



Permafrost degradation on a warmer Earth: Challenges and perspectives

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Abstract

Permafrost, the permanently frozen ground, is warming due to global temperature rise. Permafrost research has progressed rapidly in the last decade, as large areas in the Polar Regions, in mountain environments and on high-altitude plateaus are experiencing accelerated environmental changes in response to thaw and permafrost degradation. Climate scenarios for the next decades project a reduced the extent of permafrost coverage and increasing ground temperatures, promoting changes in terrestrial and nearshore ecosystem dynamics. Future research in permafrost regions should focus on a better understanding of the biogeochemical cycles associated with abrupt and long-term permafrost degradation. Risk assessment of natural hazards and geoenvironmental engineering solutions are needed to reduce the potential dramatic socio-economic implications that permafrost degradation may entail in these regions.

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Current Opinion in Environmental Science & Health 2018, 5:14–18

This review comes from a themed issue on **Sustainable Soil Management**

Edited by Paulo Pereira and Juan Martinez-Murillo

For a complete overview see the [Issue](#) and the [Editorial](#)

<https://doi.org/10.1016/j.coesh.2018.03.007>

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Keywords

Permafrost, Frozen ground, Polar regions, Mountains, Climate.

Introduction

Permafrost – defined as the ground that remains below 0 °C for at least two consecutive years [1] – extends over a surface of $22 \pm 3 \cdot 10^6$ km², mostly in the northern hemisphere, and therefore constitutes one of the most widespread components of the cryosphere [2]. The current distribution of permafrost conditions includes high latitude regions, together with high mountain regions and high-altitude plateaus in mid- and low-latitude environments [3]. However, geomorphic evidence of past permafrost conditions shows that the area affected by frozen ground during Quaternary cold

stages, such as the Last Glaciation, was much larger than today [4,5].

In this paper, we examine recent trends in permafrost research as well as the new challenges that the changing climate will pose to permafrost environments in the forthcoming decades.

The last decade in permafrost research

The 4th International Polar Year (IPY 2007–2008) favored a substantial increase in the number and in the multidisciplinary design of permafrost studies (Fig. 1). Due to the large extent occupied by permafrost in the high latitudes of the northern hemisphere and the need of Arctic states to manage risks and opportunities arising from environmental change in the northern circum-polar regions, Arctic permafrost is the best examined permafrost region, e.g. [6–8].

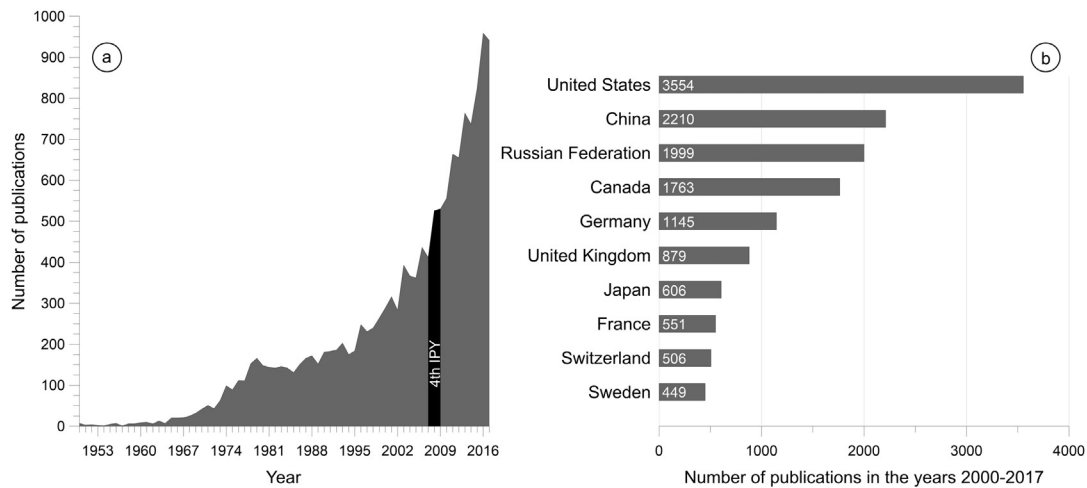
Recently, mountain permafrost and its degradation is becoming a key research topic as temperatures in high-elevation environments are increasing more rapidly than in the lowlands [9] in parallel to increased tourism pressure in these areas, which might trigger catastrophic natural hazards associated with rockfall and mudflow, e.g. [10]. In Antarctica and on high altitude plateaus, significant advances have been achieved in research on the distribution and thermal properties of permafrost, e.g. [11–14].

Since the IPY, permafrost research has focused on several key topics:

- (1) Mapping and modeling of permafrost distribution, e.g., [2,15,16].
- (2) Monitoring of thermal properties of the permafrost and active layer, e.g., [17–20].
- (3) Geomorphological processes and natural hazards, e.g., [10,21,22].
- (4) Biogeochemical and ecological shifts driven by permafrost changes, e.g., [7,23–25].
- (5) Geotechnical and engineering issues for hazard assessment and the construction of sustainable infrastructures in permafrost regions, e.g., [26–28].
- (6) Geopolitical and management policies to mitigate some of these changes, e.g., [29,30].

Most of the studies highlight the sensitivity of permafrost environments to changing climate and land-use transformations, pointing out the need to better

Fig. 1



Permafrost publication statistic (a) from 1950 until 2017 and (b) permafrost-related publications between 2000 and 2017 by country. The query was done in Scopus using the keywords “permafrost” and/or “frozen ground” in articles and reviews as publication type. Query words were applied to the title, abstract and keywords of the publications.

understand its role as key component of the cryosphere as well as its interactions with other processes, namely the climate system.

Challenges and perspectives

The air temperature increase recorded over the last decades in permafrost regions is impacting permafrost temperatures, which are rising globally and favoring a deepening of the active layer. Since the International Polar Year (IPY) 2007–2008, the global mean permafrost temperature increased by 0.31 ± 0.10 °C per decade, with an increase of 0.46 ± 0.15 °C in the continuous permafrost zone near the depth of zero annual amplitude, 0.21 ± 0.09 °C in the discontinuous permafrost, 0.19 ± 0.05 °C in mountain permafrost and 0.37 ± 0.10 °C in Antarctic permafrost [31]. This has major implications for geomorphological, hydrological and biological processes in permafrost regions [6,32], but it may also have large consequences for climate at global scale through permafrost thawing in the Arctic and associated feedback processes [33,34].

The continuation (and possible acceleration) of this warming trend recorded over the last decades may imply a significant reduction in the surface underlain by the permanently frozen ground [35]. Some permafrost regions are predicted by climate models to warm more intensely over the next decades. Consequently, the scientific community needs to generate more data to better understand the negative and possibly catastrophic effects this warming trend may have for the whole climate system, in order to anticipate and mitigate its consequences as much as possible. Depending on the rates of warming, the area occupied by permafrost

near the surface (3.5 m depth) might be reduced by between 37% and 81%, and thus retreats to higher latitudes and higher elevations are expected [36]. Consequently, most high latitude environments conditioned nowadays by the presence of permafrost will be affected by the changing climate that will make it disappear or lead to a deepening of the active layer along with higher subsurface temperatures [37].

Permafrost thawing, particularly in regions where ground temperatures are close to 0 °C, may have implications on biogeochemical fluxes and affect the carbon cycle and greenhouse gas fixation, namely CO₂, CH₄ and N₂O, e.g., [34,38–40]. Turning permafrost from a greenhouse gas sink into a source, these positive feedbacks may accelerate in the future and therefore reinforce the degree of future global warming already anticipated by international reports [36]. However, there are still large discrepancies about the rate and magnitude of the contribution of thawing permafrost to greenhouse gas emissions, which may condition smoothed, progressive or threshold-type environmental and climatic responses.

In many areas, particularly in some highly populated Arctic regions, socioeconomic activities are already affected by permafrost thawing and degradation. Ground instability is impacting the dense network of equipment and infrastructures existing in these regions [22,41,42]. With the warming climate anticipated during the next decades, it is expected that permafrost degradation will increase in these regions and therefore local, regional and national administrations will have to invest large sums to adapt the infrastructures to the changing landscape [37,42,43]. Implementing an

integrated approach combining scientific knowledge on permafrost dynamics and engineering advances is crucial to manage strategies to balance the construction of infrastructures and human development in a changing climate and provide geosystem and ecosystem services [8].

Apart from the impact on human livelihood, permafrost degradation is also expected to accelerate the effects on the natural dynamics of terrestrial ecosystems, by affecting geomorphic processes, hydrological dynamics of rivers, ponds and lakes as well as altering biodiversity in many areas. There is increased evidence that marine ecosystems will be also affected by the degradation of both terrestrial and subsea permafrost [44] as well as permafrost collapse in Arctic coastal environments [7]. Consequently, there is increased need to combine microscale experiments and large-scale remote sensing activities in order to better understand the interactions of the different land systems in changing permafrost landscapes at multiple scales.

Permafrost thaw will also affect biological dynamics in a wide range of processes; some of them are still poorly understood. There is increasing evidence of the complex diversity and functionality of the permafrost microbiome, and the impacts that thaw may have on greenhouse-gas emissions in response to accelerated microbial turnover [45]. Furthermore, a deepening of the active layer will also increase the risks of the emergence of zoonotic infectious diseases [46] or even the release of pathogenic DNA viruses stored in the permafrost [47]. Consequently, permafrost scientists need to examine the impacts of potential infectious diseases spreading across the Arctic in a warming climate and also to raise awareness of the threats that this trend may pose to local communities [46].

Conclusions

We conclude that permafrost research must be also seen as an opportunity to bridge the gap between science and society. The media response about permafrost degradation has drastically increased in recent years and contributes to raise awareness of the challenges related to a regional phenomenon of global importance. The threats posed by permafrost degradation in northern societies have become a central research focus in the scientific community, so that involving local and traditional knowledge via research co-design and stakeholder consultation is becoming a new paradigm in permafrost science. Beyond scientific literature products, education and outreach activities should not be underestimated to communicate our findings into society and to reach out for feedback [48]. Ultimately, a better understanding of permafrost evolution in a changing climate is of utmost importance, both from a local and global perspective.

Acknowledgments

Marc Oliva is supported by the Ramón y Cajal Program and the PALEO-GREEN project (CTM2017-87976-P), both funded by the Spanish Ministry of Economy and Competitiveness (RYC-2015-17597), as well as by the research group ANTALP (Antarctic, Arctic and Alpine environments). The work of Michael Fritz is supported by the Daimler and Benz Foundation (grant number 32-02/15). This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 773421 (NUNATARYUK).

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