biom study area. In *Ecological Investigations of the Tundra Biom in the Prudhoe Bay Region, Alaska*; Special Report 2; Brown, J., Ed.; Biological Papers of the University of Alaska: Fairbanks, AK, USA, 1975; pp. 80–91.
2. Barnett, D.M.; Edlund, S.A.; Dredge, L.A. *Terrain Characterization and Evaluation: An Example from Eastern Melvill Island*; Paper 76-23; Geological Survay of Canada: Ottawa, ON, Canada, 1977.
3. Everett, K.R.; Webber, P.J.; Walker, D.A.; Parkinson, R.J.; Braun, J. A geoecological mapping scheme for Alaskan coastal tundra. In Proceedings of the Third International Conference of Permafrost, Edmonton, AB, Canada, 10–13 July 1978; National Research Council of Canada: Ottawa, ON, Canada, 1978; Volume 1, pp. 359–365.
4. Melnikov, E.S.; Veisman, L.I.; Kritsuk, L.N.; Moskalenko, N.G.; Tagunova, L.N.; Todosiichuk, I.V. *Landscape Indicators of Engineering Geocryological Condition of the North of the Western Siberia and Their Interpretive Signs*; Nedra: Moscow, Russia, 1974. (In Russian)
5. Tumel, V.F. About permafrost survey. *Izv. AN USSR Ser. Geogr. Geophys.* **1945**, *9*, 135–144. (In Russian)
6. Baranov, I.Y. *Geocryological Map of the USSR at a Scale of 1:10,000,000*; Explanatory note; Obruchev Permafrost Institute: Moscow, Russia, 1960. (In Russian)
7. Kudryavtsev, V.A. Permafrost survey as the main type of permafrost research. In *Permafrost Research*; MSU: Moscow, Russia, 1961; Issue 1; pp. 3–10. (In Russian)
8. Jorgenson, M.T.; Romanovsky, V.; Harden, J.; Shur, Y.; O'Donnell, J.; Schuur, E.A.G.; Kanevskiy, M.; Marchenko, S. Resilience and vulnerability of permafrost to climate change. *Can. J. For. Res.* **2010**, *40*, 1219–1236. [CrossRef]

9. Jorgenson, M.T.; Frost, G.V.; Dissing, D. Drivers of Landscape Changes in Coastal Ecosystems on the Yukon-Kuskokwim Delta, Alaska. *Remote Sens.* **2018**, *10*, 1280. [CrossRef]
10. Kokelj, S.V.; Trevor, C.; Lantz, T.C.; Tunnicliffe, J.; Segal, R.; Lacelle, D. Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. *Geology* **2017**, *45*, 371–374. [CrossRef]
11. Wang, T.; Wu, T.; Wang, P.; Li, R.; Xie, C.; Zou, D. Spatial distribution and changes of permafrost on the Qinghai-Tibet Plateau revealed by statistical models during the period of 1980 to 2010. *Sci. Total Environ.* **2019**, *650*, 661–670. [CrossRef] [PubMed]
12. Lara, M.J.; Nitze, I.; Grosse, G.; McGuire, A.D. Tundra landform and vegetation productivity trend maps for the Arctic Coastal Plain of northern Alaska. *Sci. Data* **2018**, *5*, 180058. [CrossRef] [PubMed]
13. Frost, G.V.; Christopherson, T.; Jorgenson, M.T.; Liljedahl, A.K.; Macander, M.J.; Walker, D.A.; Wells, A.F. Regional Patterns and Asynchronous Onset of Ice-Wedge Degradation since the Mid-20th Century in Arctic Alaska. *Remote Sens.* **2018**, *10*, 1312. [CrossRef]
14. Harris, C.; Vonder, M.D.; Isaksen, K.; Haeberli, W.; Sollid, J.L.; King, L.; Holmlund, P.; Dramis, F.; Guglielmin, M.; Palacios, D. Warming permafrost in European mountains. *Glob. Planet. Chang.* **2003**, *39*, 215–225. [CrossRef]
15. Jorgenson, M.T.; Shur, Y.L.; Erik, R.; Pullman, E.R. Abrupt increase in permafrost degradation in Arctic Alaska. *Geophys. Res. Lett.* **2006**, *33*, L02503. [CrossRef]
16. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau: A review of recent research. *Earth-Sci. Rev.* **2010**, *103*, 31–44. [CrossRef]
17. Guo, D.; Wang, H. The significant climate warming in the northern Tibetan Plateau and its possible causes. *Int. J. Climatol.* **2011**, *32*, 1775–1781. [CrossRef]
18. Liljedahl, A.K.; Boike, J.; Daanen, R.P.; Fedorov, A.N.; Frost, G.V.; Grosse, G.; Hinzman, L.D.; Iijima, Y.; Jorgenson, J.C.; Matveyeva, N.; et al. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nat. Geosci.* **2016**, *9*, 312–318. [CrossRef]
19. Maximov, T.C.; Ivanov, B.I. Monitoring of the conditions of permafrost ecosystem: Spasskaya Pad, Yakutsk. *Contemp. Probl. Ecol.* **2008**, *12*, 777–781.
20. Boike, J.; Kattenstroth, B.; Abramova, K.; Bornemann, N.; Chetverova, A.; Fedorova, I.; Fröb, K.; Grigoriev, M.; Grüber, M.; Kutzbach, L.; et al. Baseline characteristics of climate, permafrost and land cover from a new permafrost observatory in the Lena River Delta, Siberia (1998–2011). *Biogeosciences* **2013**, *10*, 2105–2128. [CrossRef]
21. Bosikov, N.P.; Vasiliev, I.S.; Fedorov, A.N. *Permafrost Landscapes of Reclaimed Zone of Leno-Aldan Interfluve*; Permafrost Institute: Yakutsk, Russia, 1985. (In Russian)
22. Varlamov, S.P. Landscape typological mapping as a basis for stationary research extrapolation. In *Regional and Engineering Geocryological Studies*; Klimovsky, I.V., Kuzmin, G.P., Eds.; Permafrost Institute: Yakutsk, Russia, 1985; pp. 132–137. (In Russian)
23. Gravis, G.F.; Drozdov, D.S.; Stashenko, A.I. Possibilities of landscape indication in geotechnical surveying in the south of Central Yakutia. In *Questions of Geocryological Mapping*; Permafrost Institute: Yakutsk, Russia, 1986; pp. 85–96. (In Russian)
24. Fedorov, A.N. *Permafrost Landscapes of Yakutia. Classification and Mapping Issues*; Permafrost Institute: Yakutsk, Russia, 1991. (In Russian)
25. Fedorov, A.N.; Botulu, T.A.; Varlamov, S.P.; Vasiliev, I.S.; Gribanova, S.P.; Dorofeev, I.V.; Klimovsky, I.V.; Samsonova, V.V.; Soloviev, P.A. *Permafrost Landscapes in Yakutia. Explanation Note to the Permafrost-Landscape Map of the Yakut ASSR at a 1:2,500,000 Scale*; GUGK: Novosibirsk, Russia, 1989. (In Russian)
26. Fedorov, A.N.; Botulu, T.A.; Vasiliev, I.S.; Varlamov, S.P.; Gribanova, S.P.; Dorofeev, I.V. *Permafrost-Landscape Map of the Yakut ASSR, Scale 1:2,500,000, 2 Sheets*; Melnikov, P.I., Ed.; Gosgeodezia: Moscow, Russia, 1991. (In Russian)
27. Torgovkin, Y.I. Landscape Indication and Mapping Permafrost Conditions of the Lena River Basin. Ph.D. Thesis, Permafrost Institute, Yakutsk, Russia, 2005. (In Russian)
28. Fedorov, A.N.; Torgovkin, Y.I. Variety of permafrost landscapes of the Lena river basin. In *Scientific Readings Devoted to the 100th Anniversary of the Birth of Academician Viktor Borisovich Sochava: Materials of the International Conference (Irkutsk, June 20–21, 2005)*; Publishing House of the Institute of Geography of the Siberian Branch of the Russian Academy of Sciences: Irkutsk, Russia, 2005; pp. 39–42.

29. Fedorov, A.N.; Gorokhov, A.N.; Makarov, V.S.; Vasilyev, N.F. Landscape mapping of the Central Aldan gold-bearing region using GIS technologies. *Probl. Reg. Ecol.* **2008**, *2*, 128–131. (In Russian)
30. Shestakova, A.A. Mapping of the Permafrost Landscapes Taking into Account Vegetation Succession (for Example of the Prilensky Plateau). Ph.D. Thesis, Permafrost Institute, Yakutsk, Russia, 2011. (In Russian)
31. Romanovsky, V.E.; Sazonova, T.S.; Balobaev, V.T.; Shender, N.I.; Sergueev, D.O. Past and recent changes in air and permafrost temperatures in eastern Siberia. *Glob. Planet. Chang.* **2007**, *56*, 399–413. [CrossRef]
32. Beer, C.; Fedorov, A.N.; Torgovkin, Y.I. Permafrost temperature and active-layer thickness of Yakutia with 0.5-degree spatial resolution for model evaluation. *Earth Syst. Sci. Data* **2013**, *5*, 305–310. [CrossRef]
33. Beer, C.; Porada, P.; Ekici, A.; Brakebusch, M. Effects of short-term variability of meteorological variables on soil temperature in permafrost regions. *Cryosphere* **2018**, *12*, 741–757. [CrossRef]
34. Arkhipov, Y.V.; Grebennikov, G.A.; Kolpakov, V.V.; Mikhailov, M.V.; Mishnin, V.M.; Spektor, V.B.; Frumkin, I.M.; Chertovskikh, G.N.; Sheikanova, V.T. *Geological Map of the Yakut ASSR. Scale 1:1,500,000*; Krasny, L.I., Ed.; GUGK: Moscow, Russia, 1979. (In Russian)
35. Elovskaya, L.G.; Petrova, E.I.; Teterina, L.V.; Naumov, E.M. Soil map. In *Agricultiral Atlas of Yakut ASSR*; GUGK: Moscow, Russia, 1989; pp. 30–31. (In Russian)
36. Andreev, V.N.; Galaktionova, T.F.; Karpel, B.A.; Perfilieva, V.I.; Chugunova, R.V.; Shurduk, I.F. Vegetation map. In *Agricultiral Atlas of Yakut ASSR*; GUGK: Moscow, Russia, 1989; pp. 42–43. (In Russian)
37. Zastrozhnov, A.S.; Minina, E.A.; Shkatova, V.K.; Tarnogradsky, V.D.; Krutkina, O.N.; Ryzhkova, V.N.; Astakhov, V.I.; Gusev, E.A. *Map of Quaternary Formations of the Russian Federation. Scale 1:2,500,000*; Petrov, O.V., Ed.; VSEGEI: Moscow, Russia, 2014. (In Russian)
38. Abolin, R.I. *Geobotanical and Soil Description Leno-Vilyui Plains*; Academy of Science: Leningrad, Russia, 1929. (In Russian)
39. Soloviev, P.A. *The Cryolithozone of Northern Part of the Lena-Amga Interfluve*; Academy of Sciences: Moscow, Russia, 1959.
40. Soloviev, P.A. Map of engineering-geological zoning of the Yakut ASSR. Scale 1:5,000,000. In *Hydrogeology of USSR*; Nedra: Moscow, Russia, 1970; Volume 20.
41. Zolnikov, V.G. Topography and soil forming deposits in the eastern part of Central Yakutia. In *Materials on Environmental Conditions and Agriculture in Central Yakutia*; Academy of Science USSR: Moscow, Russia, 1954. (In Russian)
42. Rusanov, B.S.; Borodenkova, Z.F.; Goncharov, V.F.; Grinenko, O.V.; Lazarev, P.A. *Geomorphology of Eastern Yakutia*; Book Publishing House: Yakutsk, Russia, 1967. (In Russian)
43. Lugovoi, P.N. *Features of the Mountain Permafrost Regions Condition*; Nauka: Moscow, Russia, 1970. (In Russian)
44. Petrova, E.I. *Soils of Southern Yakutia*; Book Publishing House: Yakutsk, Russia, 1971. (In Russian)
45. Fotiev, S.M.; Danilova, N.S.; Sheveleva, N.S. *Geocryological Conditions of the Middle Siberia*; Nauka: Moscow, Russia, 1974. (In Russian)
46. Trush, N.I.; Chizhov, A.B.; Chizhova, N.I.; Vsevozhskaya, M.A.; Pavlova, A.P.; Khrutsky, S.F.; Piotrovsky, M.V.; Kondratieva, K.A.; Melentiev, V.S.; Gavrilov, A.V.; et al. *South Yakutia*; Kudryavtsev, V.A., Ed.; Moscow State University: Moscow, Russia, 1975. (In Russian)
47. Nekrasov, I.A. *Permafrost of the North-East and the South of Siberia and the Regularities of Its Development*; Book Publishing House: Yakutsk, Russia, 1976. (In Russian)
48. Vasiliev, I.S. *The Regularities Seasonal Thawing in Eastern*; Nauka: Novosibirsk, Russia, 1982. (In Russian)
49. Vasiliev, I.S. *Spatio-Temporal Patterns of Formation of the Active Layer in Landscapes of Western Yakutia*; Nauka: Novosibirsk, Russia, 2005. (In Russian)
50. Ivanov, M.S. *The Cryogenic Structure of Quarternary Deposits of the Leno-Aldan Depression*; Nauka: Novosibirsk, Russia, 1984. (In Russian)
51. Zheleznyak, M.N. *Geotemperature Field and Cryolithozone of the Southeast of the Siberian Platform*; Nauka: Novosibirsk, Russia, 2005. (In Russian)
52. Shats, M.M.; Dorofeev, I.V.; Fedorov, A.N. Experience the landscape and permafrost mapping Southern Yakutia. In *Natural Conditions Reclaimed Regions of Siberia*; Permafrost Institute: Yakutsk, Russia, 1987; pp. 49–55.

53. Bartalev, S.A.; Egorov, V.A.; Isaev, A.S.; Lupyan, E.A.; Uvarov, I.A. *Vegetation Map of Russia. Scale 1:5,000,000*; Space Research Institute of the Russian Academy of Sciences and the Center for Problems of Ecology and Forest Productivity of the Russian Academy of Sciences: Moscow, Russia, 2014.
54. Soloviev, P.A. *Zonality of the Distribution and Regional Features of the Permafrost/Map-Inset to the Permafrost-Landscape Map of the Yakut ASSR, Scale 1:2,500,000*; Gosgeodezia: Moscow, Russia, 1991.
55. Milkov, F.N. *Landscape Geography and Practice Questions*; Mysl: Moscow, Russia, 1966. (In Russian)
56. Kondratieva, K.A.; Afanasenko, V.E.; Gavrilov, A.V.; Dunaeva, E.N.; Zamolotchikova, S.A.; Trush, N.I.; Khrutsky, S.F. *Geocryological Map of the USSR. Scale 1:2,500,000*; Ershov, E.D., Ed.; Moscow State University: Vinnitca, Ukraine, 1996. (In Russian)
57. Melnikov, E.S.; Moskalenko, N.G.; Voitsekhovskaya, I.V.; Kritsuk, L.N.; Chekrygina, S.N. *Map of the natural complexes of the North of Western Siberia*; Gosgeodezia USSR: Moscow, Russia, 1991.
58. Zou, D.; Zhao, L.; Sheng, Y.; Chen, J.; Wu, T.; Wu, J.; Xie, C.; Wu, X.; Pang, Q.; Wang, W.; et al. A new map of permafrost distribution on the Tibetan Plateau. *Cryosphere* **2017**, *11*, 2527–2542. [CrossRef]
59. Wang, Z.; Wang, Q.; Zhao, L.; Wu, X.; Yue, G.; Zou, D.; Nan, Z.; Liu, G.; Pang, Q.; Fang, H.; et al. Mapping the vegetation distribution of the permafrost zone on the Qinghai-Tibet Plateau. *J. Mt. Sci.* **2016**, *13*, 1035–1046. [CrossRef]
60. Fedorov, A.N.; Torgovkin, Y.I.; Shestakova, A.A.; Vasilyev, N.F.; Makarov, V.S.; Kalinicheva, S.V.; Basharin, N.I.; Egorova, L.S.; Konstantinov, P.Y.; Samsonova, V.V.; et al. Permafrost-Landscape Map of the Republic of Sakha (Yakutia). 2018. Available online: http://mpi.ysn.ru/images/mlk20182.pdf (accessed on 31 October 2018).