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Editorial

Degrading permafrost and its impacts

1. Introduction

Permafrost is present extensively in polar, high-plateau, alpine, and mountainous regions, with a model-estimated total extent of permafrost regions at 22.79 million km^2 (Gruber, 2012). However, among ever increasing modeling results, these estimates are based on applications of different permafrost models of various validity, but with a large range of uncertainty. Permafrost affects terrestrial ecosystems and ground hydrothermal dynamics, biogeochemical cycles, engineered infrastructures, and socioeconomic development to varied extents. Under a warming climate, permafrost has been degrading extensively. Permafrost studies have been flourishing due to increasing concerns on the climatic feedbacks of permafrost carbon, ecological impacts from degrading permafrost, sustainable water supplies, and engineering ramifications.

In permafrost regions, natural and anthropogenic systems are undergoing unprecedented changes, with rapidly thawing permafrost as one of the most striking impacts and also drivers. In addition to the potential adverse effects on global climate, ecosystems, and public health security, warming and thawing of near-surface permafrost may impair critical infrastructures and ecosystems. These could pose serious threats to the logical and efficient utilization of cryogenic resources, to the proper and prudent management of cold regions environments, and to the sustainable and healthy development of northern and highland communities. Some important and rapid progress have been made in the relevant studies. However, these studies are still inadequate in their spatiotemporal extents and resolutions, in assimilation and integration of multi-source data, as well as in predictive numerical modeling. Future research priorities should be thus given to better understanding, modeling, and evaluating thawing permafrost and to a more effective mitigation of its adverse impacts.

To ensure the sustainable development of cold regions under a warming climate, we need to design and manage our environmental and engineering projects scientifically, prudently and adaptively. Meanwhile, we need to research and communicate on the cutting edge of science, technology and engineering practices. Under the theme of Permafrost Environments under Persistent Warming: Challenges for Scientific Assessment and Engineering Practice, the 12th International Conference on Permafrost will be held in Lanzhou, China on 20−24 June 2022. To harvest the proceedings of this conference, this special topic, degrading permafrost and its impacts, is dedicated to the research to understand the degrading permafrost under a warming climate and its impacts. The subjects include: 1) evolution and degradation of permafrost (Liu et al., 2021; Zhang et al., 2021); 2) ecological, hydrological and engineering impacts from degrading permafrost (Jin et al., 2021; Li et al., 2021); 3) adaptation to and sustainability of degrading permafrost environments (Mei et al., 2021; Peng et al., 2021), and; 4) methods and approaches for studying and assessing the degrading permafrost and its impacts (He et al., 2021).

2. Degrading permafrost

Under a warming climate, permafrost has been degrading as evidenced by shrinking areal extent, rising temperature, reducing thickness, melting ground-ice, and extensive thermokarst development, ground-surface subsidence, and thaw settlement. Latest progress in permafrost studies *per se* can be classified into five types: 1) distribution and thermal state of permafrost (Romanovsky et al., 2007, 2010, 2017; Jin et al., 2011; Gruber, 2012; Luo et al., 2016; Biskaborn et al., 2019); 2) hydrothermal dynamics of the active layer (Zhang et al., 2019); 3) landscape changes and freeze-thaw geohazards induced by degrading permafrost (Lewkowicz and Harris, 2005; Kokelj and Jorgenson, 2013; Hjort et al., 2018; Lewkowicz and Way, 2019); 4) geo-ecological and hydrological impacts from degrading permafrost (Bense et al., 2012; Cheng and Jin, 2013; Lamontagne-Hallé et al., 2018), and; 5) adaptive and mitigative measures (Chappin and van der Lei, 2014; Melvin et al., 2017; Ma, 2018).

Long-term data from the Global Terrestrial Network-Permafrost (GTN-P) and Circum-Arctic Active Layer Monitoring (CALM) networks show a general ground warming over

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the last four decades, with the greatest warming rates in the zone of continuous (≥ 90%) and cold (< −1 °C) permafrost, while the zones of discontinuous (< 90%) and warm (< −1 °C) permafrost show a less pronounced warming (Romanovsky et al., 2010, 2017). Global mean annual ground temperature (MAGT) rose by 0.29 ± 0.12 °C during 2007−2016 (Biskaborn et al., 2019). Many locations have experienced the lowering of the permafrost table and talik development (e.g., Jin et al., 2009; Wu and Zhang, 2010; Lebedeva et al., 2019; Luo et al., 2020). Permafrost warming and thawing has occurred in natural, undisturbed conditions (e.g., Marchenko et al., 2006; Romanovsky et al., 2007). Thawing of permafrost formed in the Holocene and Little Ice Age, or older, has been observed at many locations, resulting in enhanced activities of post-cryogenic processes, such as thermokarst, thermal erosion and retrogressive thaw slumps, affecting the stability of ecosystems and infrastructure (Jin et al., 2020; Kokelj and Jorgenson, 2013). Alpine permafrost degradation could weaken the bearing capacities of engineered foundation soils in permafrost regions, leading to the activation of permafrost hazards, such as thaw slumps, mudflows, detachment failures, frozen debris lobes and landslides.

In short, it is evident that: 1) permafrost is warming; 2) there are some places without a noticeable increase, but no known sites for long-term cooling; 3) warming of permafrost is generally at 0.02−0.5 °C per decade in MAGT; 4) ALT is increasing at some locations, and there are many more locations where the active layer no longer freezes completely every year; 6) long-term permafrost thawing has already started at some locations in undisturbed conditions, and; 7) the nature and rate of permafrost degradation differ substantially in different regions.

3. Impacts from degrading permafrost

3.1. Hydrological impacts of degrading permafrost

Degrading permafrost has remarkable impacts on water systems in cold regions. During the past decade, significant progress has been made in studies of hydrogeological impacts of degrading permafrost (e.g., Muskett and Romanovsky, 2009; Cheng and Jin, 2013). Due to its minimal hydraulic conductivity, permafrost strongly affects water dynamics; at the same time, water-flows also exert strong influences on formation, distribution, and evolution of permafrost and talik mainly by heat advection along preferential flow paths (e.g., Jin et al., 2009; Bense et al., 2012; Walvoord and Kurylyk, 2016; Lamontagne-Hallé et al., 2018). This interplay, in addition to feedbacks from physical, chemical, and biogeochemical processes, creates complex permafrost−groundwater interactions.

A solid understanding of hydrogeological changes induced by climate warming and the subsequent permafrost thaw is key to predicting and evaluating the changing ecosystem structures, dynamics and serviceability at local, basin-wide, regional, and global scales, especially for improving our ability to quantify carbon fluxes (Ma et al., 2019a, 2019b). Increasingly more advanced technologies have provided efficient tools for understanding the complex links between surface and subsurface water−systems cycles. Although substantial progress has been made, knowledge gaps remain large. Critical limitations still remain in key data coverage, surface and subsurface characterization, and process-based and integrated models (e.g., Ma and Jin, 2020; Luo et al., 2019; Liu et al., 2021).

3.2. Ecological impacts of degrading permafrost

Permafrost degradation has been changing permafrost ecosystems and the soil-vegetation system. Because of direct ecosystem impacts from permafrost degradation and indirect impacts on carbon and nitrogen cycles and fluxes, more interests are focused on these topics (e.g., Turetsky et al., 2019). Permafrost degradation can result in losses of some boreal forests, shifts in plant composition and productivity, and changes in vegetation communities through changing ecological and hydrological dynamics, soil nutrients, and soil biogeochemistry in an environment of deepening active layer and/or lowering permafrost and groundwater tables (Holloway et al., 2020; Li et al., 2021) and in newly developed taliks.

In turn, these changes have important implications for hydrothermal regimes of near-surface permafrost and active layer through altering the vegetation interception of snowfall and solar radiation and through evapotranspiration changes (Li et al., 2019, 2021). Understanding the ecological impacts of permafrost degradation and their mechanisms is very important for proper simulation and more accurate predictions of ecological successions and coupled C and N cycles in permafrost regions under a warming climate (Jin et al., 2021).

Although there have been some regional and thematic research on ecological impacts of degrading permafrost, impact mechanisms of permafrost degradation on vegetation have not yet been investigated systematically and in-depth. These impact mechanisms are crucial for many stakeholders under a changing climate. Based on about 150 articles mainly published in the latest decade, the review of Jin et al. (2021) focuses more on impacts of degrading permafrost on vegetation and its hydrothermal mechanisms, identifies the inadequacies and provides the priorities in the studies of ecological impacts from degrading permafrost.

3.3. Engineering impacts of degrading permafrost

Rapid and accelerating permafrost degradation has induced thermokarst, thaw slumping, detachment failures, and many other permafrost related hazards, altering the freeze-thaw cycles and impacting the stability and vulnerability of engineered infrastructures (Melvin et al., 2017; Streletskiy et al., 2019). Thawing near-surface permafrost has resulted in the changed serviceability of many basic infrastructures (Hjort et al., 2018; Mei et al., 2021). These impacts of changing stability of infrastructures in permafrost regions needs to be systematically quantified under a persistently warming climate (Jin and Brown, 2007). These evaluation programs should include the relationships between public infrastructures and environments, lifespan, and the operational and maintaining costs of the infrastructures. The rockfalls, debris flows and landslides as results of thawing permafrost and subsequently accelerating mass wasting would severely impact the basic engineering infrastructures, such as those along the China−Pakistan and China−Nepal highways, China−Mongolia−Russia Engineering Corridors, and the proposed high-speed rail-link between Beijing and Moscow (Ma, 2018). In particular, the design, building and safe operation of the Beijing−Moscow High-speed Rail-link has prompted the demand for engineering safety and stability in discontinuous permafrost zones, and greater challenges are laid out for engineers regarding the construction and controlling techniques to sustain the thermal stability of soils in road foundations (Wu et al., 2020).

Thus, we need to study the complex and dynamically changing interactions among the degrading permafrost, regional tectonics and geological structures, geohazards and key engineering infrastructures, and their impacting mechanisms on engineered infrastructures and their long-term serviceability (Mei et al., 2021). The Silk Road over the Ice within the framework of the Road and Belt Initiative would include arctic coastal and sea ice engineering related to the arctic passages, which would inevitably be confronted by thawing and rapidly eroding coastal permafrost. Monitoring and proper management of temporary or short-term snow and ice roads, short- and long-term runways and seaports/platforms, thermo-erosion and slumping of coastal and subsea permafrost would be the key to successful and safe basic infrastructures. In the meantime, comprehensive exploration, exploitation, and transportation of natural resources and energy products in Arctic regions would mandate stern and adaptive strategies and policies on environmental management and protection and on engineering safety and efficiency of mining and transportation.

3.4. Socioeconomic impacts

Most of studies on the impacts from degrading permafrost and climate warming have highlighted the probable adverse aspects (Anisimov, 2016), such as diminishing useable water, declining agricultural and husbandry production, more and severe droughts and wildfires, spreading contagious diseases, re-mobilization of viable microorganisms, and permafrost-hazard-troubled infrastructures, among others. In the last 30 years, scientists, engineers and policymakers have been working hard on trying to mitigate and manage the related hazards and risks through adaptative strategies (Chappin and van der Lei, 2014). In contrast, many consequences of climate change in permafrost regions may also present new benefits. Potential local and regional opportunities have received sustained attention in regional and global studies, such as ameliorated climate and human health, expanding productive vegetation and traffic zones and seasons, larger ranges of ecosystem services, and altered water resources and droughts (Anisimov, 2016). Overall, these changes would more benefit the social and economic development of some northern and highland regions. Comprehensive assessment of the balance between the adverse and beneficial climate-induced and anthropogenic changes in permafrost regions is urgently needed for communities and stakeholders, especially those gaining immediate and often short-term benefits from the new local to regional opportunities. It may be questionable to assert global challenges from climate change. Because the impacts of climate change are region- and/or group-specific, pinpointed adaptation strategies are more pertinent and readily adopted; there is simply no panacea for the adaptation to climate changes at all levels.

Rapid and extensive climate warming in permafrost regions has become the key to dramatic and massive impacts on natural-social coupled systems. These changes might be greater than the systematic adaptability. In addition, limited abilities and less reliable climate projections further complicate adaptative approaches. In this case, regional strategies are generated for local adaptation with some net social and economic gains. While climatic change and permafrost degradation have already led to great impacts, policymakers, business society, and population are reluctant and slow in making decisions and changes, or in prioritizing climate adaptation. In recent years, some scholars have been focused on advising governmental policymakers. However, scientists should focus more on educating the public awareness regarding climate warming and ensued permafrost degradation and the adaptative strategies and mitigative measures.

4. Mitigative measures and adaptive strategies

Climate-induced permafrost degradation is causing dramatic environmental changes, increasing the vulnerability of infrastructure. Economic impacts of permafrost degradation have been evaluated in many regions or disciplines, such as those on cold regions infrastructures under various climate scenarios. Additionally, proactive adaptation has influenced economic impacts on selecting infrastructure types and first-order estimates of potential property and other economic losses, such as those associated with coastal erosion or elongated ice-free season, have been studied for some arctic communities (Melvin et al., 2017). Cumulative expenses from climate-induced damage to unadapted infrastructures may be huge in permafrost regions in the future. Extensive damages to linear infrastructures and buildings in association with thawing of near-surface permafrost and the resultant supra-permafrost subaerial talik formation would happen, but smaller damages to the foundations of airports, railroads, and pipelines have been observed and more are anticipated. Proactive adaptation would help effectively reduce total lifespan project expenditures induced by persistent climate warming and permafrost degradation.

An improved approach to more accurately predict and evaluate climate-induced damages to basic facilities deems urgent and promising. Additional predictive modeling capabilities for more reliably and accurately catching damages to ports, telecommunications, and other infrastructure types would provide a more integrated evaluation of vulnerability and damage (Melvin et al., 2017; Hjort et al., 2018; Streletskiy et al., 2019). Additionally, analysis for community-level evaluation at a finer resolution is very important for better evaluating damages resulting from the thaw of both near-surface and deeper, ice-rich permafrost. It is thus suggested that, in permafrost regions, we would need to proactively adapt the design, construction, operation and maintenance of engineered infrastructures in the near-term for dramatical reduction of damages in the 21st century. In addition, variations and trends in the progressive stages of damages and adaptative benefits to different infrastructures may help decision-makers to prioritize their investments.

5. Summary

At present, permafrost occurs on one-quarter of the exposed land surfaces on the earth, but the permafrost extent and its estimate have been changing rapidly. Under a warming climate, permafrost has been degrading extensively, persistently, and rapidly. This degradation of permafrost has resulted in profound hydrological, ecological, and socio-economic consequences. To sustainably develop resources in the cold regions while prudently protect the permafrost environment under a constantly changing climate, we need to design and manage our environmental and engineering projects by creative and innovative thinking and with rapidly improving technologies. The articles in the special issue are important for understanding the changing permafrost environment and proactively adapting to and effective management of these rapidly changing cold regions environment with the latest technologies.

Declaration of competing interest

The authors declare no conflict of interest.

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