EDITORIAL PAPER

PERMAFROST REGIONS IN TRANSITION: INTRODUCTION

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ABSTRACT. Russian permafrost regions are unparalleled in extent, history of development, population presence, and the scale of economic activities. This special issue, «Permafrost Regions in Transition», provides a timely opportunity to (a) examine major issues associated with changing permafrost conditions in natural environments and areas of economic development; (b) present insights into new methods of permafrost investigations; and (c) describe new opportunities and risks threatening sustainable development of Arctic populations and industrial centers in Russia. The issue begins with papers focused on methods of permafrost research, followed by papers focused on examining changes in permafrost under natural conditions, and in Arctic settlements. The last two papers examine potential impacts of permafrost degradation on the Russian economy and potential health implications.

KEYWORDS: permafrost, thermokarst, climate change, infrastructure, Arctic, massive ice, permafrost landscape, petrography, radon

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INTRODUCTION

Russian permafrost regions are unparalleled in extent, history of development, population presence, and the scale of economic activities. This special issue, «Permafrost Regions in Transition», provides a timely opportunity to (a) examine major issues associated with changing permafrost conditions in natural environments and areas of economic development; (b) present insights into new methods of permafrost investigations; and (c) describe new opportunities and risks threatening sustainable development of Arctic populations and industrial centers in Russia. The issue begins with papers focused on methods of permafrost research by **Vasil'chuk et al. (2021), Tikhonravova et al. (2021), and Zotova (2021)**, followed by papers focused on examining changes in permafrost under natural conditions by **Tregubov et al. (2021) and Grebenets et al. (2021)**, and in the Russian Arctic settlements by **Kotov** and **Khilimonyuk (2021)** and **Kamnev et al. (2021)**. The last two papers examine potential impacts of permafrost degradation on the Russian economy **(Badina and Pankratov 2021)** and potential health implications **(Puchkov et al. 2021)**.

METHODS OF PERMAFROST RESEARCH

Geocryological conditions and the response of permafrost landscapes to changing climate and economic development depend on several factors, including permafrost extent, temperature regime, the thickness and cryogenic structure of permafrost, the depth of seasonal freezing and thawing, as well as the combination of area-specific cryogenic processes. The paper by **Zotova (2021)** reviews the main landscape indicators used in geoecological assessments and mapping of permafrost conditions, arguing that the landscape-indicator method is an effective tool, but only at large to medium geographic scales (1: 25 000–1: 100 000), as generalization of permafrost properties at smaller geographic scales hinders the real distribution of permafrost characteristics. Generally, in similar landscape conditions, the resilience of permafrost to economic development increases toward the northern and eastern parts of Russia.

Petrographic methods are commonly used in paleo reconstructions. However, ice recrystallization is a major limiting factor in arriving at correct interpretation of sedimentary environments, and significantly limits the use of petrographic methods in the determination of ground ice genesis in permafrost. **Tikhonravova et al. (2021)** examine the processes responsible for ice crystal growth and provide examples of characteristic patterns of crystal arrangements for various types of ice, including glacier ice, lake ice, segregated ice, and injection ice, among others that can be useful for determining ice genesis. The authors also discuss the formation of secondary ice structures resulting from ice recrystallization, which have to be considered in effective applications of petrographic methods.

Massive ice bodies are widespread in the coastal lowlands of the Chukotka region, yet the origin of these bodies is not well understood. Vasilchuk et al. (2021) use cryostratigraphy and stable isotopic composition methods to evaluate the genesis of ground ice collected at seven coastal exposures in the northern part of Chukotka. Depletion of isotopic composition in massive ice bodies was found with increasing climate continentality, moving from coastal locations inland. This is attributed to the corresponding depletion of precipitation, which is the major source of water for massive ice formation. The authors determined that the ice was formed underground from atmospheric precipitation, surface, and ground waters, and is not the product of buried glacier ice. More dating and pollen analysis is needed to reinforce this conclusion.

Permafrost in Natural Landscapes

Monitoring of permafrost temperature and the active layer facilitates comprehensive understanding of changing climatic conditions in cold regions. The importance of permafrost is underscored by its recognition as one of the essential climatic variables by the Global Climate Observing System of the World Meteorological Organization (Biskaborn et al. 2019). Progressive thickening of the active layer under a warming climate has the potential to involve previously frozen organic material, which may have global implications for climate, while changing permafrost at local and regional scales has detrimental impacts on ecosystems, hydrology, and vegetation (Streletskiy et al. 2021). The response of permafrost to climate forcing differs substantially between different landscape types, so considerable knowledge is required at site-specific scales, where the roles of non-climatic factors and vegetation feedbacks may modulate the atmospheric signals and the response of permafrost to them.

Grebenets et al. (2021b) provide a thorough analysis of long-term active layer thickness (ALT) and dynamics, and their relations with climate variables and micro-landscape features at a Circumpolar Active Layer Monitoring (CALM) site in a remote region of Western Taymyr, Russia (Nelson et al. 2021). One of the main results of the study is that a strong statistical relationship was not found between ALT and summer air temperature. The effects of precipitation have an important modulating effect on this relationship. The study also found evidence of shrub expansion within the 1 ha monitoring site over the 16 years of observation.

Lakes in permafrost areas are another important indicator of changing climatic conditions in the Arctic (Kravtsova and Rodionova 2016; Veremeeva et al. 2016). Tregubov et al. (2021) analyze the dynamics of thermokarst lakes in the Anadyr lowland of northeast Russia over the last 65 years. Their study reveals that under the combined influence of climate warming, active layer thickening, and thermal erosion, lake area has shrunk 24% over this period. Based on field observations and remote sensing data, the authors propose two main scenarios of lake drainage in this area. They discovered 3-12 year cycles of intensive lake drainage and formation of frost-mound bogs within drained lake basins. The authors were also able to distinguish cases of lake drainage having ameliorative effects through both natural and anthropogenic causes.

Permafrost in Arctic settlements

Permafrost degradation is commonly execrated in areas of human presence and economic activities, and may negatively impact the sustainable development of the regions. Indigenous communities practicing subsistence lifestyles have first-hand experience with the direct impacts of permafrost degradation on food security, water quality, infrastructure stability, and thermal erosion. The majority of the population in the Russian permafrost regions is, however, concentrated in large industrial settlements, many of which have a substantial number of thaw-related deformations of building and structures (Grebenets et al. 2012).

Vorkuta is one of the largest settlements built on permafrost. Due to the complexity of its geological environment, its long history of development, and the diversity of construction techniques employed there, Vorkuta presents an unparalleled opportunity to examine various principles of construction used historically in permafrost regions (Shiklomanov et al. 2020). Using a combination of archival materials and field surveys, Kotov and Khilimonyuk (2021) assess the housing stock in the city and outline the major reasons responsible for infrastructure failure, including lack of proper attention to geocryological conditions, lack of high-quality construction materials, improper operation of building crawl spaces, limited ventilation, and inadequate water drainage, among others. An important conclusion from this study is that structures built using passive methods of construction on permafrost (also known as Principle I) are most vulnerable to climate warming.

Permafrost monitoring in areas of concentrated human activities is essential to support sustainable development of the Arctic regions, yet many settlements built on permafrost lack reliable and up-to-date data on changes in permafrost temperature under buildings and other infrastructure that can be used to assist geotechnical evaluations and prevent deformation within the built environment. Kamnev et al. (2021) provide methodological approaches and discuss preliminary results from the establishment of a program of permafrost temperature monitoring under a residential building in Salekhard, Russia. Preliminary results from this combined program of automated temperature monitoring in boreholes and computer modeling indicate that this is a promising approach that provides improved reliability and safety to residential buildings on permafrost, and can be implemented widely in settlements built on permafrost.

Permafrost impacts on economy and health

Permafrost degradation under projected climate warming can have severe economic consequences in terms of direct damage to infrastructure, as well as indirect costs associated with maintenance, insurance, salability, and mortgage availability. Better understanding of the extent and magnitude of potential risks is critically important for planning and development of adaptation strategies in the Russian Arctic regions. However, the economic forecast of permafrost-related damage is a relatively new area of research. Previous estimates (Streletskiy et al. 2019; Melnikov et al. 2021) relied on governmentally available statistics on regional values of fixed assets on permafrost in relation to population distribution at municipal levels.

Badina and Pankratov (2021) argue that using economic data directly from the enterprises operated in permafrost regions may significantly improve the evaluation of costs associated with permafrost degradation. This is because population distribution in the Arctic does not always correspond with fixed asset allocations, such as buildings and structures. The authors compiled a database on more than thirteen thousand enterprises operating in the Arctic regions and estimated the market value of buildings and structures based on the average share values of those assets in the total structure of fixed assets, by economic sector. The total value of fixed assets in the Arctic Zone of the Russian Federation's (AZRF) Asian sector was 14.8 trillion rubles with 10.7 in buildings and structures. The authors, in collaboration with permafrost scientists, plan to overlay this information with regions where permafrost degradation is projected to have the highest risks.

Permafrost regions are known for having large quantities of materials that may have health implications, such as mercury, as well as byproducts of mining, petroleum development, and solid waste (Grebenets et al. 2021a; Schaefer et al. 2020). **Puchkov et al. (2021)** present a compelling review focused on yet another potential hazard associated with permafrost degradation – release of radon that may have detrimental impacts on the health and well-being of communities and industrial centers on permafrost. The authors outline major areas where permafrost degradation and a large presence of radionuclides in the environment may result in elevated radon concentrations. They call for development of radon monitoring programs and legislation focused on mitigating potential threats from release of radon to improve public health and safety in regions on permafrost.

CONCLUSION

Historically, permafrost has played a very important role in the advancement of Russian science and engineering. Under rapidly changing climatic conditions and in areas of economic development, international attention should be focused on Russia's regions on permafrost in transition by virtue of the degree of development and extent of infrastructure on permafrost, as well as the accomplishments of Russian scientists and engineers engaged in permafrost research and applied work. Unfortunately, much of the research on this topic is not readily available to non-Russian speaking audiences. We hope that the papers in this special issue of Geography, Environment, Sustainability will narrow this gap and provide a diverse readership with an opportunity to delve more deeply into the latest developments and advances of research focused on Russia's permafrost regions.

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