On the (melting) rocks: climate change and the global issue of permafrost depletion

Walter Leal Filho[1,2], Maria Alzira Pimenta Dinis[3,4], Gustavo J. Nagy[5], Umberto Fracassi[6]

Science of the Total Environment 903 10 Dec 2023

https://www.sciencedirect.com/science/article/abs/pii/S0048969723052403?dgcid=rss_sd_all

1. Walter Leal Filho. Research and Transfer Centre “Sustainable Development and Climate Change Management" Hamburg University of Applied Sciences, Germany, e-mail: walter.leal2@haw-hamburg.de; ORCID: 0000-0002-1241-5225

2. Department of Natural Sciences, Manchester Metropolitan University, Chester Street, Manchester M1 5GD, U.K.

3. Maria Alzira Pimenta Dinis. UFP Energy, Environment and Health Research Unit (FP-ENAS), University Fernando Pessoa (UFP), Praça 9 de Abril 349, 4249-004 Porto, Portugal

4 Fernando Pessoa Research, Innovation and Development Institute (FP-I3ID), University Fernando Pessoa (UFP), Praça 9 de Abril 349, 4249-004 Porto, Portugal; E-mail: madinis@ufp.edu.pt; ORCID: https://orcid.org/0000-0002-2198-6740

5. Gustavo J Nagy.Instituto de Ecología y Ciencias Ambientales, Facultad de Ciencias, Universidad de la República (FC-UdelaR), e-mail: gnagy@fcien.edu.uy; ORCID: 0000-0002-8296-4465, Iguá 4225, Montevideo, Uruguay.

6. Umberto Fracassi. Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605, 00143 Rome, Italy, E-mail: umberto.fracassi@ingv.it; ORCID: 0000-0001-7102-514X

Permafrost thawing due to climate change can affect **or upend several aspects associated with life and prosperity on Earth, demanding far greater attention. Some suggestions are provided for reducing the impacts of permafrost depletion.**

Permafrost is essential in the Arctic region as it plays a significant role in undergirding the ground, thus supporting infrastructure and countering erosion, which can be globally impactful[1,2]. In addition, permafrost is vital in storing carbon[3]. However, in the past few decades, the Arctic has experienced increased temperatures, driving permafrost to thaw and releasing greenhouse gases (GHGs) into the atmosphere[3]. The thawing of permafrost has large-scale environmental implications and impacts the economy and culture of coastal communities and beyond[2,4,5]. Figure 1 presents an overview of the ice thickness in the northern hemisphere. The dataset contains permafrost active layer thickness data produced in the European Space Agency's (ESA) Climate Change Initiative (CCI) Permafrost project.

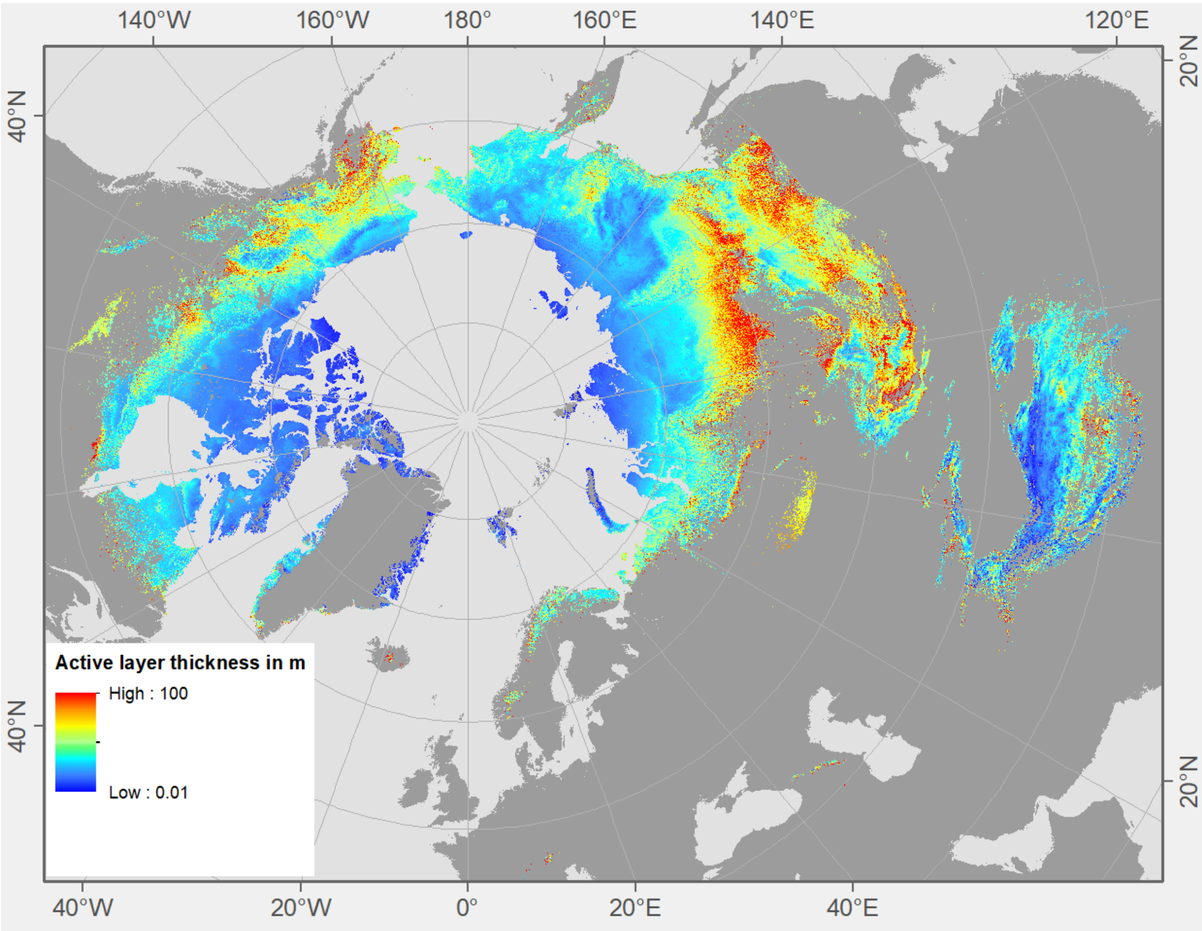

Fig. 1. Permafrost active layer thickness for the Northern Hemisphere, v3.0 from MODIS LST, ERA5, 1997-2019. Source: AWI, Germany

The intensive, ubiquitous burning of fossil fuels since the mid-1800s has led GHGs to spike in the atmosphere, responsible for the permafrost melt in various areas, including the

Arctic[6,7]. Between 2007 and 2016, for instance, the ground temperature near the depth of zero annual amplitude in the continuous permafrost zone increased by 0.39 ± 0.15 °C[8].

Due to decreasing ice cover over most Arctic regions, the 'snow-ice albedo feedback' has been affected. As a result, less solar radiation is reflected, and more heat is absorbed on the surface, causing further warming and thus increasing permafrost thawing[9].

Permafrost contains carbon-based organic matter, consumed by microorganisms whenever it thaws, releasing methane and other gases[10], which, in turn, impacts microbial communities[4]. Moreover, the current permafrost thaw will likely intensify under this century's projected global warming, releasing GHGs that will exacerbate the problem. Since soil respiration responds to warming more strongly in colder climates than in warmer ones, these emissions are of particular concern[12], resulting in increased CO_2 emissions and CH_4[13], thus intensifying climate change.

The impacts of permafrost thaw

Continuous and discontinuous permafrost covers about 24% of the land surface in the northern hemisphere[14,15]. Retreating and spatial shifting in the distribution of frozen ground alters the forest cover, hydrology, species habitats and human life in the areas affected[16]. The thawing of permafrost not only exerts consequences on terrain, ecosystems and infrastructure but may also delay or impair international efforts concerning sustainable development[17] and CO_2 abatement[3,18], influencing the various climate scenarios[5]. Figure 2 captures the multi-faceted, diverse impacts of permafrost depletion.

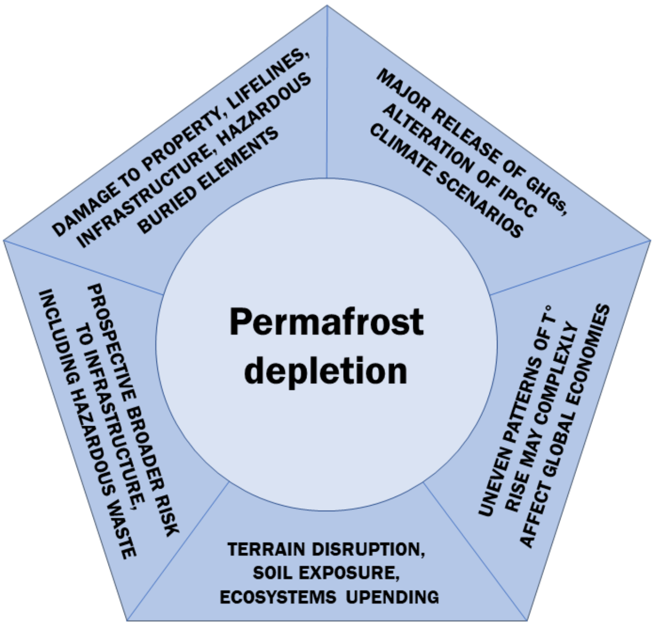

Fig. 2. Physical and geophysical consequences of permafrost depletion.

The anatomy of the rock and sub-soil structure involved in how permafrost unfolds, and the spatial extents, geometry, and shallow-seated mechanism of how the affected terrain ruptures due to thawing[15], unveils a peculiar shallow behaviour. For instance, thawing has waned the concrete integrity of ground/foundations where infrastructure has been built over the decades[17,19]. Threats to existing infrastructure related to permafrost thawing include active layer thickenings and thaw-related hazards, such as thermokarst and mass wasting[7,11].

The risk of permafrost-related degradation will likely increase significantly by 2050, with infrastructural impairment already documented in swaths of Russian territory, where many buildings are experiencing damage. For example, in the Qinghai-Tibet Plateau, 30% of roads were reported to have been affected[17]. In addition, the risk of structural damage and leakage of hazardous waste is projected to be very significant over the following decades, whatever the reference climate scenario[19].

Apart from causing terrain rupture and ensuing damage to the built environment, permafrost thawing has been driving vast alterations to the natural landscapes of the northern regions since the 1960s[18]. In high-altitude areas hosting glaciers, rapid transformation due to permafrost degradation has led to the onset of new lakes and drainage networks, with ensuing reduced slope stability that may further trigger flooding due to mobilised deposits and water mass[20], ultimately adding potential strain to infrastructure and human life in the exposed regions.

The thawing of permafrost releases chemical, biological and radioactive components that have been locked under various forms in both the cryosphere and the geosphere over the 10^3-10^5 yr span, resulting in vast disruptions of ecosystems, altered wildlife populations and prospective endangerment to the human health[5,21].

Permafrost thaws at different rates[5], and slower thawing tends to affect the shallower, more recently frozen layers of soil, rock and ice, penetrating the deeper sections of permafrost. However, abrupt thawing, capable of dismantling whole rock and soil sections, affects older, deeper layers[18]. While the thawing phase depends on temperature and precipitation changes and may occur gradually, the rate increases as temperatures are consistently higher – all the more in Arctic regions – and vast areas and volumes can be lost per decade[22].

Moving forward: addressing an issue more global than commonly perceived

The rapid depletion of permafrost in the Arctic threatens efforts to reduce global warming. In addition, it heightens climate change in other regions[5,10], to the extent that may elude – both in space and time – the assumed geographic boundaries of cold permafrost regions "up North". This has contributed to a somewhat slow and sparse perception throughout societies of the phenomenon, its long-time onset, and its cascading spatial effects, despite ample literature[5].

Abrupt thawing occurring through extreme temperature fluctuations can expose older permafrost horizons more rapidly than earlier estimated. Depending on local conditions and the rock and soil fabric involved, such a phenomenon may initiate the release of compounds from deeper layers much faster than expected[18].There are also concerns that permafrost degradation will eventually expose ancient burial sites, thus possibly reviving vectors that, under present-day temperature conditions, could spread deadly infections or allow the re-emergence of pathogens, thus endangering human health[23]. Therefore, actionable, effective solutions are needed to slow down the rate at which permafrost thawing grows – including the engagement of the public discourse.

Some of the measures which may help to handle permafrost thawing are:

a) **Installing permafrost insulation** to shield permafrost from the heat of the sun and other environmental factors affecting the terrain's integrity. This could include insulation boards and thermal blankets around buildings, pipelines, and other structures built on permafrost.

2. **Planting more cover crops** can help to keep permafrost cool and stabilise the ground. Perennial grasses and trees can provide shade, which can help reduce the permafrost thaw rate. In addition, these plants may help to keep the soil moist and add organic matter to help improve the soil quality.

3. **Facilitating groundwater recharge** can help keep permafrost cool and reduce the thaw rate. This can be attained by constructing rainwater harvesting systems and using porous pavings to increase the amount of rainwater stored in the ground.

4. **Improving snow cover** can help keep permafrost cool and reduce the thaw rate. This can be done by planting trees and shrubs to create shade or using snow fences to accumulate snow and reduce the speed at which it melts.

Permafrost melting is an urgent environmental issue, as it can contribute to global warming and impact the environment in a diverse range of issues across vast regions. It is crucial to reduce emissions of GHGs, which are critical drivers of permafrost melting, to address this issue. It is also essential to understand the local impacts of permafrost melting, such as increased flooding, erosion, and water and soil contamination. In some areas, protecting infrastructure, ecosystems, and communities from the effects of permafrost melting may be necessary. Finally, it is vital to monitor permafrost to detect early signs of melting so that appropriate measures can be taken.

References

1. Beer, C., Zimov, N., Olofsson, J., Porada, P., & Zimov, S. (2020).
2. Larsen, J. N et al.. *Sustainability, 13*(5). (2021)Schuur, E. A. G. et al.. *Annual Review of Environment and Resources, 47*, 343-371. (2022)
3. Schuur, E. A. G. et al. (2022). Annual Review of Environment and Resources, 47, 343-371. doi:10.1146/annurev-environ-012220-011847
4. Lamoureux, S. F., & Lafreniere, M. J.. *Wiley Interdisciplinary Reviews-Water, 5*(1). (2018).
5. Intergovernmental Panel on Climate Change (IPCC). (2022). The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University
6. Friedlingstein, P. et al.. *Earth System Science Data*, *11*(4), 1783–1838. (2019)
7. Schuur, T.. Scientific American, 315(6), 56-61. (2016)
8. Biskaborn, B. K. et al.. *Nature Communications*, *10*(1). (2019)
9. Riihelä, A., Bright, R. M., & Anttila, K.. Nature Geoscience 14:11, 14(11), 832–836. (2021)
10. Masyagina, O. V., & Menyailo, O. V. (2020). Environmental Research, 182.
11. Schuur, E. A. G. et al.. Nature, 520(7546), 171–179. (2015)
12. Carey, J. C. et al. (2016). Proc Natl Acad Sci U S A, 113(48), 13797-13802.
13. Grant, R. F., Mekonnen, Z. A., Riley, W. J., Arora, B., & Torn, M. S.. *Journal of Geophysical Research-Biogeosciences, 124*(5), 1323-1341. (2019)
14. Brown, J., O. Ferrians, J. A. Heginbottom, & E. Melnikov (2002). Boulder, Colorado, USA. National Snow and Ice Data Center.
15. Smith, S.L., O’Neill, H.B., Isaksen, K., Noetzli J. & Romanovsky V.E. Nature Rev. Earth Environ., 3, 10-23 (2022).
16. Czerniawska, J., & Chlachula, J.. Arctic, 73(4), 509-528. (2020)
17. Hjort, J. et al. M.. *Nature Reviews Earth & Environment, 3*(1), 24-38. (2022)
18. Turetsky, M. R. et al. 569(7754):32-34. In: Nature Publishing Group. (2019)
19. Langer, M. et al.. Nature Commun., 14, 1721. (2023)
20. Haeberli, W., Schaub, Y., & Huggel, C.. Geomorphology, 293, 405-417. (2017)
21. Miner, K. R. et al.. *Nature Climate Change, 11*(10), 809-819. (2021)

22. Turetsky, M. R. et al. *Nature Geoscience, 13*(2), 138-143. 2020)

23. Huber, I. et al.. *International journal of circumpolar health, 79*(1), 1715698. (2020)