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Review

Permafrost Landscape Research in the Northeast of Eurasia

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Abstract: The results of permafrost landscape studies on northeastern Eurasia are presented in this review. The assessment of permafrost vulnerability to disturbances and global warming was the basis for the development of these studies. The permafrost landscape, considering the morphological features of the landscape and the permafrost together, is a timely object of study. The theoretical developments of Soviet physical geographers and landscape scientists are the basis for permafrost landscape studies. Over the past four decades, numerous permafrost landscape studies have been carried out on northeastern Eurasia (and Russia). Considering the results of these studies is the main objective of this article. The analysis of the problems of permafrost landscape identification, classification, and mapping and the study of their dynamics and evolution after disturbances and long-term development were carried out. Permafrost landscape studies employ the research methods of landscape science and geocryology. Environmental protection and adaptation of socioeconomic conditions to modern climate warming will determine the prospects for studying permafrost landscapes.

Keywords: permafrost landscape; classification; mapping; succession; evolution; northeast Eurasia; Yakutia

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1. Introduction

The landscapes of the North are unique natural formations, easily vulnerable, and slowly restored after disturbance or impact. The cold climate, permafrost, and low biological productivity determine the uniqueness of these landscapes. Tumel [1], Baranov [2], Kudryavtsev [3], and others considered the landscape method to be one of the main methods of geocryological mapping. They relied on the characteristics of the landscape and permafrost, which indicated the permafrost conditions.

Studying the relationship between permafrost and landscapes is associated with protecting the northern environment. The stability of northern landscapes depends on permafrost conditions [4–6]. The ice content and temperature of permafrost, the active layer depth, and cryogenic processes strongly influence the functioning of landscapes.

The study of integral natural systems characterized by a single state of external and internal properties determines the theory of the permafrost landscape. Functional links between the components determine the use of exterior morphological features of landscapes (mainly combinations of relief and vegetation) as indicators of permafrost conditions. The indication method is the main method used in engineering geocryology and geocryological mapping. The indicator properties of the external appearance of the landscape have been well considered in the works of Tyrtikov [7–9], Melnikov et al. [10–12], Konstantinova [13], and others.

Landscape indicators are used to study the relationship between relief and permafrost [14–18]. Inter-component relationships between vegetation and permafrost, as well as the temporal variability of permafrost properties, depending on vegetation dynamics, were considered in the works of Tyrtikov [7–9], Lazukova [19], Moskalenko [20–22], and others.

The theoretical basis of permafrost landscape studies originated in the developments of Soviet physical geographers and landscape scientists [23–27]. Traditional classifications, mapping techniques, and applied interpretations in landscape studies have not previously used permafrost criteria. Therefore, researchers of permafrost landscapes have used them, eventually adapting them to the conditions of permafrost based on the goals and objectives of the research.

For the first time, the taxonomy and classification of permafrost landscapes were compiled by Melnikov [12,28] (pp. 36-57 in ref. [12]). The landscape classification hierarchies and principles of systematization that were established made it possible to successfully carry out a range of studies in the northern area of Western Siberia [12,29,30].

In recent years, a significant contribution to the development of permafrost landscape studies and to the study of the dynamics of permafrost conditions has been made by Drozdov et al. [31], Varlamov et al. [32], Osadchaya [33], Tumel and Zotova [34], and others. This was the beginning of environmental studies in the permafrost zone [35–38].

Permafrost landscape studies are in continuous development. The use of new methods makes it possible to obtain new data on the distribution and evolution of permafrost [39–42]. The accumulated experience in studying permafrost landscapes has made it possible to consider the problematic issues of their classification and functional mapping for assessing their resistance to anthropogenic impacts.

The permafrost landscape is a relatively homogeneous natural formation that functions under the influence of cryogenesis, with certain combinations of permafrost characteristics found only in this landscape [43]. Permafrost landscapes are an integral part of the landscape sphere of Earth, where the upper part of the lithosphere is permafrost. The main factors determining the differentiation and development of permafrost landscapes are climatogenic, lithogenic, biogenic, and anthropogenic factors. The term permafrost landscape is close in meaning to periglacial landscape [5,44]. However, periglacial landscapes may be non-permafrost. Therefore, we use the term permafrost landscape. Permafrost landscape identification resembles the classification of permafrost—syngenetic and epigenetic permafrost [45].

Comprehensive landscape studies, which are the basis for monitoring, modeling, and forecasting [46], are necessary to improve the effectiveness of environmental protection measures in the field of permafrost distribution. At the same time, the permafrost landscape acts as an integral indicator of the state of the environment. This is recognized as the main objective in developing the concept of rational nature management in the permafrost zone.

The purpose of the article is to summarize the methodologies and results of permafrost and landscape studies carried out in northeastern Eurasia in order to understand the features of the natural environment and their dynamics under the influence of anthropogenic disturbances and the modern impacts of climate change.

2. Materials and Methods

Scientific material on the permafrost and permafrost landscapes of northeastern Eurasia has been included in the literature and materials of the Melnikov Permafrost Institute SB RAS since the 1940s. These materials have considered different scale permafrost maps, the study of the dynamics of permafrost landforms and temperature regimes, the relationship between permafrost and taliks, permafrost monitoring, heat balance studies of permafrost ecosystems, etc. New scientific materials on the composition and properties of permafrost have appeared, carried out in engineering–geological surveys and monitoring observations of the permafrost dynamics.

Until the 1980s, geomorphological zoning was used in geocryological surveys to indicate permafrost conditions [14,47]. Mapping of the permafrost in mountainous areas was carried out by considering high-altitude landscape zones [17]. These works used aerial photo interpretation, which became available in the mid-1940s in connection with continuous topographic mapping of the northeastern USSR.

Landscape studies appeared widely in the 1980s, and they focused on studying the spatial diversity of permafrost landscapes and their mapping [48–50]. The permafrost characteristic combinations—ice content and ground temperature, active layer thickness, and cryogenic processes—were mapped using landscapes.

The cryoindication method is the primary method for identifying permafrost landscapes. The study of permafrost landscapes utilizes field surveys and descriptions and aerial and satellite image interpretation. The taxonomy and classification of permafrost landscapes in Yakutia have been compiled, considering permafrost criteria [43]. Ground temperature and active layer thickness are used as additional selection criteria in detailed permafrost landscape studies. In medium-scale studies, cryogenic structure and ice content are used as selection criteria. In small-scale studies, along with latitudinal-zonal and altitudinal-zonal soil–plant communities, climatic parameters are used, including freezing and thawing indices. In recent years, the cryoindication of permafrost conditions has employed modern methods to interpret satellite images—NDVI, LST, InSAR, and others.

Monitoring observations of the dynamics of permafrost landscapes in northeastern Eurasia are carried out almost everywhere, but they all have different goals and objectives. The most complex studies are carried out at stations with meteorological, heat balance, and permafrost observations (Samoilovsky Island, Tiksi PGO, Spasskaya Pad, Neleger, etc.). Many monitoring sites prefer studying individual permafrost characteristics or processes; these include observation sites under the GTN-P and CALM programs, which are part of global permafrost observation networks. There are also many observation networks for changes in ground temperature, active layer thickness, surface subsidence due to the melting of underground ice, etc.

The results of permafrost landscape studies are now used in GIS modeling [39–41]. The differentiation of the ground temperature and the active layer thickness in permafrost landscapes, and the spatial distribution of these important permafrost characteristics were modeled using the permafrost landscape map of the Yakut ASSR [51]. GIS and permafrost landscape maps have provided the impetus for thematic mapping, and it is possible to compile special geocryological maps. The interpretation of old aerial photographs and a retrospective analysis of permafrost landscapes in comparison with modern maps based on high-resolution satellite images have made it possible to determine the tendencies in the development of permafrost landscapes [52]. Remote sensing methods have made it possible to map the dynamic state of permafrost landscapes by the age of recovery successions after wildfires [53]. The methodology for mapping permafrost landscapes is also being updated using new remote sensing methods [54].

Existing modeling experience indicates that cartographic interpretations can be very useful to researchers for the operational assessment of the permafrost situation, primarily for specialists working in the permafrost zone. GIS modeling is primarily associated with assessing the vulnerability of permafrost landscapes to anthropogenic impacts and global warming. Identification of the main factors of vulnerability of permafrost landscapes—ice content and ground temperature, the active layer thickness—has made it possible to determine the most sensitive permafrost landscapes [55].

3. Permafrost Landscapes as an Object of Study

About a quarter of the land surface area is occupied by permafrost landscapes. In Russia, they occupy about 65% of the territory. These landscapes mainly occupy high-latitude and high-altitude locations, are distinguished by harsh natural conditions, and are characterized by the development of specific cryogenic processes and phenomena.

Permafrost landscapes have been the subjects of environmental–geocryological studies focused on studying territories' vulnerability to technogenic impacts [6,34,49,56–59]. The development of landscapes often leads to an ecological imbalance once the disturbance becomes one of our time's pressing problems.

The study of the main relationships between the components of the natural environment is carried out by creating multifactorial models of the environment or integral systems in the form of a landscape. The landscape is a set of interrelated objects and natural phenomena representing historically established, continuously developing geographical complexes [60]. In other words, this is a spatially limited set of components united by a relatively close interaction [26]. Any landscape definition implies a unified system of morphological (external) and internal (lithogenic) factors.

In permafrost conditions, the development of landscapes and their transformation or restoration after disturbance largely depends on the properties of the permafrost—temperature regime, cryogenic structure, ice content, and active layer thickness. The leading nature of the cryogenic factor in northern landscapes is determined by the specifics of the environment of the northern regions, primarily the presence of ice in the lithogenic base and phase transitions during freezing and thawing.

This understanding of the landscape corresponds to modern ideas about geocryological systems, which are understood as a special type of geosystem in which energy and mass transfer lead to the formation and existence of a specific mineral–ice [61]. Defining the role of the cryogenic factor in the functioning and differentiation of the landscapes of the north requires a certain revision of taxonomy, classification, and mapping methods. In this regard, permafrost distribution and temperature, cryogenic structure, ice content, and active layer thickness have been proposed as criteria for the classification and mapping of permafrost landscapes [43]. Close to this definition are the cryogenic geosystems of Melnikov et al. [62].

Gavrilova [63] determined which climatic parameters—the mean annual air temperature, the average temperature of the coldest month, and the freezing and thawing indices—are characteristic of landscapes of continuous, discontinuous, and sporadic distribution of permafrost zones. She also indicated the regional features: what climatic parameters are typical for northern Eurasia, Canada, Alaska, and Fennoscandia, as well as for the regions of Russia, such as the European territory, western and eastern Siberia, the mountainous regions of Siberia, and the Far East.

Popov [64,65] proposed an independent type of lithogenesis–cryolithogenesis, and Katasonov [66] proposed cryolithogenic formations as the basis for identifying permafrost landscapes by their cryogenic structure and ground ice content (for example, yedoma, alas, foothill–glacial, etc.). Furthermore, the following criteria can serve as lithological-facies complexes: homogeneous lithological complexes in sediment composition [67].

Vegetation cover significantly influences the temperature distribution of the permafrost and active layer thickness. The role of biogenic factors is essential in the functioning and development of permafrost landscapes. At the present stage of environmental development, human influence greatly affects the functioning of landscapes. Technogenic disturbances cause the activation of cryogenic processes, leading to restructuring of permafrost landscapes. Permafrost conditions change significantly in technogenic systems, such as industrial complexes, reclamation systems, agricultural lands, etc. These complexes belong to anthropogenic (technogenic) landscapes [68,69].

The relationship between landscape morphological features and permafrost characteristics is powerful, and this is especially true for the environmental problems of permafrost. Therefore, the permafrost landscape, which is a complex territorial interweaving of environmental components, ensures the equilibrium state of the natural environment in the permafrost zone or tends to do so after a disturbance.

The permafrost landscape should be characterized by the properties of permafrost. A distinctive feature of permafrost landscapes is that complexes with different permafrost characteristics, such as differences in the development of ice wedges or contrasting ground temperatures (-4 or -1 °C), represent other classification units [43].

Permafrost is the main system-forming factor. Changes in ground temperature and active layer thickness, ice content, and cryogenic processes determine the state of the permafrost landscape, which can lead to a loss of stability.

4. Permafrost Landscape Mapping

Normal mapping of permafrost landscapes in northeastern Eurasia began in the 1980s. However, this was preceded by pre-landscape mapping based on physical–geographical generalizations; these were geomorphological maps. A classic example of permafrost studies based on geomorphological units is Soloviev's work on the permafrost zone in Central Yakutia [14], which is still in great demand. Ivanov [18] used geomorphological zoning to assess the distribution of ground ice and the sensitivity of the surface to anthropogenic impacts.

The ground temperature and permafrost thickness were analyzed by Nekrasov [17] using landscape zonality in northeastern and southern Siberia. The schematic maps of Nekrasov well reflect the patterns of permafrost distribution in various mountainous areas of this immense territory.

Grave [57] drew up a scheme for zoning the territory of Yakutia according to the degree of sensitivity of the surface to technogenic impacts. The accumulative plains of the Novosibirsk Islands and the Primorskaya lowland, with the development of thick ground ice up to 50–80 m, occupied by tundra and forest–tundra, were classified as highly vulnerable areas. Plains, foothill and intermountain depressions, plateaus with the development of thick underground ice up to 40 m with tundra and northern and middle taiga were classified as moderately sensitive areas. Slightly sensitive areas are developed in mountains and high plateaus with low ice deposits. The monograph "Surface Disturbance and Its Protection during the Development of the North" [6] became the basis for environmental work in northeastern Eurasia. The relevance of this work has increased in recent decades because of the activation of cryogenic processes in the conditions of modern climate warming.

There are works on this topic by geomorphologists [70–73], geocryologists [74–79], soil scientists [80–85], and botanists [86–93]. The physical–geographic zoning studies of Mikhailov [94], Parmuzin [95,96], Mikheev and Pavlov [97], and others created the basis for modern schemes of permafrost landscape zoning of northeastern Eurasia.

Vasiliev's monograph, "Regularities of seasonal thawing of soils in Eastern Yakutia" [48], is practically a permafrost landscape work, although landscape classifications were not used. Like previous works, this study of one of the permafrost's main characteristics—the active layer's depth spatial distribution—was carried out based on the physical–geographic systematics of relief, soils, and vegetation. Compiled by Vasiliev, the "Map of thawing soils of Eastern Yakutia" at a scale of 1:2,500,000 [48], presented as an inset map to the monograph, is of value for studying permafrost landscapes. The primary method was the imposition of two layers: geological–genetic complexes with a specific lithological composition of 23 units and plant groups of 20 units. The map perfectly reflects both the latitude-zonal and altitudinal-zonal differentiation of vegetation and the active layer thickness. This work is considered the first permafrost landscape work on northeastern Eurasia.

Further permafrost landscape studies were carried out regularly. The monograph "Permafrost landscapes of the development zone of the Lena-Aldan interfluve" [49] became one of the first significant works on permafrost landscape studies. The monograph was devoted to frozen landscapes and was written based on two years of field research materials along the Tommot-Nizhny Bestyakh railway development zone (Yakutsk). The studies were carried out at the level of terrain types (subtypes), with their identification based on stratigraphic–genetic complexes (alluvium Q_4, alluvium $Q_{2–3}$, lacustrine-alluvial $Q_{2–3}$, eluvial Q_4, etc.), each with a peculiar complex of ground and vegetation. Ten physical–geographical regions were distinguished by a relatively homogeneous terrain type (subtype) combination. Each type (subtype) of terrain in the region was assessed by sensitivity to the activation of cryogenic processes after disturbances. Attached to the monograph was an inset map, "Landscape-cryoindication map of the development zone of the Lena-Aldan interfluve" from Tommot to Yakutsk, with the allocation of types (subtypes) of terrain and regions with a table of permafrost landscape characteristics.

In the late 1980s and early 1990s, the Melnikov Permafrost Institute compiled a permafrost and landscape map of the Yakut ASSR at a scale of 1:2,500,000 [50], with an extensive explanatory note [51]. The map reflected 22 terrain types in terms of geological and geomorphological features and 26 types (subtypes) of landscapes in terms of bioclimatic features. The types of terrain—inter-alas, alas, moraine, outwash, low terrace, glacier-water-valley, upland, slope, etc.—differed in stratigraphic–genetic complexes, cryogenic structures, and volumetric ice content of surface deposits. The types (subtypes) of landscapes were characterized by relatively similar climate characteristics: freezing and thawing indices, types of vegetation, and their productivity. Ground temperatures and active layer thickness were systematized by overlaying the terrain types and landscape types (subtypes). Thus, each landscape classification unit was characterized by specific combinations of permafrost parameters. Such a classification showed a close combination of landscape and permafrost conditions necessary for environmental assessments.

Based on combinations of terrain types and landscape types (subtypes) and geological and geomorphological structures, the permafrost landscape zoning of the Yakut ASSR territory was compiled. A total of 54 permafrost landscape provinces were identified, with relatively homogeneous combinations of terrain types and types (subtypes) of landscapes in three physiographic regions: central Siberia, northeastern Siberia, and the mountains of southern Siberia. In addition to methodological descriptions of the mapping, the explanatory table contained a landscape cadaster comprising a combination of geological, geomorphological, soil, and plant characteristics in types of terrain in each of the 54 permafrost landscape provinces. Thus, the map and the explanatory note have become reference material for those interested in the permafrost and landscape conditions of Yakutia.

In addition, many permafrost landscape maps of various scales were compiled for various developed territories of Yakutia. Map scales varied from detailed (1:5000–1:25,000) to medium scale (1:100,000–1:300,000) to small scale (1:500,000–1:2,500,000). Large-scale maps reflected permafrost landscape conditions at the taxonomic level of a facies [98–100], medium-scale maps reflected at the level of terrain types (subtypes) [101–103], and small-scale maps overlaying terrain and landscape types [104].

In 2018, the Melnikov Permafrost Institute team updated the permafrost landscape map [50] to receive new permafrost data based on satellite images and a change in the mapping technology: the transition to GIS technologies (Figure 1). The new permafrost landscape map of the Republic of Sakha (Yakutia) at a scale of 1:1,500,000 [105] showed partially change classification, both in types of terrain and in types (subtypes) of landscapes such as groups of vegetation. The authors identified 20 terrain types. The main difference was that the types of terrain were not distinguished into plain and mountainous when the stratigraphic–genetic complexes of surface deposits were the same. Instead of the types (subtypes) of landscapes, the authors used plant groups to better show the contrast between ground temperature and the active layer thickness. The total number of vegetation groups was 36. The map legend shows 145 permafrost landscapes—combinations of terrain types and plant groups—compared with 87 permafrost landscapes on the 1991 map.

Using GIS technologies, Shestakova et al. [55] modeled individual maps of ground temperature, active layer thickness, ice content of surface deposits (Figure 2), and cryogenic processes using the permafrost landscape map [51]. Previously, permafrost temperature interpretations had also been modeled based on the permafrost landscape map of the Yakut ASSR at a scale of 1:2,500,000 [39–41]. Along with permafrost landscape maps, permafrost maps were compiled, which are necessary to determine the degree of vulnerability of permafrost landscapes. These works include the assessment and sensitivity of carbon accumulations in the permafrost of northeastern Yakutia [106], the assessment of the stability and degradation of permafrost in eastern Chukotka [107,108], and maps of yedoma in northeastern Eurasia and North America [109].

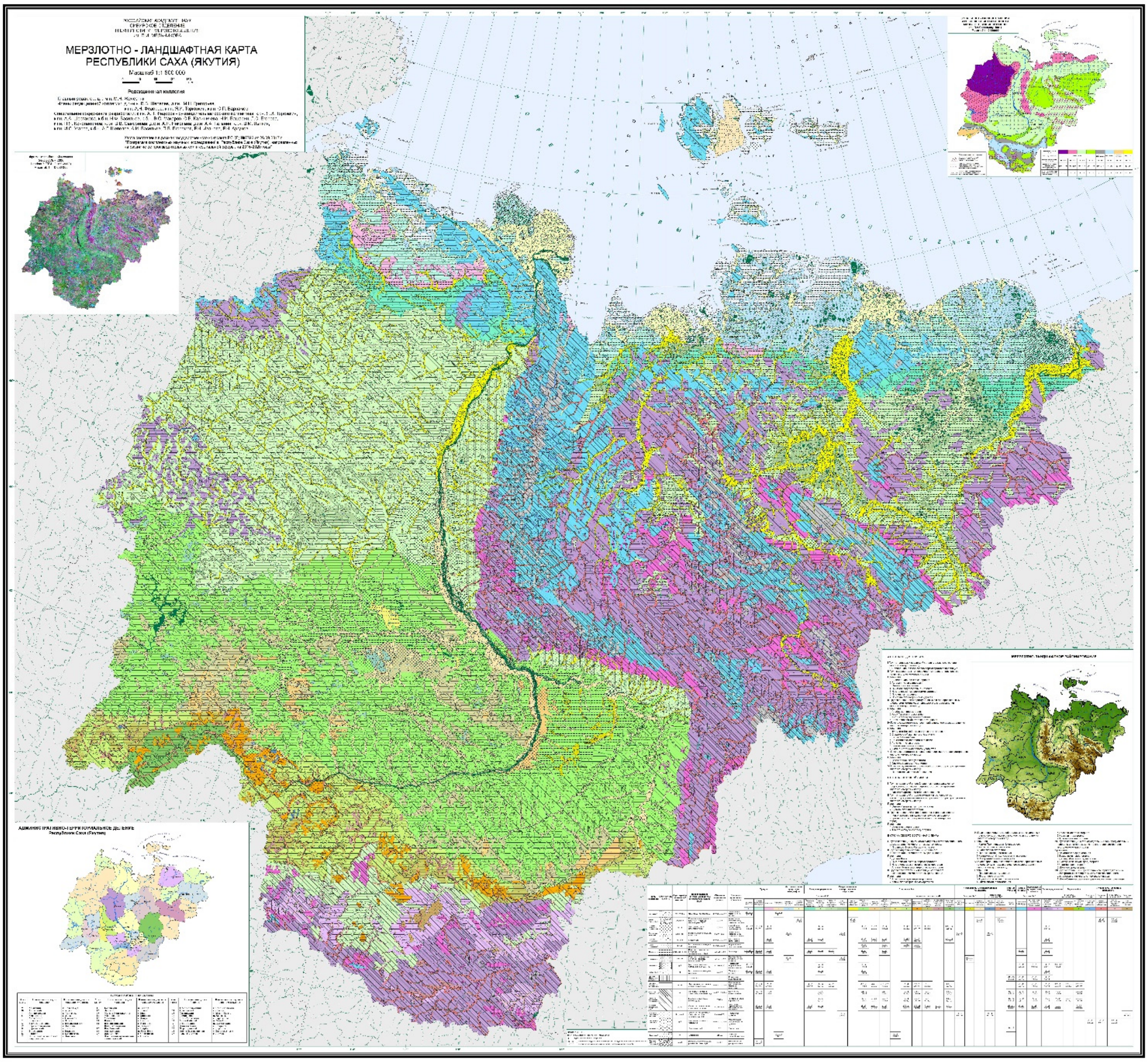

Figure 1. Permafrost landscape map of the Republic of Sakha (Yakutia) on a scale of 1:1,500,000 [105].

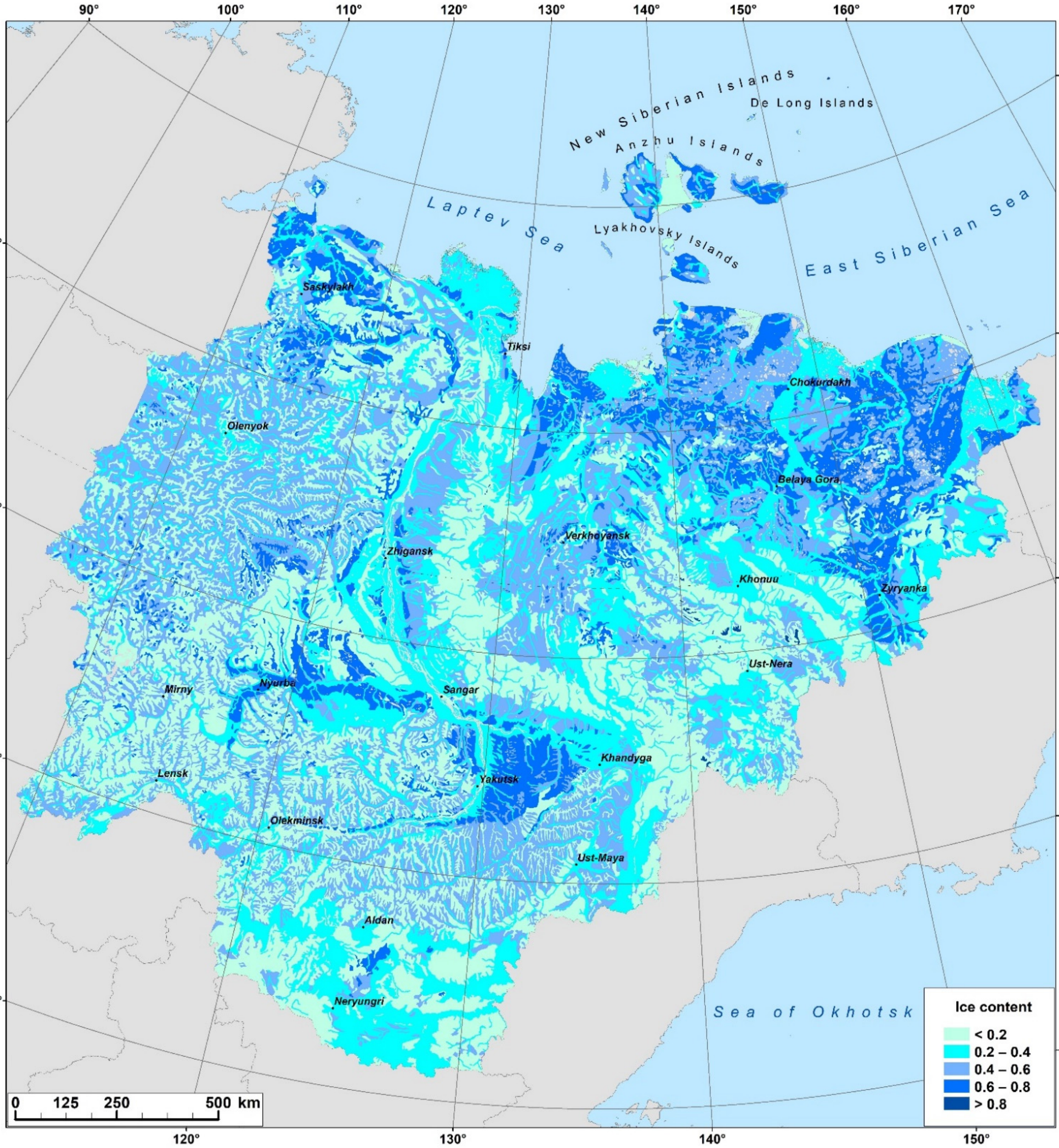

Figure 2. Ice content of surface deposits map [55] based on the permafrost landscape map of the Republic of Sakha (Yakutia) on a scale of 1:1,500,000 [51].

5. Study of the Dynamics and Evolution of Permafrost Landscapes

The study of the dynamics and evolution of permafrost landscapes in northeastern Eurasia has been widely developed. A characteristic study of the dynamics of permafrost landscapes is that of the stages of development of thermokarst landforms. The applicability of the Yakut names in classifying the stages of thermokarst development was first noticed by Efimov and Grave [110]. They noted that the initial thermokarst subsidence in its further development turns into "eie", subsided depressions, where the grooves between the hillocks are filled with water. The next stage in thermokarst development is the "duede"—a rounded lake with low but steep banks and high-centered polygons in the bottom. Over time, the "duede" turns into a water-filled lake with a flat bottom and steep banks. The subsided lake eventually turns into an alas.

Later, Soloviev [14] supplemented and improved this classification of thermokarst landforms (Figure 3). He singled out the following stages:

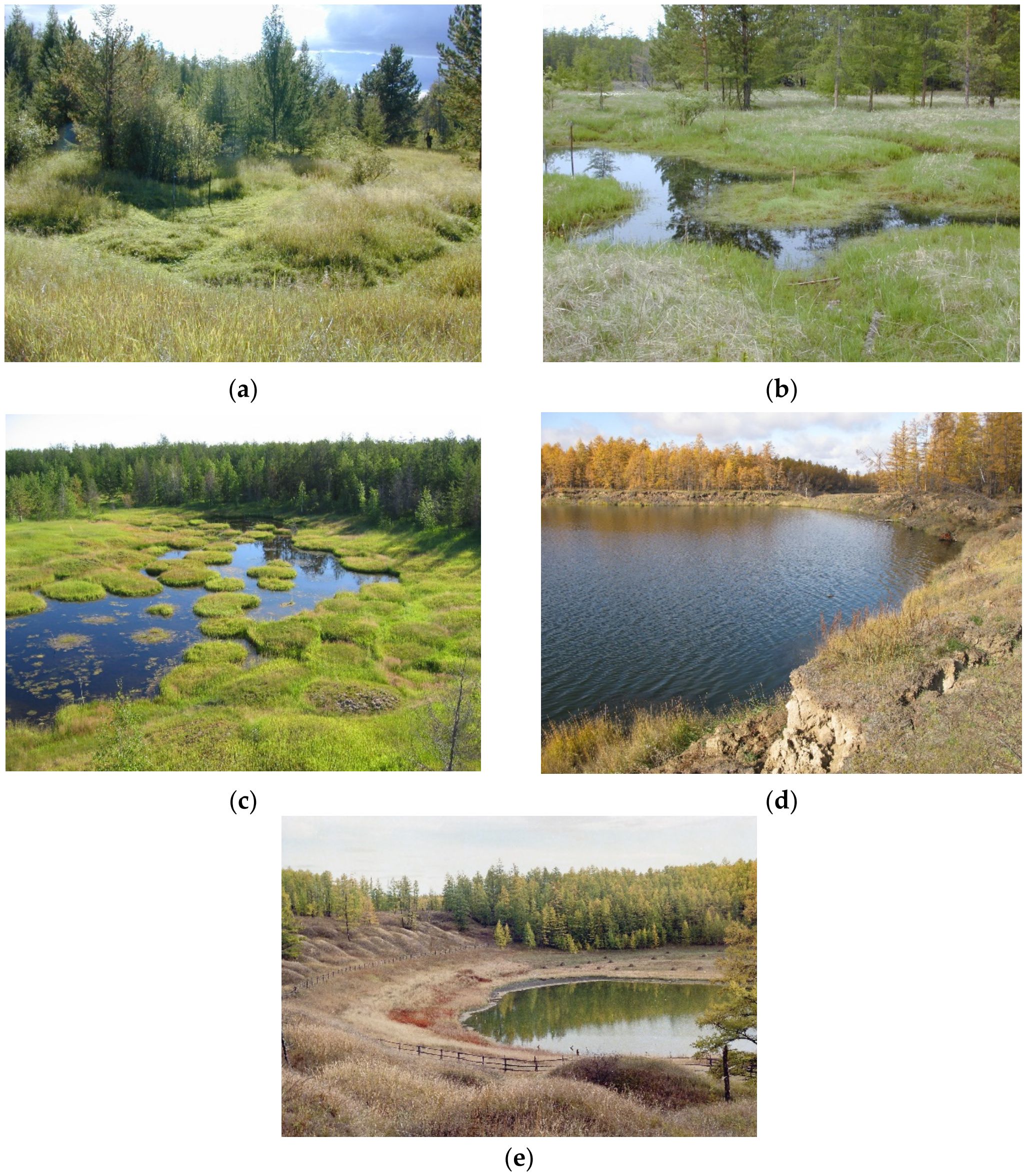

Figure 3. Stages of thermokarst landforms (Central Yakutia). (**a**)—bylar, (**b**)—eie, (**c**)—duede, (**d**)—tympy, (**e**)—alas.

(1) The initial bylar—slightly lowered areas deformed by separate subsidence holes and troughs.
(2) Bylar—lowered areas where the troughs connected, forming a high-centered polygon depression.
(3) Eie is a high-centered polygon depression. In the eie, the troughs between the hillocks are filled with water [110].
(4) Duede is a depression with pronounced banks, with high-centered polygons at the bottom and banks. Efimov and Grave [110] noted that it is filled with water.
(5) Tympy is the first stage of alas. The underground ice at the bottom of the basin melted. The floor of the depression is leveled by alas sediments. The depression is sharply expressed. Usually, tympy is a completely subsided depression with a full lake [110].

(6) Alas is a depression with a relatively flat, leveled floor and steep, sharply defined banks. Evaporation of water forms alas from the tympy [110].

We placed the classification of thermokarst landscapes before the formation of alas. At the same time, Soloviev [14] identified the further development of the alas relief from elementary alas to complex alas, mature alas with bulgunnyakh (pingo), marginal alas, khonu, and a relict post-alas basin. To this classification, one can add "bajdzherakhs"—thermokarst-erosion landforms on the slopes of alas (river valleys and seacoasts) formed when ice wedges thaw. Thanks to the classifications of Efimov and Grave [110] and Soloviev [14], we have a coherent dynamic classification of the thermokarst landscape. In the English language scientific literature, this classification was first described by Czudek and Demek [111] with reference to Soloviev [112].

Permafrost landscape conditions are used in paleogeographic studies. Here, we can trace the evolution of landscapes over a long period of development, as some landscape and climatic conditions have been replaced by others [113–117]. During periods of warming in northeastern Eurasia, larch woodlands with an admixture of spruce developed in the modern tundra zone. In the contemporary larch middle taiga, larch forests combined with spruce and pine forests grew. During periods of cooling in central Yakutia, the areas of yerniks increased, and in Allered (until 11,500 years ago), tundra-steppes dominated.

Based on the work of palaeogeographers, we assessed permafrost conditions during periods of Holocene warming [118]. The optimum ground temperature in the Holocene in the tundra areas was 5–6.5 °C warmer than at present (before the current warming, or before 1980), in the northern taiga by 2.5–4 °C, and in the middle taiga by 1.5–2.5 °C. In assessing the evolution of permafrost conditions in eastern Siberia in the Pleistocene–Holocene, one can be guided by the work of Fotiev [119], which is based on the interpretation of the Baikal chronicle of diatom deposits [120].

Permafrost landscape studies have played a significant role in determining the modern dynamics of the natural environment during disturbances, primarily during forest fires and deforestation. Restorative successions after disturbance reflect the restoration of permafrost conditions. The characteristics of successional stages in the development of permafrost landscapes and their duration have been determined [98,121–123]. In central Yakutia, the complete restoration of the permafrost landscape after disturbance takes 120–130 years. Detailed studies on the succession's influence on the active layer thickness in central Yakutia were carried out by Gabysheva (Lytkina) [35,124,125]. The study of succession stages of development served as the basis for mapping the dynamic state of permafrost [53].

At the Neleger Station near Yakutsk City in central Yakutia, the Melnikov Permafrost Institute experimented with clear-cutting a larch forest and studied the initial stage of restorative succession though a detailed assessment of the dynamics of permafrost conditions [126,127]. An increase in the productivity of biota serves to restore permafrost conditions after disturbances and to measure the impact of succession stages on the state of permafrost landscapes. To assess the aforementioned impact, boreal forests must be studied [128–131]. Our observations in central Yakutia showed that under the conditions of modern climate warming, successions cause a decrease in permafrost temperature [123], which is quite natural.

Some researchers have noted a weak response of boreal permafrost landscapes to climate warming through ground temperature and active layer thickness and have attributed this to the snow accumulation regime [132,133]. However, in their works, they did not consider the biological component of the permafrost landscape, which can influence active layer thickness.

The permafrost landscape features of the territories have impacted the increase in soil temperature during the current climate warming. Thus, there has been an increase in soil temperature from average long-term values of 0.5 °C in central Yakutia to 2–3 °C in Arctic Yakutia [134,135]. Such changes have led to the degradation of permafrost landscapes on ice-rich permafrost (Figure 4). Many researchers have noted the more intense response of tundra permafrost landscapes, especially in the formation and expansion of thermokarst lakes [136–138]. Boike et al. [139] identified changes in lake areas, vegetation, land surface temperatures, and the area covered by snow using data from remote sensing. Such changes will undoubtedly have an impact on the state of permafrost landscapes.

(a)

(b)

Figure 4. Ice-wedge exposure (**a**) and abandoned arable land from thermokarst development in the ice-rich permafrost (**b**) near the Syrdakh settlement in central Yakutia.

The change in soil and vegetation cover determines the dynamic state of the permafrost landscape and the evolution of the environment. It is also essential for predicting the change in permafrost in the context of global warming.

Lapenis et al. [140] noted that the biomass of green parts (leaves, needles, understory, and green forest floor) had a steady upward trend from 1960–2000 during modern climate change. Analysis of satellite data revealed a slight increase in the normalized difference vegetation index (NDVI) in northern Eurasia. The development of biota productivity can slow down the increase in ground temperature and active layer thickening in boreal landscapes because vegetation cover is a good heat insulator [141,142].

For example, an increase of 158% in tundra sedge meadow productivity in Canada's Arctic zone from 1980 to 2005, with an average increase in the mean annual air temperature by 0.8 °C per decade, resulted in a statistical decrease in the active layer thickness from 76.8 $\pm$ 8.1 cm in the 1980s to 76.1 $\pm$ 10.6 cm in 2005 [143]. This explains the stable state of active layer thickness obtained during the long-term monitoring of permafrost boreal landscapes in central Yakutia from 1982 to 2012 [32]. A noticeable growth of annual larch rings during the period of Arctic warming in the 1930s–1940s and a decrease in its growth rates in the 1940s–1980s [144,145], noted during periods of warming and cooling of the climate, reflect the impact of changes in biota productivity on the state of permafrost conditions.

Changes in the organic material in permafrost soils are taken into account in geocryological modeling [142]. In Yakutia, experimental work was carried out in the tundra near the town of Chokurdakh in Yakutia, which found that shrub expansion may reduce permafrost thaw in summer [146]. In the alases of central Yakutia, the temperature regimes of soils in meadows with different biomasses were determined [147], as well as change patterns during successions in boreal forests after the disturbance [123].

The stability of permafrost landscapes depends not only on permafrost conditions, but also on the dynamics and evolution of biota. The widespread activation of forest fires in northeastern Eurasia during climate warming in recent decades has caused a disruption of the permafrost temperature regime and the subsequent development of restorative successions. Permafrost disturbances cause an imbalance in greenhouse gases, illustrating the dynamism of changes in permafrost landscapes. In the permafrost landscapes of Yakutia, studies are being carried out on both carbon dioxide [148–151] and methane content in permafrost [152–154] and their emissions [155–159].

The degradation processes of permafrost and the restoration of native landscapes require developing adaptation measures to life in these new conditions. Permafrost landscape studies can benefit this development. Recently, suggestions for permafrost temperature management by controlled grazing to ensure permafrost sustainability and reduce greenhouse gas emissions have attracted interest [147,160–162].

6. Summary

Permafrost landscape studies, based on the theoretical developments of Soviet physical geographers and landscape scientists, have become widespread in Russia. Over the past four decades, permafrost landscape studies have been carried out widely on northeastern Eurasia. This review summarizes the main results of these studies. The main conclusions relate to the development of three directions, the main essence of which is as follows:

(1) Identifying the permafrost landscape as an object of study complements the theory of landscape science that was strongly developed in the Soviet Union (later in Russia). The parameters of the cryogenic factor have been proposed as criteria for identifying taxonomic units and classifying permafrost landscapes.
(2) The development of permafrost landscape studies made it possible to create mapping based on the classification of permafrost landscapes. Different scale permafrost landscape maps were created that reflected the unity of the morphological parts of the landscape and permafrost. Permafrost landscape maps are mainly used to identify patterns of permafrost differentiation in the environmental assessment in the North.
(3) Permafrost landscapes serve the purpose of illustrating the dynamics and evolution of permafrost. The successional stages in the development of permafrost landscapes indicate permafrost dynamics after disturbances; long-term changes in landscapes relate to permafrost evolution.

Prospects for the study of permafrost landscapes in northeastern Eurasia will primarily involve an assessment of environmental vulnerability and the adaptation of socioeconomic conditions to modern climate warming. Understanding the concept of the permafrost landscape, which connects all the components of the system [43], can solve this problem. To do this, it is first necessary to systematize the available data. Permafrost landscape zoning has served as the basis for compiling a cadaster of permafrost landscapes [51], and it is now the basis for compiling a database of geocryological data of different scales that will ensure environmental protection measures and adaptation in conditions of climate change. Second, we must determine the development trends in permafrost landscapes and permafrost in general, such as which permafrost landscapes will be the most vulnerable to modern climate warming and anthropogenic impacts, and whether there are any mechanisms for permafrost conservation. Third, it is important to determine ways of adapting socioeconomic conditions to changes in permafrost. We see the development of permafrost landscape research proceeding in these directions.

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