# Permafrost Thaw and Adapting to its Multiple Effects in the Arctic

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*In the Arctic, climate warming causes permafrost degradation. Thawing permafrost has significant effects on human health and well-being, infrastructure, ecosystems, and climate, from local to global scales. Here we provide examples of the many consequences of permafrost thaw in the Arctic permafrost region, paying particular attention to conditions in the Nordic and Russian Arctic, and interactions between the different effects. We discuss approaches used in adaptation to permafrost degradation from technological solutions to institutional and behavioural change. Our findings suggest that in-depth understanding of the various feedbacks and cross-border effects are required to adapt to the multiple effects of the thawing of permafrost. Successful adaptation requires coherence between the approaches and dialogues between stakeholders.*

## Introduction: Arctic warming and permafrost thaw

Permafrost is defined as ground (soil or rock and embedded ice or organic material) that remains at or below 0°C for at least two consecutive years. Permanently frozen ground underlies roughly 15% of the exposed land areas in the northern hemisphere, most of the Arctic land area and extends under parts of the Arctic Ocean (AMAP, 2017; Ran et al., 2022).

In the Arctic the climate warming exceeds the global average due to the Arctic amplification (Pithan & Mauritsen, 2014), and causes permafrost degradation (IPCC, 2019). Permafrost thaw has been investigated using in situ measurements, various modelling approaches and analysis of

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satellite data (Guo & Wang, 2016; Aalto et al., 2018; Biskaborn et al., 2019; Udawalpola et al., 2021). Severe thawing, i.e., accelerating abrupt permafrost thaw, takes place in locations which have been identified as hot spots of permafrost thaw (Miner et al., 2022), e.g., Greenland, Siberia, and Svalbard.

Temperatures in the permafrost have risen by up to 2°C over the past two to three decades, particularly at colder sites (Romanovsky et al., 2017). The depth of soil above the permafrost that seasonally thaws each year, i.e., the active layer, has increased in Scandinavia, Arctic Russia west of the Urals, and inland Alaska, according to the assessment of Miner et al. (2022). Furthermore, the southern limit of the permafrost retreated northward by 30 to 80 km in Russia between 1970 and 2005, and by 130 km during the past 50 years in Québec, Canada (AMAP, 2017). The observed trend of ground temperature in the continuous permafrost zone follows the air temperature trend in the Northern Hemisphere (Lappalainen et al., 2022). IPCC (2019) concludes that about 20% of Arctic terrestrial permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is expected to increase small lake area by over 50% by 2100 for RCP8.5 (medium confidence). Permafrost thaw can increase topsoil conditions favourable for dust emission and thus create new environmentally and climatically significant high latitude dust sources (Meinander et al., 2022). This is explained in Meinander et al. (2022) to result from climate change (warming) which causes permafrost thaw, decreases snow cover duration, and increases drought, glacial melt, and heatwave intensity and frequency – all leading to increasing the frequency of topsoil conditions favourable for dust emission (increasing soil's exposure to wind erosion) and the probability of dust storms. In their example on Svalbard, the accelerated ablation of Svalbard's glaciers and the permafrost thaw are causing accelerated growth in periglacial and proglacial areas and increasing morphogenetic processes of deflation, denudation, and sediment transport on slopes and in river channels in glaciers' marginal zones. Thus, according to Meinander et al. (2022), these areas have become potential sources of dust.

Thawing permafrost has important effects on human health, infrastructure, ecosystems, and climate, from local to global scales (Arneth et al., 2010). As permafrost thaws, greenhouse gases are released, which enhances climate warming. This is one of the several Arctic feedback mechanisms which amplify Arctic climate change (Koven et al., 2011). MacDougall et al. (2012) have estimated that permafrost thaw would induce an additional impact of 0.24 (0.10–0.69) °C by the end of this century (rcp4.5).

General effects of permafrost thaw have been assessed by the Intergovernmental Panel on Climate Change, IPCC (IPCC 2019; 2021) and of the Arctic Council's Arctic Monitoring and Assessment Programme, AMAP (AMAP, 2017). Effects on ecosystems have been assessed in reports of the Arctic Council's working group Conservation of Arctic Flora and Fauna (CAFF). The European Arctic EU-INTERACT program also provides recent updates on permafrost (Callaghan et al., 2021). Regionally, effects of climate change can be investigated with the help of the IPCC WGI Interactive Atlas (IPCC, 2021), available at http://Interactive-atlas.ipcc.ch. There is high confidence that the cryosphere amplifies climate changes through snow, ice, and permafrost feedbacks, and thawing of permafrost involves thresholds (state changes) that allow for abrupt, nonlinear responses to ongoing climate warming (IPCC, 2019). The same report also points out that projected permafrost thaw (and decrease in snow cover extent and duration) will affect Arctic hydrology and wildfires, with impacts on vegetation and human infrastructure (medium confidence). Even as the overall regional water cycle intensifies, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in snow and permafrost may lead to soil drying (medium confidence), and wildfire frequency is projected to increase (medium confidence). By 2050 70% of Arctic infrastructure is projected to be in regions at risk from permafrost thaw and subsidence, and it is estimated that adaptation measures taken in advance could reduce by half the costs arising from thaw and other climate change related impacts, including increased flooding, precipitation, and freeze-thaw events (medium confidence - IPCC, 2019).

In the Arctic, hydrological changes, overall greening, and regional browning of tundra and boreal forests, are expected to follow from permafrost thaw and snowfall decrease (IPCC 2021, high confidence). Examples of other permafrost thaw impacts listed in IPCC (2021) include: disruption to economically important transportation and supply-chain infrastructure to remote Arctic settlements; increasing risks to economies and to Arctic tourism including tourism to cultural heritage sites; changes in submarine permafrost, critical to mining infrastructure such as pipelines and offshore structures, which are expected to increase production costs and impact worker safety; and increased vulnerability of Siberian nomadic reindeer herding and fishing livelihoods.

Hence, there is a broad general understanding and there are numerous examples of the consequences of permafrost thaw, but analyses of the possibilities to adapt to permafrost thaw are only emerging. The aim of this study is to provide examples of the effects of permafrost thaw in the Arctic permafrost regions, paying special attention to Greenland, Siberia, and Svalbard, and to discuss options for adapting to the thawing of permafrost. We focus on effects that have immediate societal relevance, i.e. impacts on infrastructure (including the built environment and communities), environment (including ecosystems and ecosystem-atmosphere feedbacks), sources of livelihood, economy, and health. The literature survey was prepared by the members of the IBA-Permafrost project (https://en.ilmatieteenlaitos.fi/iba-project).

## Effects of permafrost thaw

In this section we systematically examine the effects of permafrost thaw on societies and ecosystems, based on literature, and including the Eurasian Arctic permafrost thaw hot spots of Greenland, Siberia, and Svalbard. We explore the following topics: effects on infrastructure; effects on health; effects on ecosystems and ecosystem-atmosphere feedbacks; examples of recent findings in Siberia, Greenland, and Svalbard. We conclude with a section on cross-border impacts of permafrost thaw and interactions between the different effects (Figure 1).

### Effects on infrastructure

Permafrost change imposes various threats to infrastructure through warming, active layer thickening and thaw-related hazards, such as thermokarst and mass wasting. Permafrost thaw can demolish buildings and roads, potentially causing tens of billions of dollars additional costs to Arctic infrastructure in the near future. Poor design in the past may also be a contributing factor and the process of construction can itself thaw permafrost, but the effects are greatly exacerbated by climate change. Transport and energy infrastructure, such as railways and oil and gas pipelines, appears to be the most vulnerable. Infrastructure maintenance and repair costs related to the loss of permafrost's carrying capacity could reach approximately $30 billion USD in the Arctic by 2060 (Hjort et al., 2022).

Access to many areas becomes more difficult as ice roads melt earlier and freeze later and as permafrost degrades (AMAP, 2017). Consequently, industrial operations relying on ice roads and frozen ground will need to concentrate heavy load transport into the coldest part of the year. Shorter seasons where ice and snow roads can be used impact communities that rely on land transport of goods to maintain reasonable retail costs and ensure economic viability. In the Eurasian Arctic region, this is the case particularly in Russia (AMAP, 2017). New design methods are being developed that consider the likelihood of environmental change.

Hjort et al. (2018) project that risks from permafrost thaw will be disproportionately high for industrial infrastructure along major pipeline systems in Alaska and natural gas extraction areas in the Yamal-Nenets region in north-western Siberia, Russia, by mid-century. In Russia, 54% of residential buildings are projected to be affected by significant permafrost degradation by the mid-century (Streletskiy et al., 2019).

Except for the negative economic effects of thawing permafrost on infrastructure, economic opportunities also arise. Engineering solutions can mitigate the effects of degrading permafrost, although their economic cost is often high. The large-scale physical changes that are underway in the Arctic are likely to lead to substantial investments into new infrastructure in the Arctic region, with the potential to generate multi-billion-dollar annual revenues over the coming years and decades. However, investment decisions in the Arctic are particularly difficult due to its restricted geographic access, environmental concerns, highly contrasting seasons, and constrained markets, as well as the fact that many projects are transborder in nature since they include several Arctic states, giving rise to sensitive geopolitical issues (Alvarez et al., 2020).

### Effects on health

Climate change and related changes to ecosystems may impact human health in various ways, including through infectious diseases (Parkinson et al., 2014). In a review for the Arctic, increasing temperature and precipitation were projected to have the greatest health impacts via infectious diseases such as tularemia, anthrax, vibriosis and various tick-borne diseases (Waits et al., 2018). For instance, the dynamics of environmental factors that led to an anthrax outbreak in the Yamal Peninsula, Siberia, during 2016 have been investigated by Ezhova et al. (2021). They found that the local permafrost was thawing rapidly for the previous 6 years before the outbreak, supporting the hypothesis that permafrost thaw contributed to this outbreak, and that the spread of anthrax was likely intensified by the extremely dry summer of 2016 in the region.

Thawing permafrost may also lead to the release into the environment of biological, chemical, and radioactive materials that have been sequestered for tens to hundreds of thousands of years, which also could pose a risk to human health (Miner et al., 2021). Thawing soils may release viable viruses, bacteria, fungi, and other microorganisms. They may belong to previously unknown microbial species, unknown genotypes of present pathogens, already eradicated pathogens, or even known pathogens that gained extremely robust characteristics due to their subjection to long-term stress (El-Sayed and Kamel, 2021). Moreover, it has also been suggested that a significant sub-Arctic population could be exposed to radon levels dangerous to health because of climate change thawing of permafrost, with implications for health provision, building codes, and ventilation advice (Glover and Blouin, 2022). Permafrost thaw may also adversely affect mental wellbeing issue through changes in environment and livelihoods in the Arctic (Hueffer et al., 2019; Cunsolo Willox et al., 2015).

Permafrost thaw leads to amplification of climate change in the Arctic and Northern areas, and therefore impacts on human health should be considered more widely. Changes in the exposure to thermal stress result in changes in temperature-related mortality and morbidity. In the last decades there has been an increase in occurrences of heatwaves in the terrestrial Arctic, and since 2002 the probability of experiencing heat waves in the Arctic is similar to lower latitudes (Dobricic et al., 2020). People adapt to the climatic conditions of their living environment. Therefore, adverse impacts of heat stress appear in the Arctic at lower temperature levels than in warmer regions to the south, and more frequent and intense heat waves due to climate change will increase heat-related health impacts (Ruuhela, 2018). However, in high-latitude countries people presumably can adapt to gradually changing average thermal conditions, and the health risks are related to hot and cold extremes of the future climate.

Ma et al. (2021) identified six climate-sensitive infectious diseases relevant for the Arctic and northern regions, namely borreliosis, leptospirosis, tick-borne encephalitis (TBE), Puumala virus infection, cryptosporidiosis, and Q fever. In another study, Campylobacter infections (commonly associated with contamination of food and leading to diarrhoea) are expected to increase due to climate change and Nordic countries may experience a doubling of cases by the end of the 2080s (Kuhn et al., 2020).

A regional One Health approach has been suggested (e.g., Ruscio et al., 2015; Hueffer et al., 2019) for assessing interactions at the Arctic human-animal-environment interface to enhance the understanding of, and response to, the complexities of climate change on the health of the Arctic inhabitants.

## Ecosystem processes and ecosystem-atmosphere feedbacks

Permafrost thaw has a wide range of effects on ecosystems and ecosystem services (Schuur and Mack, 2018). In some cases, the impacts may change ecosystems in different directions. For example, with increasing air temperatures and changing precipitation patterns, the thawing of ice-rich permafrost is expected to increasingly alter hydrological conditions by creating mosaics of wetter and drier areas (Kwon et al., 2016). Some wetlands may drain and dry out, whereas elsewhere thawing may create new wetlands (AMAP, 2017). In the long-run, ecologically valuable permafrost habitats such as palsa mires may totally disappear from northern Fennoscandia during the 21st century (Fronzek et al., 2011; Aalto et al., 2017). The decline of cryospheric habitats such as sea ice and wetlands over permafrost can have far reaching consequences by affecting the habitats and populations of migratory species of mammals and birds (AMAP, 2017).

Fewster et al. (2022) have recently presented that permafrost peatlands (i.e. palsa mires) in sub-Arctic Europe and Western Siberia would soon surpass a climatic tipping point, i.e. the complete loss of their suitable climate envelope) under scenarios of moderate-to-high warming. Of the ecosystem services, forestry may benefit from thawing permafrost in areas where there is enough water for trees to grow, but at the same time the heating may increase damages from insect pests (AMAP, 2017).

The links between permafrost thaw and fluxes of greenhouse gases are complex. Lappalainen et al. (2022) summarise and discuss the rate of permafrost thaw, and how it will affect ecosystem processes and ecosystem, with atmospheric feedbacks, including hydrology and greenhouse gas fluxes. The summary is based on studies published in the last five years (based on observation from longer periods) in the northern Eurasian region, focusing on the Russian Arctic, northern Eurasian boreal forests (Siberia) and peatlands of the PEEX programme.[1] The importance of surface and soil conditions for the energy balance and thawing is given in Göckede et al. (2019) presenting their findings on shifts in energy fluxes from paired ecosystem observations in north-eastern Siberia comprising a drained and corresponding control site. Drainage disturbance triggered a suite of secondary shifts in ecosystem properties, including alterations in vegetation community structure, which in turn influenced changes in snow cover dynamics and surface energy budget. First, the drainage reduced heat transfer into deeper soil layers, which may have led to shallower thaw depths. Second, the vegetation changes due to the drainage led to an albedo increase, which decreased the total energy income, or net radiation, into the system. Third, the drainage reduced water content available for evapotranspiration, which resulted in a reduced latent heat flux and increased sensible heat flux, transferring more energy back into the atmosphere. The reported effects led to surface and permafrost cooling. In another investigation, Kukkonen et al. (2020) compared ground temperature data from several shallow boreholes in the Nadym region, Siberia, and predicted permafrost evolution for different climate scenarios. The Nadym area represents a typical site located in the discontinuous permafrost zone. Locally, in sites with a thin snow cover (e.g., hilltops) a higher resistance to the thawing was demonstrated (Kukkonen et al., 2020). To follow up on the development of permafrost thaw in different soil types requires continuous and comprehensive observations during the coming decades.

## Examples of recent findings in Greenland, Siberia and Svalbard

In Greenland, permafrost thaw has been found to cause erosion of land, damage to infrastructure and buildings, and increased pollution risks for drinking water and food safety in Arctic communities (Rautio et al., 2020). The main concerns are that there might be a release of contaminants and heavy metals (such as mercury) and infectious agents (especially anthrax from old burial places), that have been hidden for a long time, even hundreds of years, in frozen ground. All this is a serious risk for both human and wildlife health (Rautio et al., 2020). There can also be indirect effects of permafrost thaw on mental, physical, and social health and wellness via associated socioeconomic changes in the Arctic (Rautio et al., 2020). These authors stress the importance of developing appropriate new research methodologies for understanding the dynamics of re-mobilising pollutants (contaminants, infectious agents) from permafrost thaw in the Arctic, and for estimating their risks for human and wildlife health. Ideally, such methodologies would be highly participatory, multidisciplinary, and culturally sensitive, combining social and physical science with indigenous knowledge.

In the Arctic tundra region of Siberia, the expansion of shrub vegetation in response to climatic changes has been widely reported, but how such vegetation changes contribute to stabilisation or destabilisation of the underlying permafrost has been unknown, because field studies on tundra vegetation changes in Siberia are scarce (Heijmans, 2020). Their experiment at the Chokurdakh Scientific Tundra Station in North-East Siberia showed that damaging the tundra vegetation can trigger abrupt permafrost thaw (Heijmans, 2020). Outside their experiment, in the same drained thaw lake basin, they found ‘natural’ thaw ponds with drowned shrubs, but it was unclear to them what had triggered the abrupt permafrost thaw there. At the same time as they witnessed abrupt permafrost thaw, they also saw recovery of vegetation and permafrost, probably assisted by the establishment of Sphagnum mosses. Their birch (*Betula nana*) removal experiment showed how important the tundra vegetation cover is for protecting the permafrost. Removal of a part of the vegetation resulted in a literal collapse of the ecosystem, demonstrating how fragile the Arctic tundra ecosystem can be (Heijmans, 2020). Several other local studies have also explored the differences introduced by vegetation, soil, and hydrological characteristics at the same site (Göckede et al., 2019). In far eastern Siberia, Alexander et al. (2020) sampled burned forests near Yakutsk and Cherskiy, Russia, to understand the causes and consequences of larch forest loss after fire. They found that the greatest levels of larch forest recovery in forest stands that had the highest severity of crown fire (fire damage at the top of the trees). Another recent permafrost study on gas emission craters (GEC), revealed the existence of mounds above subterranean methane that may disappear abruptly through explosive depressurization under climate warming, to form deep craters known as gas emission craters (GEC) (Leibman et al., 2020). All the known GECs appear to have formed in north-western Siberia, in the Central part of the Yamal and Gydan peninsulas close to 70° North, located in the continuous permafrost zone of West Siberia, known for its natural gas resources and layers of ground ice. These are due to climatic fluctuations and air temperature extremes associated with the warming trend over the last decade and have caused an activation of permafrost processes due to thaw of ground ice. The researchers determined, through analysis of Digital Elevation Models around each GEC, that all craters were preceded by mound-predecessors, 20 to 50 m in diameter and 2 to 6 m high. Sampling frozen crater walls showed that lake-successor water contained very high concentrations of methane. They suggest that mound-predecessors explode when pressure due to the dissociation of gas hydrates finally exceeds the strength of the ground layer covering the growing gas reservoirs. At that moment, this cover of frozen deposits breaks into very icy blocks which are ejected out into the air and thrown into the tundra where they melt, leaving small hollows filled with water or pieces of ground. The central void that formed as a result of this explosion is then flooded, and at the same time, crater walls collapse, filling the void together with rain and melting water from snow. This mixture freezes up from the bottom. Thus, in a few years, a small diameter deep hollow turns into a big shallow lake (Leibman et al., 2020).

In Svalbard, permafrost soil has been used to protect the seed strains. The Svalbard Global Seed Vault is a store for duplicates of seed strains collected from crops around the world in a safe environment, thus ensuring that the seed duplicates are safe from extinctions during large-scale regional or global crises. Instanes (2020) worked at Svalbard Global Seed Vault which is located near Longyearbyen, Svalbard (78°13'N, 15°33'E) at 130 metres above sea level. Their work was to construct a storage facility for seeds, that will remain cold, dry, and dark for the next centuries, even under the most extreme climate warming scenarios. This design was achieved by a combination of construction procedures including watertight concrete, low permeability backfill material and artificial cooling of the permafrost soils and rock (e.g., Zolkos et al., 2018).

In addition to these examples from Greenland, Russia and Svalbard, results from the H2020 EU-project NUNATARYUK, "Permafrost thaw and the changing Arctic coast: science for socio-economic adaptation", available at https://cordis.europa.eu/project/id/773421/results, provides a wide collection of 68 peer-reviewed articles on permafrost, including Greenland, Siberia, Svalbard, as well as studies across the Arctic.

### Cross-border impacts of permafrost thaw

Permafrost thaw in the Arctic can have consequences for regions outside the Arctic through effects that cascade across borders. These include impacts on infrastructure on permafrost used for international trade: transport routes and airports, energy infrastructure such as pipelines (cf. section 'Effects on infrastructure') as well as economic opportunities presented by improved access to natural resources (Carter et al., 2021; Mosoni et al. in prep.). Infrastructure damage linked to permafrost thaw can also impact the financial and insurance sector. Adaptation measures and policies to counter the effect on trade and finance by the impacted actors is necessary to address these changing conditions.

Connections of the effects of permafrost thaw to other impacts caused by warming and their cascading consequences are summarised in Figure 1.

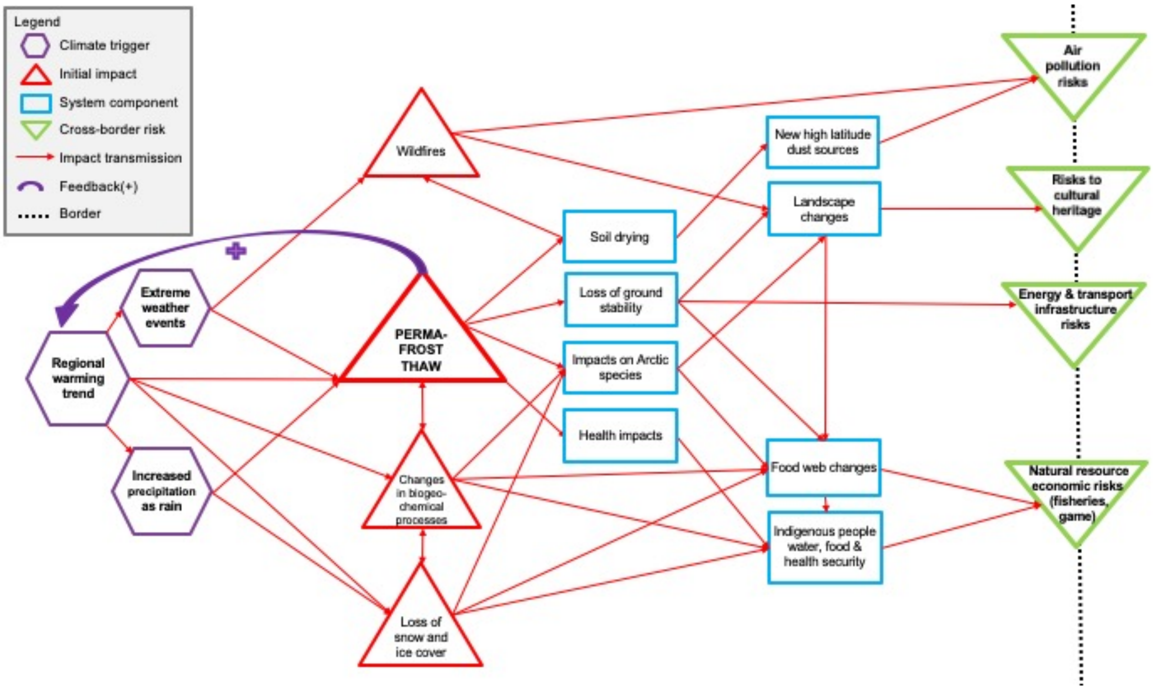

**Figure 1.** Illustration of the impact transmission system for permafrost thaw and related impacts in the Arctic addressed in this study (modified from Mosoni et al., in prep., symbols based on Carter et al., 2021).

## Planning and taking adaptive action

The many effects of permafrost thaw call for equally diverse adaptation actions. Permafrost thaw is a 'structural' change in the arctic environment and a seasonal phenomenon. As noted in Section 'Effects of permafrost thaw' it may, however, change ecosystems permanently. Relevant adaptation actions can be classified as follows:

1) Engineering approaches: the thawing of the permafrost is taken into account in construction designs and standards. (Schnabel et al., 2020).

2) Behavioural change: Practices are modified in such a way that activities cope with the relevant changes. This is one of the main options for many indigenous peoples that depend on traditional livelihoods (Takakura, 2016).
3) Organisational responses: By modifying regular activities, societies can address permafrost thaw. This may take the form of increasing funding for maintenance of infrastructure, the development of warning systems for the acute dangers that permafrost thaw may cause or participatory planning of suitable responses (Jungberg et al., 2022; Vogel and Bullock, 2021).
4) Regulatory and policy response: By modifying laws, rules, and other forms of regulation the capacity to adapt to permafrost thaw can be increased. These may include new regulations for buildings or infrastructure, rules on land use to maximise the protection of permafrost or rules on resettlement (López-Carr & Marter-Kenyon, 2015).

The different actions are obviously not fully independent but making a distinction between them is useful as the processes by which they can be adopted differ greatly. For example, engineering approaches can be used almost independently of the others in the case of industrial sites, where the owner has strong incentives to avoid technical failures. Robust constructions require detailed understanding of the different processes affecting permafrost and thawing (Vincent et al., 2013).

Behavioural adaptation is a form of autonomous adaptation that has been a necessary feature of many indigenous peoples and local communities (Schlingmann et al., 2021). In general, these climate adaptation strategies involve a modification of existing livelihood systems, which in the case of permafrost thaw may, for example, involve finding new sites for traditional ice cellars or water sources (Brubaker et al., 2011) and other ways of coping with the change that is not only physical, but also mental and cultural (Doloisio & Vanderlinden, 2020). The adaptation patterns may include gender-based differences (Potravnaya & Kim, 2020).

The behavioural adaptation may be supported or hindered by organisational responses to permafrost thawing. A crucial feature in developing institutions is the involvement of indigenous and local knowledge, that can offer important insights into the actual changes brought about by permafrost thawing (Wilson et al., 2015) and into the vulnerabilities of arctic communities (Furgal & Seguin, 2006).

Regulatory response involves active modifications of institutions that guide behavioural and organisational adaptation and the application of engineering responses. The regulatory responses may include, for example, strategic plans or zoning regulations (Jeff Birchall and Bonnett, 2020) which can address hazards but also long-term development. Regulatory response may also involve the modification of existing regulations. For example, existing regulations may limit the opportunities for funding if the community fails to qualify for emergency funding because they have not been declared a national disaster area or because they have not approved disaster mitigation plans (Government Accountability Office, 2009).

To be effective, the different responses to permafrost thawing need to be coherent. As noted by Jungserg et al. (2022) there is a risk that "individuals and institutions engage in autonomous adaptation on an ad hoc basis, rather than pursuing an overall strategy to increase the adaptive capacity in advance of future permafrost degradation". At a local or (sub)national level the coherence in responses can be achieved by systematically recognizing the different types of adaptation to permafrost degradation and by creating fora for debating and exploring options, underlining the importance of dialogues between stakeholders (Fig. 2). In order to develop such dialogues, there is a need for institutional development that brings together both public and private stakeholders, with a strong emphasis on the role of indigenous peoples, whose livelihoods and even health are key victims of permafrost thaw.

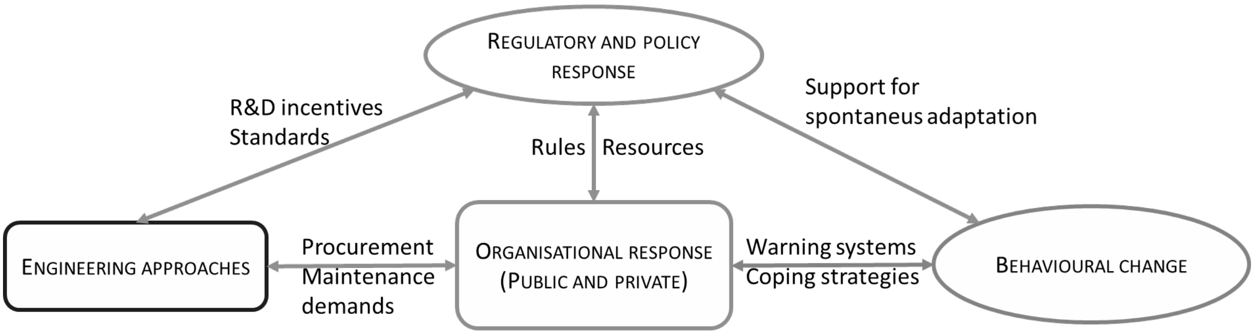

**Figure 2.** The interaction of responses to permafrost degradation. The two-way arrows indicate that all actions need to be based on interactions between stakeholders. Rounded boxes illustrate responses which tend to be incremental, gradually modifying existing structures, whereas ovals illustrate responses in which negotiations and awareness raising are particularly important.

The responses to permafrost degradation must be effective at the scale that is relevant for the (local) actors whose activities depend on the permafrost. However, permafrost degradation is also a circumpolar phenomenon that has cross-border impacts. This means that there is also scope for cross-border learning and policy response. Thus, Leonard et al (2021) have proposed that the EU should initiate and lead a global coalition for the permafrost, aimed at funding research to better assess the current status of the problem and at funding measures to urgently contain permafrost thaw. This could open possibilities for innovative solutions on a larger scale than is possible with local community adaptation. Currently, for example, the EU Arctic PASSION -project (Pan-Arctic observing System of Systems: Implementing Observations for societal Needs, https://arcticpassion.eu) considers permafrost (or living on frozen ground) as eligible to be included within the concept of a Shared Arctic Variable (SAV) as part of the Sustaining Arctic Observing Networks' (SAON) Roadmap for Arctic Observing and Data Systems (ROADS) (Starkweather et al., 2021).

## Conclusions

This study has provided a literature-based summary of the multiple effects of thawing permafrost - permanently frozen ground - in the Eurasian Arctic. The literature demonstrates diverse and interacting effects of permafrost thaw (or degradation). The complexity of the effects, which span ecological, cultural, economic and health impacts, puts specific demands on adaptation to climate change in the Arctic. We identify several different categories of response to permafrost degradation but argue that they have to be considered and developed in a coherent manner in order to be effective. This implies that there is a need for institutional development that supports action to reduce permafrost thaw and actions that help in adapting to inevitable degradation. We argue that there is scope for such institutional arrangements at different levels of governance from the local to the international.

## Notes

1. The Pan-Eurasian Experiment (PEEX) Science Plan, released in 2015, addressed a need for a holistic system understanding and outlined the most urgent research needs for the rapidly changing Arctic-boreal region (Laappalainen et al. 2015)

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