RESEARCH PAPER

LANDSCAPE INDICATION OF PERMAFROST CONDITIONS FOR GEOECOLOGICAL ASSESSMENT & MAPPING AT VARIOUS SCALES

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ABSTRACT. In this paper, the features of landscape indication of permafrost characteristics required for assessing the environmental state at various research scales are discussed. A number of permafrost characteristics affect the geoecological state and stability of natural landscapes, especially in the context of climate warming and technogenic surface disturbances. These include the distribution, temperature regime, thickness and cryogenic structure of permafrost, seasonal freezing and thawing, as well as the development of cryogenic processes. Their determination through the landscape view, however, is ambiguous. The choice of certain permafrost characteristics for geoecological assessment is based on many years of experience in creating cryo-ecological maps on a landscape basis by the school of Faculty of Geography, Moscow State University. The recent studies on the identification of regional cryoindicators are analyzed, including the issues of cryogenic landscapes classification and clarification of the boundaries of geocryological zones using the landscape structural method. The content of the two maps, «Permafrost Landscape Differentiation Map of the Russia Cryolithozone» at a scale of 1: 15,000,000 and «Permafrost Landscape Map of the Republic of Sakha (Yakutia)» at a scale of 1: 1,500,000, is presented, as well as their use as a basis for environmental planning and geoecological assessment.

KEYWORDS: permafrost; cryolithozone; landscape indication, cryogenic processes, geoecological mapping

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INTRODUCTION

Landscape indicators related to permafrost characteristics have found wide application in scientific research and survey, especially in engineering and geocryological mapping. The method is based on the relationship between the external appearance of landscape components and their internal structure followed by interpretation based on reliable indicators (Viktorov and Chikishev 1990). The relief, vegetation and ground cover are the most indicative physiognomic components of the landscape.

Since the 1930s, landscape indication of the permafrost state has been used in different regions, especially if the information on the research subject was limited. V. Tumel (1945), A. Tyrtikov (1956, 1969) and V. Kudryavtsev (1961) were the first scientists to point out the benefits of this landscape indication method in permafrost studies. In 1960, I. Baranov (1960) compiled the first landscape-based geocryological map of the USSR at a scale of 1:10,000,000. In the 1970s, the first surveys and mapping using the landscape indication method were carried out in Alaska (Everett et al.1978), Canada and in the north of Western Siberia (Melnikov et al.1974). A special place in landscape indication studies of permafrost is occupied by the pioneering developments of E. Melnikov (1983) on the taxonomy and classification of landscapes in the north of Western Siberia.

The permafrost landscape indication is the main method of geocryological mapping at all scales. It is an important research tool for the interpretation of remote sensing data, as well as studying the dynamics and evolution of permafrost, including the problems caused by the current climate warming. This article considers some ecological aspects of this method for assessing and mapping the permafrost zone.

Ambiguity of landscape indication

The development of landscapes within the permafrost zone and their recovery after disturbances largely depends on the properties of permafrost, which include the permafrost distribution, temperature and thickness, ground ice composition, depth of seasonal thawing-freezing and presence of cryogenic processes. These parameters are usually used as criteria for the classification and mapping of permafrost landscapes. However, not all of these features are equally amenable to landscape indication.

Permafrost distribution. In the continuous permafrost zone, taliks under river beds and lakes are present, while outside this zone, islands of frozen rocks, in which permafrost is primarily formed and preserved, can be found. Accordingly, a reliable indicator of permafrost distribution is peat and peat landscapes. Permafrost develops in these landscapes because in summer, due to the high heat capacity of water, peat prevents soil heating, while in winter high ice content determines the soil thermal conductivity and its intense cooling.

For the *permafrost average annual temperature*, there is no indicator. Only a qualitative assessment of the heat content can be given based on the physiognomy of a landscape: the coldest or the «warmest» permafrost areas can be identified.

Permafrost thickness is poorly amenable to landscape indication, except for the southern isolated permafrost zone. In conditions of continuous permafrost distribution and its significant thickness (more than 100 m, up to 500-700 m), the indication is impossible.

Permafrost ice content is an indicated characteristic since it depends primarily on the composition of rocks, which is quite simple to distinguish based on vegetation using aerial and satellite images. At any scale, the ice content increases from minimum to maximum values is as follows: bedrocks – sand – sandy loam – loam – peat. On a small scale, this is a fairly reliable indicator, but on a large scale, the composition of rocks is insufficient to indicate their ice content. Within one lithological type, it is necessary to know the genesis of rocks, which determines moisture (ice content). For example, ice content in lacustrine loams is much higher than in moraine loams.

Depth of seasonal thawing/freezing is usually mapped on a medium to large scale. Tundra vegetation is clearly correlated with the depth of seasonal thawing. However, without field studies of the active layer depth, its interpretation is possible only at the qualitative level – deep, medium, shallow, etc. The primary indicator of the depth is the composition of rocks. This is followed by the presence of moss vegetation cover. The latter is an indisputable indicator of shallow thawing. For seasonal freezing, vegetation is replaced by snow cover.

Cryogenic processes such as thermokarst, thermoerosion, solifluction, etc., usually create forms of meso- and micro-relief, which are easily recognized on images and mapped on large and medium scales. To identify these processes, a complex of geomorphological indicators is used, which includes the relief dissection, presence of lake depressions and small erosional forms, nature of the meso- and microrelief, as well as the appearance of landscapes along with the hydrographic network. These indicators have their own set of features – a characteristic color, tone, structure, pattern, etc.

Cryogenic landforms, which develop as a result of a certain process, are indicated on any scale with one caveat. The larger are these forms, the more reliable is their identification. Cryogenic relief is the most significant indicator of geocryological zoning in the northern territories. In the southern permafrost zone, it is mainly represented by vast areas occupied by frost heave mounds in the growth stage; in the north, there is ancient polygonal block relief (Osadchaya and Tumel 2012). The most reliable landscape indicator of cryogenic processes is the tundra zone. Forested permafrost is a very difficult object to interpret. Within its boundaries, depending on the region, only some physiognomic landscapes work. In Western Siberia, for example, these are lacustrine-bog landscapes; in Central Yakutia – negative landforms, alases; in Transbaikalia – slope exposure.

Indicators of relief-forming processes in different regions of the Russian permafrost zone are well studied and published in scientific literature. For Western Siberia, these are the works of E. Melnikov et al (1974), N. Ukraintseva et al (2011), M. Pupyrev (2013) and others. For the European North – the works of G. Osadchaya (2012,2015), F. Rifkin et al (2008), for Yakutia – numerous works of the Permafrost Institute (Fedorov 1991; Fedorov et al. 2004; Shestakova 2011; Torgovkin 2005, etc.). A. Kizyakov and M. Leibman (2016) published a review of 110 publications of Russian and international researchers devoted to the study of cryogenic relief-forming processes.

Reliability of landscape indication in the permafrost zone increases from north to south which is explained by the increasing role of vegetation cover in the indication. In the north of cryolithozone, the value of geobotanical indicators is not so high and landscape indication of temperature conditions depends to a greater extent on the relief. The most reliable indicators in the permafrost zone are the external appearance of the landscape, its pattern and combinations with each other (Viktorov and Chikishev 1990; Tumel and Zotova 2017).

The landscape permafrost classification

The level of detail used for the indicators is determined by the research scale. When creating maps on a small scale for evaluation, strategic and scientific purposes, indicators at the level of landscapes are used. On a larger scale, at the design stages for specific engineering projects, the type of terrain, tracts and facies are analyzed. Thus, only natural complexes of a certain rank can reliably characterize the geocryological situation. For example, in the area of the Spasskaya Pad station near the city of Yakutsk, based on long-term studies it was established that, at the local level, the type of natural boundaries (tracts) is a good indicator of thickness and moisture content of the seasonally thawed layer. On a medium scale, the differentiation of landscapes according to the cryogenic structure and ice content, annual mean temperature of rocks and seasonally thawed layer thickness is well indicated by the type of terrain. Higher rank geosystems used in small-scale research (1: 5,000,000) in the basin of the Lena River only allowed to reveal the nature of frozen and thawed rocks distribution (Torgovkin 2005).

The functioning of landscapes in the permafrost zone and their transformation after disturbances largely depends on the permafrost properties – frozen rocks distribution, their temperature regime, cryogenic structure, ice content and active layer thickness, which are used as the lithocryogenic factors of landscapes stability. A striking example of their practical use in classification and mapping is the digital version of the «Permafrost landscape map of the Republic of Sakha (Yakutia) at a scale of 1: 1,500,000.

The map was compiled in ArcGIS 10.1 based on the interpretation of Landsat and Modis satellite imagery and a specialized base of geocryological data with more than 800 geocryological observation points, including individual geothermal wells. In total, 20 types of terrain and 36 types of plant groupings were identified, the combination of which made it possible to systematize 145 types of permafrost landscape (Fedorov et al. 2018).

To develop the classification, the authors used permafrost criteria corresponding to taxonomic units. The type of landscape corresponds to the nature of permafrost distribution; types of terrain (identified by the stratigraphic-genetic complex) – to the cryogenic structure and ice content in the sediments; types of tracts and facies – to the temperature of rocks and active layer thickness. In this case, geological and geomorphological factors (rank of terrain types) were compared with vegetation groups. This permafrost landscape classification can serve as a basis for assessing the resilience of landscapes to climate change and anthropogenic impact in this region. The unified matrix legend (Fig.1) allows to quickly determine physiographic and permafrost characteristics of the selected landscapes. This map introduces new methodological and classification solutions.

Forecasting indication studies of permafrost conditions

In recent years, a number of scientists have carried out significant studies to identify tracts as indicators of permafrost conditions in various regions to optimize environmental management in the permafrost zone (Osadchaya 2012, 2015; Medvedkov 2018; Shestakova 2011; Makarycheva 2015 etc.).

For example, based on the detailed long-term studies in the European North-East, it has been established that in this region peatlands are a universal cryoindicator of geocryological zoning. Their characteristics were used to clarify the boundaries between geocryological subzones. On the border between the sporadic and isolated permafrost, the change of subzones is indicated by the appearance of flat-topped polygonal peatlands, while on the border between discontinuous and continuous permafrost, an abrupt disappearance of dome-shaped peatlands and appearance of polygonal ones can be observed. As a result, the Bolshezemelskaya tundra geocryological map at a scale of 1: 1,000,000 was compiled and environmental restrictions on nature management were formulated taking into account the differences in permafrost landscapes (Osadchaya 2012, 2015).

The response of landscapes in the boreal isolated zone of permafrost rocks in the Yenisei River basin to climate warming was determined based on reliable indicators of their frozen and thawed state. The number of biogenic landforms in the landscape structure of this subzone increases and the processes of solifluction and kurum desertification are intensified (Medvedkov 2018).

A separate field of studies is focused on the indication of the temperature of rocks along with the thickness of seasonally thawed and protective layers using the successive stages of vegetation development after an external impact. The well-known monograph by N. Moskalenko (1999) describes a technique for constructing ecological genetic series of phytocenoses on the example of Western Siberia northern natural zones. The work of Shestakova (2011) is devoted to mapping geocryological conditions based on the identification of the vegetation succession series on different scales. For example, in a comparative analysis of natural and disturbed landscapes of the Prilenskoye plateau, it was found that the temperature of frozen rocks in new successions increases by 1°C, and the seasonal thaw layer thickness increases by 0.5–1.0 m compared to natural ones. These works make it possible to model the development of permafrost landscapes after disturbance, which is necessary for predicting and assessing environmental impact.

From the regional perspective, the work on the identification of thermokarst phenomena in the southern permafrost zone within the route «Eastern Siberia-Pacific Ocean» should be noted. Based on the interpretation of aerial images, the areas with loose cover and presence of ice were identified, indicating all types of thermokarst phenomena, which are confined to peatlands, bush mari, river floodplains, etc. As a result, the zoning of the oil pipeline 3 km buffer zone was carried out over more than 2,600 km in order to locate the observation points for monitoring thermokarst processes (Makarycheva 2015).

It is known that the dynamics of thermokarst lakes is considered as an indicator of climate change in the Arctic regions (Kravtsova and Tarasenko 2011). The reliability of this indication is confirmed by the spatial data obtained from a series of satellite images and the results of their automatic interpretation using the ERDAS Imagine package combined in ArcGIS (Kravtsova and Rodionova 2016). Remote sensing data have been widely used for monitoring thermokarst lake dynamics not only in the Russian permafrost zone but also in Alaska, Canada, China and Sweden (Kizyakov and Leibman 2016). The established decrease in the surface area of lakes (due to the formation of coastal strips with floating bog vegetation) has the paramount importance in the context of active thermokarst development (Chen et al. 2013). Thermokarst

Terrain type	Designation	Stratigraphic-genetic complex	Prevailing criogenic textures and trapped ice	Volumetric ice content	Basic cryogenic processes	Tundra			
						Tundra in continuous cryolithozone			
						Arctic tundra grassinoid	Typical tundra low shrub/lichen and moss	Scutherm tunra shrub	Sparse vegetation of marshes
						1	2	3	4
Marshes		mH, mH1-2	Massive, lenticular	<0.2...0.2-0.4	Frost cracking, heaving	-11...-13 / 0.2-0.4			-11...-13 / 0.2-0.6
Low terrace		aH, aIII-H	Massive, lenticular, layered; Hclocene ice wedges	0.2-0.4	Frost cracking, thermokarst, heaving				
Mid terrace		aII-III	Massive, rarely sheet ice	0.2-0.4	Frost cracking, thermosuffusion	-10...-12 / 0.2-0.4	-8...-10 / 0.3-0.5	-6...-8 / 0.5-0.8	
Inter-ridge-lowland		aII-III, bH	Massive, lenticular, layered	0.2-0.4 (0.6)	Frost cracking, thermokarst, heaving				
High terrace		aI, aI-II	Massive	<0.2...0.2-0.4	Frost cracking			-6...-8 / 0.5-0.8	
Old terrace		lpH, LH	Massive, cortiical, lenticular	<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 / 0.2-0.4	-8...-10 / 0.3-0.5	-7...-8 / 0.4-0.6	

Fig. 1. Fragment of the legend to Permafrost Landscape Map of the Republic of Sakha (Yakutia) (Fedorov et al. 2018)

lakes tend to increase in number and size within the continuous permafrost zone and decrease in its more southern parts (Jones et al. 2011). Thus, the response of thermokarst to recent climate warming shows no uniform trend for the permafrost zone. In the context of climate change, methods for mathematical modeling of the landscape morphology in thermokarst lake and erosion plains are being developed. (Victorov et al. 2015).

The landscape indication method is widely used in international monitoring programs TSP (Thermal State of Permafrost) and CALM (the Circumpolar Active Layer Monitoring) – the world's main information sources on the permafrost temperature as well as seasonal freezing and thawing layer (Brown et al. 2000). CALM monitoring network, established in the late 1990s, observes the long-term response of the active layer and near-surface permafrost to changes and variations in climate at more than 125 sites distributed in both hemispheres. Several groups of sites are used to create regional maps of the active layer thickness (Ukraintseva et al.2011; Maslakov et al. 2019 etc.)

Permafrost landscape structure

In the permafrost area mapping one more indicator is used – the landscape structure, which characterizes its spatial organization. Taking this indicator into account, the boundaries of regions, zones, and provinces can be identified more reliably based on inter-component relationships (Osadchaya et al.2016). Secondly, more informed decisions on the economic development of a particular region can be made when considering possible environmental risks of nature management related to the complex differentiation of permafrost landscapes (Osadchaya and Hohlova 2013).

Application of the landscape indication method on a small scale can be seen in «Permafrost Landscape Differentiation Map of the Russia Cryolithozone» on a scale of 1: 15,000,000 (Fig. 2), compiled based on the A. Isachenko's map on a scale of 1: 4,000,000. The permafrost characteristics were obtained from the synthesis of geocryological maps on scales of 1: 2,500,000 (1997) and 1: 5,000,000 (1977), Permafrost landscape map of Yakut ASSR on a scale of 1: 2,500,000 and a number of maps from regional atlases.

In terms of permafrost distribution (% of the area occupied by permafrost), four types of areas can be defined: with continuous (> 95%), discontinuous (50-95%), sporadic (10-50%), isolated (<10%) distribution. Permafrost distribution is shown on the map with a colored background, types of landscapes – with indices and boundaries of different thickness. Figure 3 shows the 23 zonal landscape types, which are subdivided into regional sectors (European, Siberian, Far Eastern, etc.) denoted by letters (Tumel and Zotova 2017).

The comparison of regions with four main types of permafrost distribution and zonal types of landscapes within their boundaries was made back in 1954 by I. Baranov. N. Tumel and N. Koroleva (2008) conducted a similar analysis on their map using modern GIS technologies and have got interesting conclusions. For example, several tundra and taiga landscapes are found in each permafrost subzone (from continuous to isolated), which means that they cannot be used as indicators of the permafrost conditions (this statement does not apply to regions). The most homogeneous landscape structure is observed within the continuous permafrost zone, while the greatest diversity corresponds to the sporadic permafrost zone (Fig 4).

Also, it was established that allocation of the sporadic zone as a separate area is not justified since the set of landscapes and their percentage in this area is similar to the discontinuous zone, which means they can be combined. Moreover, permafrost occupies more than 40%

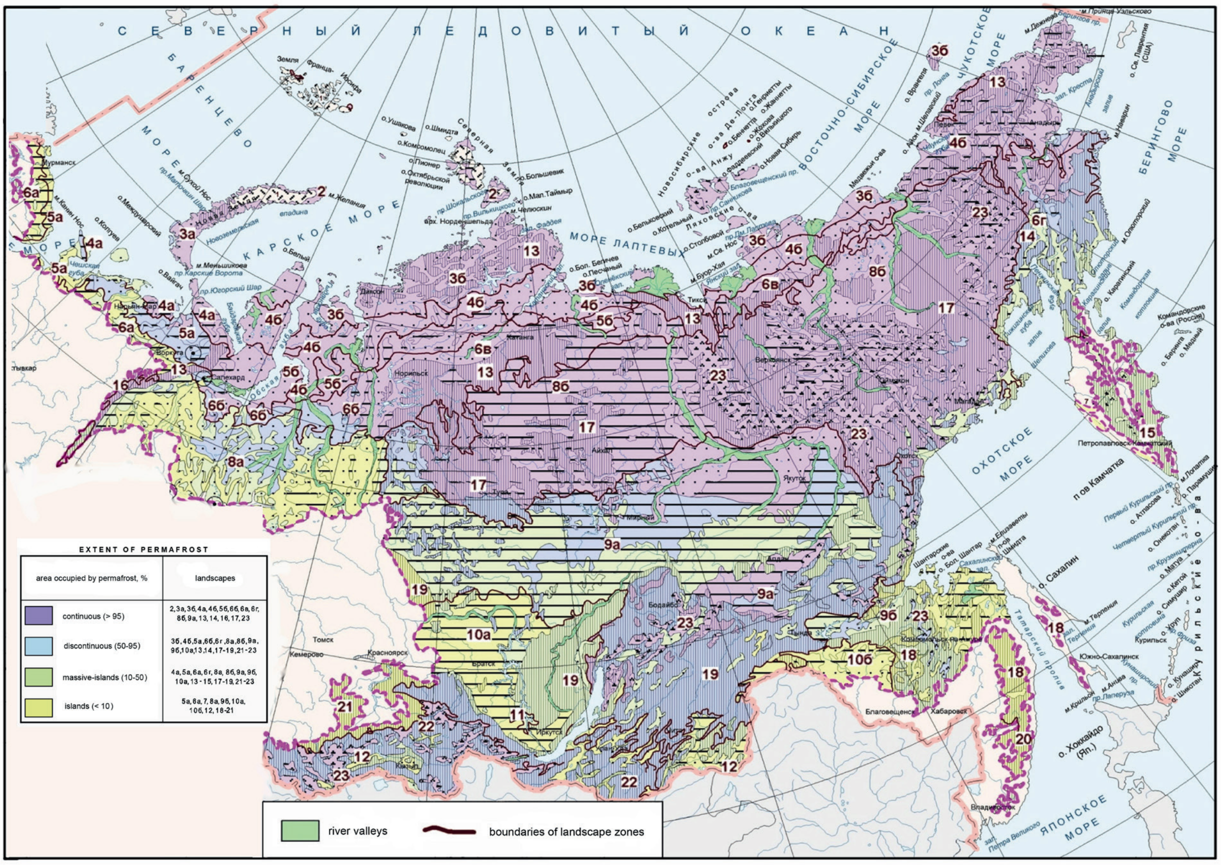

Fig. 2. «Permafrost Landscape Differentiation Map of the Russia Cryolithozone» on a scale of 1: 15,000,000 (Tumel and Koroleva 2008)

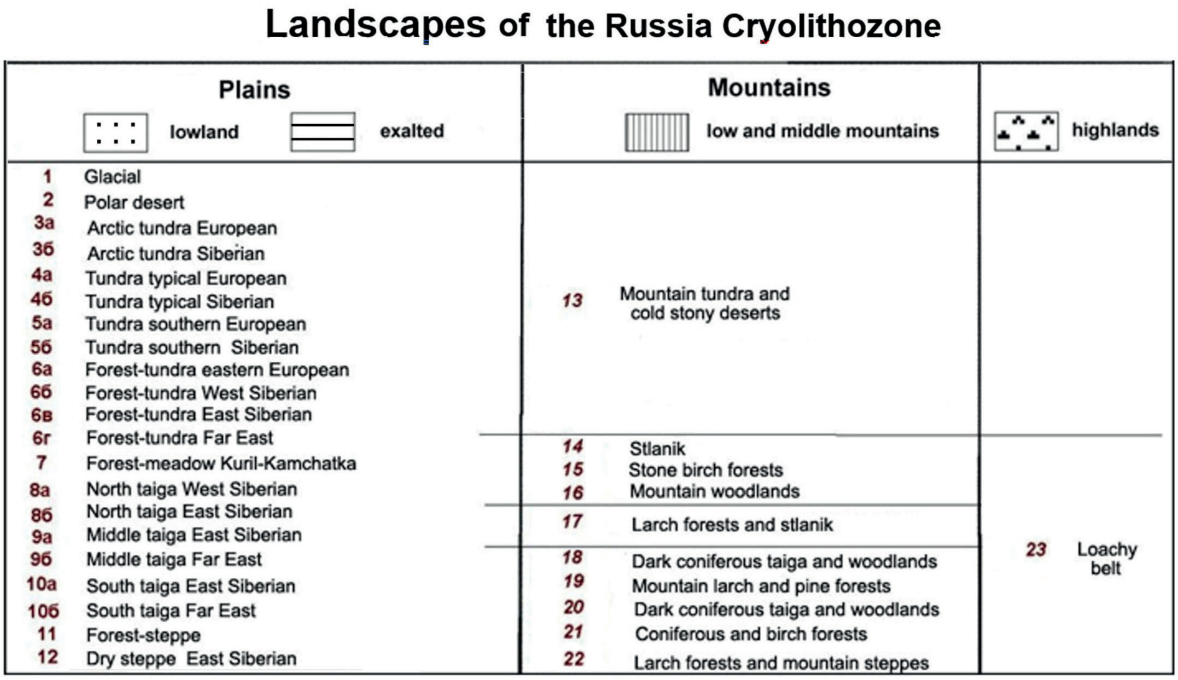

Fig. 3. «Fragment of the legend to the Permafrost Landscape Differentiation Map of the Russia Cryolithozone» (Tumel and Koroleva 2008)

there. Therefore, not four, but only three areas of permafrost distribution should be distinguished, as it is done in the well-known circumpolar permafrost map (Brown et al. 2002). This statement, however, cannot be considered as universal. It is applicable to the entire permafrost zone, which is characterized by a contrasting landscape structure. At the same time, in the western sector of cryolithozone, including the Bolshezemelskaya tundra, it is not recommended to combine the sporadic and discontinuous distribution subzones due to its flat topography, which determines the leading role of zonal factors (climate and vegetation) in the formation of permafrost conditions.

The absence of a definite connection between the boundaries of zonal landscapes and the main types of permafrost distribution can be seen in the behavior of the southern border of the Russian permafrost zone. In the west of the European North, it runs along the border of the southern tundra, while in the Bolshezemelskaya tundra and Western Siberia it «cuts» through the northern taiga, descends far to the south approximately along the Yenisei river meridian and then cuts the southern taiga and steppes of Central Siberia (Fig. 2). Approximately the same discrepancy is observed between the landscape boundaries and the main types of permafrost distribution,

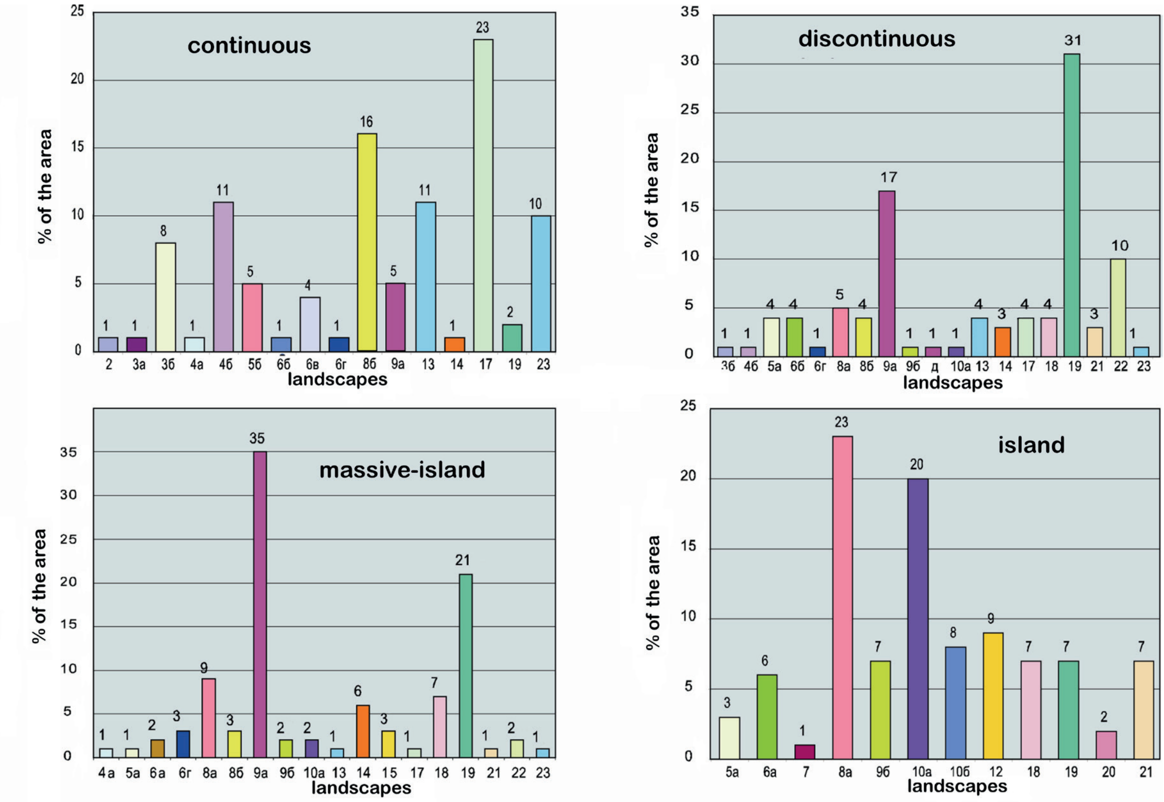

Fig. 4. Landscape differentiation of the four permafrost distribution zones in Russia, % of the area in each zone (Tumel and Koroleva 2008)

especially when considering the Russian permafrost zone in general. However, if we consider small-scale maps (from 1: 2,500,000 and smaller) of individual regions (European North, Western Siberia, Yakutia, Eastern Siberia), landscape indication starts to work very effectively again. This primarily applies to accumulative and denudation plains, within which the permafrost distribution, temperature, thawing depth, and often ice content, correspond to one of the landscapes.

The ambiguity of landscape indication should be taken into account when performing geoecological sustainability assessment of identical landscapes with different permafrost characteristics. In the northern geocryological area it easier to assess the resilience of landscapes to mechanical disturbances of the surface, hydrocarbon pollution, climate warming, etc. since the variety of permafrost conditions within the same landscape there is significantly lower compared to landscapes located to the south. In the central part of the permafrost zone, within the discontinuous and sporadic permafrost subzones, it is most difficult to determine the degree of ecological risk due to the maximum variety of permafrost landscape conditions. Such landscape diversity defines the spatial variation of the mean annual temperature, seasonal thawing and cryogenic structures. The southern permafrost zone is less difficult for economic development (Tumel and Koroleva 2008). The most typical landscapes in all permafrost regions correspond to Central and Eastern Siberia, which include the most extensive platform massifs with similar landscape conditions prevailing in a long historical development.

DISCUSSION

Indication of permafrost conditions is very complex. It is based on the idea of dependence of the vegetation cover in the permafrost zone on the thermal properties of substrate and seasonal processes of thawing and freezing. The combination of geomorphological, geobotanical and hydrological indicators can be used to identify the permafrost properties of landscapes with certain accuracy.

However, the degree of the «landscape – permafrost» connection is different. Zonal landscape indicators, with rare exceptions, are not universal and can be used only for a specific region. So, on a small scale, most landscapes are not reliable indicators of permafrost conditions. Thus, the scale of research imposes limitations on the effectiveness of the landscape indication method. It is most effective for medium-scale mapping (1:25,000–1:100,000). Small-scale studies within the permafrost zone require a more careful approach to the «permafrost-landscape» relationship, although in this case, landscape units serve as the basis for the permafrost mapping.

When creating small-scale maps, a large amount of information is generalized using landscape classification and geoinformation mapping. In the most famous geocryological maps, such as the «Geocryological map of the USSR» (Baranov 1960) and «Circum-Arctic map of permafrost and ground ice conditions» (Brown et al. 2002), the method of landscape indication was used indirectly. The only map of permafrost that fully exploits regional landscape differentiation is the updated «Map of Permafrost and Landscapes of the Republic of Sakha (Yakutia)» on a scale of 1:1,500,000 (Fedorov et al. 2018), as well as a number of maps created by the Earth Cryosphere Institute (Drozdov et al. 2003; Drozdov et al. 2018). Successful examples of cryogenic landscape mapping in high-altitude areas are the latest maps of the Tibet Plateau based on the new MODIS land surface temperature method (Zou et al. 2017; Wu et al. 2018).

Cryoindication studies are of great importance for the development of geoinformation technologies in permafrost research. Individual landscape components are considered in GIS as permafrost indication factors. GIS technologies simplified permafrost landscape classification as well as interpretation of maps by introducing overlay methods and approaches such as attribute tables (Drozdov et al. 2003; Torgovkin 2005; Fedorov et al. 2018 etc.). GIS is widely used in engineering and geocryological research, geoinformation modeling of permafrost conditions and mapping (Drozdov 2004; Rivkin et al. 2008; Torgovkin 2005; Victorov et al. 2015 etc.). New methods of spatial analysis significantly increase the content of various maps allowing for a more comprehensive analysis of permafrost regions.

In Russia, the most significant results in the field of regional, local, and regime studies of landscape-based permafrost mapping were obtained by the Earth Cryosphere Institute, Tumen, Moscow (ECI SB RAS) (Melnikov 1983; Drozdov et al. 2018, etc.), Melnikov Permafrost Institute SB RAS, Yakutsk (Fedorov 1991; Fedorov et al. 2018, etc.) and Lomonosov Moscow State University, Faculty of Geography (Shpolyanskaya and Zotova 1994; Tumel and Koroleva 2017; Tumel and Zotova 2019; Maslakov et al. 2021 etc.). These are well-known scientific schools with many years of research and mapping experience. Their works fully reflect the current state of landscape indication research in the permafrost zone.

CONCLUSIONS

The study and mapping of the permafrost zone are based on the geosystem approach, in which landscape indication is considered as one of the main methods. It is important to pay attention to two points when using it in environmental assessment studies. Firstly, to the reliability of displaying the boundaries of permafrost zones, because as the boundaries change, the qualitative characteristics of permafrost and its stability also change. Secondly, to the manifestation of cryogenic processes, such as thermokarst, thermoerosion, solifluction, frost heaving, ice formation, etc., which are dangerous both for natural landscapes and for the functioning of engineering structures. These processes are the most important indicator of the reaction of northern landscapes to anthropogenic disturbances.

There is a certain sequence in the cryogenic processes indication. First of all, the ice content of frozen rocks is identified, as it determines the activation of cryogenic processes. After that, islands of frozen and thawed landscapes are revealed, which are associated with the manifestation of ecologically hazardous cryogenic processes. This is followed by the thickness of the seasonal thawing and freezing layer (a key indicator of the degree of cryogenic processes development) and, in some cases, the average annual temperature of permafrost. Permafrost temperature is a background characteristic that promotes or prevents the development of cryogenic processes. Temperature above -5°C is favorable for their activation, while temperature below -5°C contributes to their attenuation. Permafrost thickness affects the ecological situation mainly in the south of the permafrost zone, where its profile is no more than 5–20 m and there is a danger of complete thawing. Cryogenic processes themselves and the cryogenic landforms they produce are an integral part of the indicative landscape properties.

The use of landscape indication in the studies of permafrost conditions has large-scale limitations. The smaller is the scale of research, the more limited is the application of the landscape indication method. For small-scale studies, the reliability of the «landscape – permafrost» relationship decreases from north to south. Resistance to anthropogenic surface disturbances in the same landscapes with different permafrost characteristics increases to the north and east. The central part of the Russian permafrost zone is the most difficult to develop due to the maximum variety of permafrost landscape conditions.

REFERENCES

Baranov I. (1960). Geocryological Map of the USSR at a Scale of 1:10,000,000; Explanatory note; Obruchev Permafrost Institute: Moscow, Russia (in Russian).

Brown J., Ferrians O., Heginbottom J., Melnikov E. (2002). Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2.; NSIDC—National Snow and Ice Data Center: Boulder, CO, USA.

Brown J., Hinkel K., Nelson F. (2000). The circumpolar active layer monitoring (CALM) program: Research designs and initial results. Polar Geogr., 24, 166-258.

Chen M., Rowland J., Wilson C., Altmann G., Brumby S. (2013). The importance of natural variability in lake areas on the detection of permafrost degradation: A case study in the Yukon Flats, Alaska. Permafrost and Periglacial Processes, 24, 224-240, DOI: 10.1002/p.1783.

Drozdov D., Korostelev Y., Malkova G., Melnikov E. (2003). The set of eco-geologic digital maps of the Timan-Pechora province. In Proceedings of the Permafrost: 8th International Conference on Permafrost, ICOP, Zurich, 21 July–25 July 2003, 205-210.

Drozdov D., Malkova G., Romanovskij V., et al. (2018). Digital maps of permafrost zone and estimation of modern first name in the permafrost zone. In Actual Problems of Permafrost; Collection of Reports. 15-16 May 2018, 1. Part 4; KDU University Book: Moscow, Russia, 295-301.

Everett K., Webber P., Walker D., Parkinson R., Braun J. (1978). A geoecological mapping scheme for Alaskan coastal tundra. In Proceedings of the Third International Conference of Permafrost, Edmonton, AB, Canada, 10–13 July 1978, 359-365.

Fedorov A. (1991). Permafrost landscapes of Yakutia: a method of isolation and mapping issues / A.N. Fedorov. – Yakutsk, 140. (in Russian).

Fedorov A., Vasilyev N., Torgovkin Y., Shestakova A., Varlamov S., Zheleznyak M. et al. (2018). Permafrost-landscape map of the Republic of Sakha (Yakutia) at scale 1:1,500,000. Geosciences, 8, 465, DOI: 10.3390/geosciences8120465.

Geocryologic Map of the USSR. Scale 1:2, 500,000 (1997). Yershov E.D., Ed.; State Cartographic Factory: Vinnytsia, Ukraine. (in Russian).

Jones B., Grosse G., Arp M., Jones K., Walter A., Romanovsky V. (2011). Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. J. Geophys. Res., 116, G00M03, DOI: 10.1029/2011JG001666.

Kizyakov A., Leibman M. (2016). Cryogenic relief formation processes: a Review of 2010-2015 Publications. Earth's Cryosphere, XX(4), 40-52, DOI: 10.21782/ KZ1560-7496-2016-4(45-58).

Kravtsova V. and Rodionova T. (2016). Investigation of the dynamics in area and number of thermokarst lakes in various regions of Russian cryolithozone, using satellite images. Earth's Cryosphere, XX(1), 81-89 (in Russian with English summary).

Kravtsova V. and Tarasenko T. (2011). Thermokarst lakes dynamics in Central Yakutia under climate changes since 1950. Earth's Cryosphere, XV(3), 31-42 (in Russian with English summary).

Kudryavtsev V. (1961). Permafrost survey as the main type of permafrost research. In Permafrost Research; MSU: Moscow, Russia, 3-10. (in Russian).

Makarycheva E. (2015). Thermokarst phenomenon typification approaches near the southern border of the permafrost zone. In: Engineering Geology for Society and Territory. Vol. 1. Springer International Publishing Switzerland, Torino, 331-334.

Maslakov A., Shabanova N., Zamolodchikov D., Volobuev V., Kraev G. (2019). Permafrost degradation within Eastern Chukotka CALM sites in the 21st century based on CMIP5 climate models. Geosciences, 9(5), 232, DOI: 10.3390/geosciences9050232

Maslakov A., Zotova L., Komova N., Grishchenko M., Zamolodchikov D., Zelensky G. (2021). Vulnerability of the Permafrost Landscapes in the Eastern Chukotka Coastal Plains to Human Impact and Climate Change. Land, 10, 445, DOI: 10.3390/land10050445.

Medvedkov A. (2018). Indication of the state of taiga permfrost landscapes on the southern periphery of cryolithozone under conditions of a changing climate. in: Bulletin of the Moscow Region State University. Series: Natural Sciences, 1, 18-28, DOI: 10.18384/2310-7189-2018-1-18-28.

Melnikov E. (1983). Landscapes of the permafrost zone of West-Siberian Gas-Bearing Province; Nauka: Novosibirsk, Russia. (in Russian).

Melnikov E., Veisman L., Kritsuk L., Moskalenko N., Tagunova L., Todosiichuk I. (1974). Landscape indicators of engineering geocryological condition of the North of the Western Siberia and their interpretive signs. Nedra: Moscow, 132. (in Russian).

Moskalenko N. (1999). Anthropogenic dynamics of the plain vegetation within permafrost zone of Russia. Nauka: Novosibirsk, Russia, 280. (in Russian).

Osadchaya G. and Tumel N. (2012). Local landscapes as indicators of geocryological zoning (case study: European north-east) Earth's Cryosphere, XVI(3), 62-71 (in Russian with English summary).

Osadchaya G. and Hohlova E. (2013). Optimisations of nature management during the industrial exploitation of territorial resources of Bolshezemelskaya Tundra southern cryolitozone. Earth's Cryosphere, XVII(3), 35-43 (in Russian with English summary).

Osadchaya G., Tumel N., ZenginaT., Lapteva E. (2015). The development of the review Geocryologic Map of Bolshezemelskaya Tundra on the bases of landscape method. In Proceedings of the International Conference «Arctic, Subarctic: mosaic, contrast, variability of the Cryosphere»/V.P.Melnikov and D.S. Drozdov(ed) – Tyumen: Epoha publishing house, 2015, 287-290.

Osadchaya G., Tumel N., Koroleva A. (2016). Morphological structure of cryogenic landscapes of the Bolshezemelskaya Tundra. Earth's Cryosphere, XX(3), 14-23. (in Russian with English summary).

Pupyrev M. (2013). Deciphering and indication of modern exogenous processes in permafrost geocryological monitoring // Vestn. Tyum. State University, 4. 67-75 (in Russian with English summary).

Rivkin F., Popova A. et al. (2008). Mesoscale and detailed geocryological mapping as a basis for carbon budget assessment (East European Russian Arctic, CARBO-North Project). 9th International Conference on Permafrost, University of Alaska, Fairbanks, Volume 2,1493-1498

Shestakova A. (2011). Mapping of the permafrost landscapes taking into account vegetation succession. Ph.D. Thesis, Permafrost Institute, Yakutsk, Russia. (in Russian).

Shpolyanskaya N. and Zotova L. (1994). Map of potential landscapes stability of Western Siberia Cryolithozone; Moscow University Bulletin, Series 5. Geography; Moscow University Press: Moscow, Russia, 56-5. (in Russian with English summary).

Torgovkin Ya. (2005). Landscape indication and mapping of the river Lena permafrost conditions. Ph.D. Thesis, Permafrost Institute, Yakutsk, Russia. (in Russian).

Tumel N. and Koroleva N. (2008). Permafrost-landscape differentiation Russian permafrost zone as the basis of ecological and geological studies. Eng. Geol. 2, 11-14. (in Russian).

Tumel N. and Koroleva N. (2017). Ecological Atlas of Russia; LLC Feoriya: Moscow, Russia, 183-188, ISBN 978-5-91796-034-0. (in Russian).

Tumel N. and Zotova L. (2019). Diagnostics and Mapping of Geoecological Situations in the Permafrost Zone of Russia. Geosciences, 9, 353, DOI: 10.3390/geosciences9080353.

Tumel N. and Zotova L. (2017). Permafrost Geoecology: Training Aid for Bachelors and Masters, 2nd ed.; Yurite: Moscow, Russia, 2017, 220, ISBN 978-5-534-04227-6. (in Russian).

Tumel V. (1945). About permafrost survey. Izv. AN USSR Ser. Geogr. Geophys. 9, 135-144. (in Russian).

Tyrtikov A. (1969). Vegetation cover influence on freezing and thawing of soils Moscow: Moscow State University Publishing House, 192. (in Russian).

Ukraintseva N., Drozdov D., et al. (2011). Landscape indication of local variability of permafrost properties (Urengoyskoye field in Western Siberia). Earth,s Cryosphere, XV(4), 37-40. (in Russian).

Victorov A., Kapralova V., Trapeznikova O. (2015). Mathematical model of the thermokarst lake plain morphostructure under changing climatic conditions. Earth's Cryosphere, XIX(2), 23-31.

Viktorov S. and Chikishev A. (1990). Landscape indication and its practical application. Moscow: Moscow State University Publishing House, 200. (in Russian).

Wu X., Nan Z., Cheng G., Zhao S. (2018). Spatial modeling of permafrost distribution and properties on the Qinghai-Tibet Platea. Permafr. Periglac. Process. 29, 86-99, DOI: 10.1002/ppp.1971.

Zou D., Zhao L., Sheng Y., Chen J., Wu T., Wu, J., Xie C., Wu X., Pang Q., Wang W., et al. (2017). A new map of permafrost distribution on the Tibetan Plateau. Cryosphere, 11, 2527-2542.