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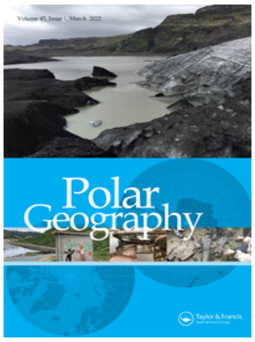

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Adaptive capacity to manage permafrost degradation in Northwest Greenland

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ABSTRACT
Global warming has reduced the extent of permafrost, increased permafrost temperatures, and deepened the active layer across the Arctic. Permafrost degradation has detrimental effects on infrastructure and negative impacts on ecosystem services for many Arctic communities. This study examines the adaptive capacity for managing permafrost degradation in Northwest Greenland. The methods are based on questionnaire and interview data from fieldwork, frozen ground temperature records and published data forecasting the deepening of the active layer. Results illustrate the impact of permafrost degradation on the physical environment, hunting and harvesting, housing, and the economy in Northwest Greenland. House owners are mending damage caused by ground movement, and local institutions are concerned with the maintenance of roads and other public infrastructure impacted by permafrost. The scientific knowledge needed to inform decision-making is useful for identifying overall changes, but existing data sources are scarce, and more detailed permafrost maps are needed for long-term town planning. The study concludes that many 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 in Northwest Greenland.

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Introduction

In past generations, permafrost conditions were not a cause of concern. Communities and lifeways were built with little consideration for the subsurface, or else on the assumption that permafrost would continue in perpetuity. However, global warming has reduced the extent of permafrost, increased the temperature of the permafrost and deepened the active layer in numerous locations across the Arctic (Aalto et al., 2018; Biskaborn et al., 2019; Doré et al., 2016; Streletskiy et al., 2012). Some of the common societal effects include coastal erosion, archaeological and cultural heritage sites eroding into the sea,

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collapsing fill around the pilings supporting public infrastructure, the destabilization of roads, and ice cellars thawing and flooding (Doloisio & Vanderlinden, 2020; Doré et al., 2016; Instanes & Anisimov, 2008; Larsen et al., 2021; Shiklomanov et al., 2017).

Climate scenarios for the coming decades predict the permafrost thaw will continue to have negative effects on engineered constructions, socio-economic activities and natural ecosystems (AMAP, 2018; Hjort et al., 2018; Vincent et al., 2013). The detrimental effects on infrastructure and various negative ecosystem impacts require long-term adaptation planning. Studies of the social impact of permafrost illustrate that more effort is needed to increase the geographic coverage of observations, to improve local-level projections and to reduce uncertainty (Allard et al., 2012; AMAP, 2018; Doré et al., 2016). To prepare for future changes, the Arctic Council has recommended expanding the documentation of adaptation responses by Arctic communities (Arctic Council, 2017). Several communities in Canada and Alaska have already developed strategic plans on adaptation planning for permafrost (Allard et al., 2012; Hong et al., 2014; Jeff Birchall & Bonnett, 2020).

Findings from research in Northwest Greenland estimate 200 areas face a risk of permafrost thaw leading to rock slope stability issues. Of these, 18 are in the vicinity of human settlements and infrastructure, and therefore expose these communities to the risk of rockslides induced by permafrost degradation (GEUS, 2018; Schultz-Nielsen, 2019). While several researchers have studied adaptation in the context of climate change in Greenland (Hastrup, 2018; Naalakkersuisut, 2012, 2017), gaps remain in our understanding of adaptation practices to cope with permafrost degradation and, even more importantly, for assessing the adaptative capacity needed to manage the impact in the future (Ramage et al., 2021). The ability to cope with manage permafrost change is also influenced by community capacity and local perceptions of the impact (McNamara & Buggy, 2017; Piggott-McKellar et al., 2019).

In this article, we will examine the adaptive capacity to cope with permafrost changes in Northwest Greenland. Our analysis builds on a theoretical framework encompassing three dimensions, each informed by the adaptive capacity studies. In the first dimension, we assess *community awareness of permafrost change*. In the second, we assess the *institutional organization of adaptation measures for permafrost*, and in the third, we assess the *scientific knowledge needed to inform decision-making about permafrost*.

Theoretical framework: adaptive capacity

Adaptive capacity has its roots in organizational theory and has attracted considerable attention through work published by the Intergovernmental Panel on Climate Change (IPCC). The IPCC defines adaptive capacity as the ability of a system to cope with both the risk and the opportunities related to change (Engle, 2011; Smit & Wandel, 2006). Adaptive capacity is closely linked to other commonly used concepts, including vulnerability, resilience, coping ability, management and response capacity, stability and robustness (Berrang-Ford et al., 2011; Engle, 2011; Siders, 2019; Smit & Wandel, 2006). Adaptive capacity dynamics inform research and help us better understand vulnerability in a local context. A low adaptive capacity assessment means that a community is highly vulnerable (Engle, 2011).

The level of adaptive capacity is influenced by a range of different factors. Much of the research on adaptive capacity characterizes the important factors relevant in specific case study areas (Engle, 2011; Siders, 2019). Different factors, dimensions and determinants impact the adaptive capacity and these all depend on local conditions. On an aggregated level, however, we can observe that these factors revolve around the community, the institutions and the access to knowledge (Engle, 2011; Ford & King, 2015; Gupta, 2010; Koop et al., 2017; Siders, 2019; Smit & Wandel, 2006). In a community context, the focus is on the impact experienced locally, the sense of connectedness, networking and social agency, and the ability to solve problems (ibid). The role of relevant institutions in responding to environmental change can stimulate or prevent the development of adaptive capacity (Bronen & Chapin, 2013; Ford & King, 2015; Gupta, 2010). Institutions enhance their adaptive capacity through informed decision-making and action on adaptation planning. Informed decisions are dependent on knowledge about the ongoing change process. Monitoring ongoing environmental change is therefore highly relevant for ensuring institutional adaptive capacity (Bronen & Chapin, 2013; Siders, 2019).

In this paper, we combine several dimensions which illustrate adaptive capacity as observed in the relevant literature (Arctic Council, 2017; Baker et al., 2012; Berman et al., 2020; Engle, 2011; Ford & King, 2015; Koop et al., 2017; Siders, 2019; Smit & Wandel, 2006). We also ensure that these dimensions are informed by empirical data. The outcome of this work enables us to use the concept of adaptive capacity as an assessment tool (Engle, 2011). We have identified three crucial dimensions to assess adaptive capacity for permafrost degradation in Northwest Greenland.

The first dimension focuses on *community awareness* as an important factor in assessing the capacity of a community to manage change. In this context, we define *community* as people living in the same settlement in a specific area. Information about *community awareness* illustrates what type of adaptation practices, local networks and problem-solving abilities exist among community members. This dimension is crucial to understanding local experiences and the perceived level of urgency involved (Ford & King, 2015; Koop et al., 2017).

The second dimension focuses on the *institutional organization of adaptation measures* (Ford & King, 2015). Institutions and governance processes provide the kind of political and administrative structure that can either enable or restrict adaptation (Ford & King, 2015). This dimension looks at how municipal judgments shape local interventions (Healey, 2009). The focus is on permafrost in relation to strategy-making and spatial planning, the coordination between various actors involved, and institutional action related to adaptation measures (Healey, 2009; Smith et al., 2005).

Table 1: Analytical framework dimensions for assessing adaptive capacity in the event of permafrost change.

Dimensions	Definition	Empirical data
Community awareness of permafrost	Extent to which community members possess relevant knowledge about the challenges. Perceived impacts and assessment of ability to cope.	Questionnaire data on local observations about changes in landscape and the impact on infrastructure. Questionnaire on community members' experiences and judgments concerning permafrost thaw.
Institutional organization in relation to permafrost	Institutional capacity to address permafrost and other climate change challenges.	Review of the municipal planning strategies, and interviews with municipal representatives on current challenges related to climate and permafrost.
Scientific knowledge to inform decision-making on permafrost	Research showing measurements of permafrost change.	Frozen ground/permafrost (active layer) temperature data. Settlement data shown on maps illustrating active layer projections for 2050.

The third dimension focuses on the *scientific knowledge needed to inform decision-making* (Ford & King, 2015; Koop et al., 2017). This dimension assesses the usability of available knowledge on the thermal state of permafrost and the capacity of the relevant local authorities to make future predictions. This information is relevant for the institutional organization since they will naturally base their adaptation measures on available knowledge. For permafrost, this knowledge can be based on monitoring datasets, e.g. of active layer thickness or ground temperature, and on modeled projections. Such knowledge is vitally important as a strategic dimension and a key part of any strategy to enhance the available intelligence (Healey, 2009).

Adaptive capacity can be either enabled or restricted through all three dimensions in our analytical framework. Adaptation literature distinguishes between two types of adaptation: autonomous adaptation and planned adaptation (Forsyth & Evans, 2013; Gupta, 2010; Mersha & van Laerhoven, 2018). While the autonomous kind is characterized by independent and ad hoc adaptation solutions, planned adaptation refers to adaptation for which preparations are made well in advance – by institutions, for example. These two types of adaptation are also connected to what can be considered short-term responses, including the ability to cope with pressing changes as well as the long-term adjustments to enhance sustainability (Smit & Wandel, 2006).

Material and methods

The materials and methods section follows the three dimensions presented in the theoretical framework (see Table 1) to structure and present the empirical data. *Community awareness of permafrost change* comprises material from qualitative interviews and a community questionnaire. For the qualitative interviews, 22 participants were selected, based on snowball sampling and local contacts through our field assistant. Eight of the participants were engaged full-time in hunting and fishing; ten of them were employed in the public or private sectors, and only engaged in hunting and fishing as a leisure activity; one was enrolled in youth education, and three were entrepreneurs working with local trade and handicrafts. Not all participants were familiar with the specific term 'permafrost'. We therefore broadened the focus in some cases, involving more general observations and a broader conversation about nature. Through this, new insights emerged concerning our participants' experiences of changes involving frozen ground. The participants shared about their involvement in seasonal livelihood activities, perceptions of important issues right now and over the next 10–20 years, the biggest risks involved and the most important opportunities and challenges facing community development.

Two different questionnaires were applied – one in Qeqertarsuaq in Disko Bay, and one in Qaanaaq, the northernmost town. These questionnaires were translated into Greenlandic and distributed by two local field assistants in a face-to-face setting. One of the assistants used a printed paper version, while the other used an electronic tablet to register answers. The local field assistants were hired through a network at the University of Copenhagen Arctic Research Station. The field assistants informed all participants about the project, how the data would be used, and made it clear that participation was voluntary. All this was done before participants answered the questionnaire. The sampling strategy utilized (or benefitted from) local field assistants' knowledge of people living in the two communities. This enabled them to ensure a balanced representation of age, gender, and occupation. Those involved in construction work, hunting and fishing activities, along with municipal planning, were particularly interesting, because the people involved in these have an occupational interaction with nature and the landscape.

In Qaanaaq, 10% of all adults answered the questionnaire. The population is 646 (as of 2019) of whom 450 are above the age of 18. The number of respondents ($n = 45$) therefore represents 10% of all adults in total. The questions focused on changes observed locally, the family situation, households and other physical assets, membership of organizations, income and livelihood activities, and coping mechanisms for dealing with local environmental change. The questionnaire was conducted between February and June 2020.

In Qeqertarsuaq, 15% of all adults answered the questionnaire. The population is 854 (as of 2019), of whom 653 are above the age of 18. The number of respondents ($n = 100$) represents 15% of the total adult population. The questions focused on their use of the natural environment, changes observed in relation to the permafrost thaw, subsistence activities and adaptation measures to cope with permafrost thaw. Participants responded to the questionnaire between February and the end of April 2019.

Institutional organization of adaptation measures to cope with permafrost consists of a review of the municipalities' planning strategies for examining existing adaptation measures. One of the municipal tools for long-term planning is the municipal planning strategy. Such strategies comprise the most important tools for focusing on municipal development. For the review, we examined how permafrost challenges are articulated, and the action points listed to address these. To complement the strategy review, we also conducted a set of 10 semi-structured qualitative interviews with public sector employees, municipal planners and representatives from the construction, energy and water sectors.

All materials for building community awareness of permafrost and strengthening institutional organization on adaptation measures for permafrost thaw were collected over a two-year period. This included a 12-day fieldwork visit in February 2019 and a 24-day visit in February–March 2020. Winter and the early spring months proved beneficial, since many local people had time to meet and talk about the changes, they had experienced. Some interviews were conducted in Danish, while others were in Greenlandic with a local translator.

Scientific knowledge to inform decision-making about permafrost assesses the availability of relevant scientific knowledge. Permafrost is defined as rock or soil that remains below 0 degrees for two or more consecutive years (Ingeman-Nielsen et al., 2018). The extent and temperature of permafrost, its active layers of thickness (the maximum thaw depth at the end of summer), its subsurface geological composition and its ice contents all provide important parameters for evaluating the risk associated with thawing. Such information can be obtained from boreholes, where soil or rock samples are collected during drilling for laboratory analysis. A datalogger with temperature sensors is installed in the borehole to monitor temperatures and provide this information.

Northwest Greenland is characterized by the presence of continuous permafrost (90–100% of land underlain by permafrost), with some other areas of discontinuous permafrost (50–90% of land underlain by permafrost) (Obu et al., 2019). Active layer thickness (ALT) is a key indicator of permafrost change. We produced maps comparing the current and projected active layer thicknesses, based on statistical modeling forecasts (Aalto et al., 2018). The time period from 2000 to 2014 is referred to as the baseline scenario, and the time period from 2041 to 2060 is referred to as the future scenario by 2050. The future climate scenario is based on the representative concentration pathway (RCP) 4.5. The spatial resolution of the active layer thickness modeling the product data is 30 arc seconds (approximately 1 km). We focused on Northwest Greenland, which is the Nordic region most affected by permafrost. It is where the most pronounced changes are expected to take place. Settlements with population data from 2020 have been added as an interpretative layer on the map showing the ALT.

Study area

Greenland is one of the autonomous, self-governing areas in the Nordic Region. In 1971, Greenland was granted home rule, and in 2009 full self-government. The Danish government provides a block grant, supplying around 60% of the government revenue and 40% of Greenland's GDP (Nordic Council of Ministers, 2018). The main industry is fishing, but Greenland also has potential for further development in the tourism and mineral industry sectors. In 2009, a program of municipal reform cut the 18 municipalities to four. However, the inhabitants in Qaasuitsup municipality in Northwest Greenland expressed dissatisfaction with this. They experienced a democratic distance from governance, and increased detachment between the settlements (Hansen, 2015; Løvschall-Wedel, 2016; Turnowsky, 2016). Qaasuitsup was the largest of the merged municipalities, and continuing dissatisfaction led to the decision to split Qaasuitsup into two municipalities in 2018. These are Avannaata and Qeqertalik. The largest settlement in Avannaata is Ilulissat, with a population of 4670. In Qeqertalik it is Aasiaat, population of 3069 (Greenland Statistics, 2020).

All settlements in Avannaata and Qeqertalik are accessible by helicopter or airplane, and during the ice-free season (in the summer months) by boat or ferry, too. The main municipal planning departments are located in Aasiaat (Qeqertalik) and Ilulissat (Avannaata). There is also a municipal office with a few employees working on the environment, citizen's services and administration in the larger towns, which includes Qeqertarsuaq (Qeqertalik municipality) and Qaanaaq (Avannaata). Qeqertarsuaq is a community located on Disko Island in Qeqertalik municipality. Qeqertarsuaq has a population of 839 (as of 2019, at the time of the survey), the majority of whom are Kalaallit (Greenlandic Inuit). The community has a mixed subsistence-cash economy composed of hunters and fishers, as well as paid employment (Caulfield, 1993). The wage economy of Qeqertarsuaq is based on commercial fishing, seafood processing, public administration, tourism and seasonal labor. People living in Qeqertarsuaq use the land, the sea and the sea-ice for hunting and fishing.

The town of Qaanaaq was established in 1953, following a forced relocation from the old Thule settlement where the United States Air Force had planned the construction of an air defence site nearby. Today Qaanaaq is the northernmost town in Greenland, with a population of 646 in Avannaata municipality (as of 2019, at the time of the survey). The people of Qaanaaq migrated from Canada around 1100 CE and belong to the Inughuit tribe (Hastrup, 2018). They have a unique dialect and their own specific cultural traits, for example in their usage of harpoons when hunting. In the Qaanaaq area, fishing and marine mammal hunting deliver significant income and direct subsistence for local households. Many professional hunters still hunt the traditional way, using kayaks and harpoons to catch whales. The long winters, in which the sea-ice covers the entire coast, mean that only two Royal Arctic Line ships (one in July and one in September) are available to supply the town with materials for the built environment and other purposes.

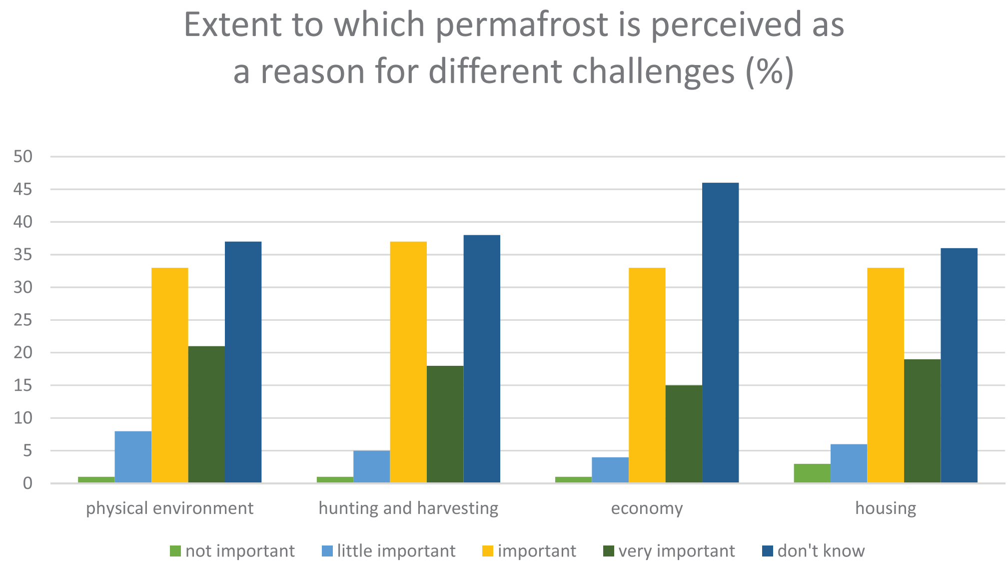

Figure 1. The extent to which permafrost is perceived as significant for different challenges in Qeqertarsuaq.

Results and discussion

Our results are structured in line with the three dimensions presented in our theoretical framework: *community awareness*, *institutional organization,* and *scientific knowledge available to inform decision-making*. Each of these analytical dimensions is examined through the lens of adaptation capacity.

Community awareness of permafrost change

There is community awareness of change in the frozen ground, and the local people experience these changes in the permafrost in the same way as they experience other climatic changes. This section concerning community awareness of permafrost illustrates how experience of changes in the permafrost interconnects with different aspects of everyday life.

Perceived impact of changes in the permafrost

People in Qeqertarsuaq experience the impact of changes in the frozen ground in several ways. Figure 1 illustrates how participants perceived whether their physical environment (54%), hunting and harvesting (55%), economy (51%) and housing (52%) were an important or very important area in relation to the challenge of permafrost degradation.

However, we should note that the most common answer is 'don't know'. This indicates that many participants don't feel confident to assess connections between societal challenges and permafrost. Even so, qualitative empirical data illustrates how inhabitants experience a diverse range of impacts, varying in effect between minor damage and large damage. The next sections present our results concerning the perceived impact of permafrost on the physical environment, hunting and harvesting, the economy and housing.

Physical environment, hunting and harvesting

Community members in Qeqertarsuaq and Qaanaaq observed changes in their physical environment during travel for recreational purposes, as well as hunting and fishing trips. The physical environment contains elements such as soil, water and air. While traveling and hunting, local people experience how these elements change the landscape. Several participants in Qeqertarsuaq had experienced natural phenomena related to permafrost, such as slumping (31%), the drying of wetland areas (16%), an increase in wetland areas (8%), the deepening of the active layer (7%) and coastal erosion (7%). Observations pointing towards permafrost degradation are changes in vegetation, increase in wetland areas, deepening of the active layer, slumping and coastal erosion.

In Qaanaaq, 58% of respondents had observed the '*ground sinking*' in different parts of the area. In winter, the ground is covered with ice and snow, but in summer one Inhughuit, aged 49, observed '*round holes in some trails, as if the ground had sunk*'. Another observation by an Inughuit, aged 62, was that '*I see more landslides today than before*'. The physical environment is a prerequisite for hunting and fishing, which remain extremely important for the Inuit people. Overall, 55% of participants in Qeqertarsuaq found that the thawing of the frozen ground had some impact on their ability to obtain food and other resources (e.g. spring water) from the land. For those working as hunters, permafrost thaw may lead to changes in hunting routes, resulting in less favorable conditions. In Qeqertarsuaq, hunting and harvesting are of great importance for households and participants estimated that subsistence activities are important for 84% of their household's food supply, with 61% of the respondents' diets consist of Greenlandic food (Vanderlinden et al., 2020).

Among the animal products most consumed are muskox, reindeer, hares, rabbits, sea-mammals, fish, crabs, seashells and antlers (see Figure 2). Participants also mentioned angelica plant (that grows wild) and Greenlandic lamb (which they received by ship) in the 'other' category. Family was considered an important source of Greenlandic food, with 90% of participants receiving food from their families several times a year.

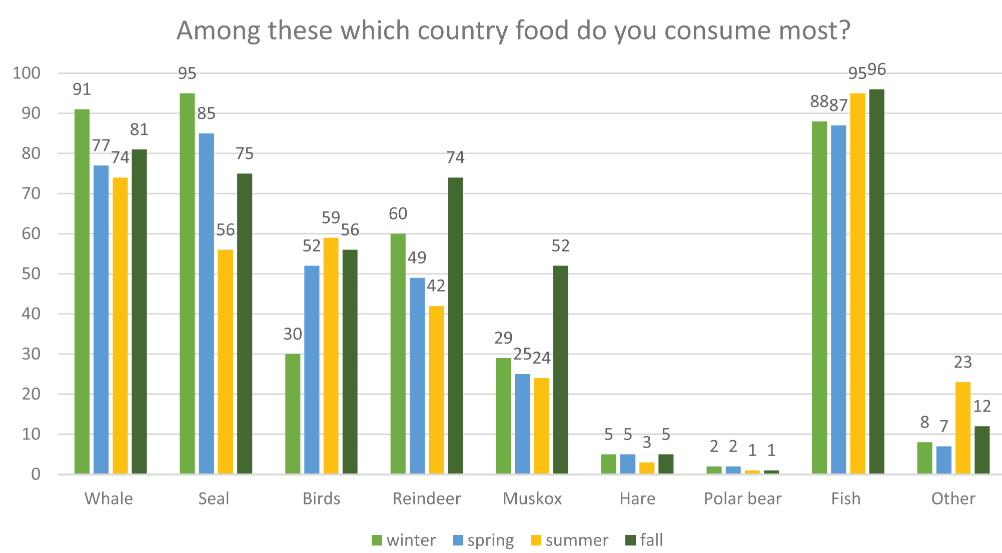

Figure 2. Most consumed species in different seasons, as a percentage of respondents in Qeqertarsuaq.

Eighty-two per cent of respondents collect berries and herbs, and a further 28% of these had observed changes in berry picking areas. These areas are sensitive and permafrost degradation, along with changes in the balance of sun and rainfall, can lead to a decrease in the volume of berries. Nature is a very important part of Inuit and Inughuit culture. Sixty-one per cent use nature for recreational activities, which illustrates its importance for the culture of the community. One woman aged 36, told of how she grew up in a family consisting of hunters and fishers. These days she goes hunting and fishing as a leisure activity. The family have a small hut where they can stay overnight during winter and summer trips. In summer they go sailing, and during those trips, they hunt, fish, and collect berries. However, with changes to the frozen ground, they have not found as many berries as usual around Qaanaaq during the rainy seasons.

Changes in the frozen ground may also limit access to recreational travel routes, or to summer cottages. One Inughuit hunter (aged 62) from Qaanaaq told us how '*old hunting cabins are now drifting into the water due to the eroding coast*'. Several other hunters who live in Qaanaaq and Qeqertarsuaq confirmed this observation. They observed how some of their small hunting cabins are now starting to slip into the water, due to coastal eroding and/or landslides. High dependence upon subsistence activities makes the local people particularly vulnerable to changes in wind, temperature, sea-ice and the permafrost. A close connection to nature and to local hunting and harvesting practices indicates a correspondingly high dependence upon the surrounding ecosystems. Permafrost degradation is already changing landscapes, and the participants report on several changes that impact their livelihood.

Housing and economy

Since more houses in Qeqertarsuaq are built on bedrock than in Qaanaaq, a higher proportion of the population has experienced problems with housing in Qaanaaq. In Qeqertarsuaq, 52% said that they see challenges for housing, buildings and roads. One of the Inuit respondents, aged 45, elaborated further, noticing '*… changes in the foundation of buildings*'. In Qaanaaq, most houses are built on sedimentary deposits, and are therefore more prone to deformations due to thawing, making built structures more vulnerable to differential settlement making the house had become skewed. Several Inughuit inhabitants explained how they experienced problems with their houses after the summer period. Typical experiences included floors slanting, doors or windows not closing, and window glass cracking due to differential settlement. One Inhughuit woman, aged 62, said:

> *Suddenly the main entrance door wouldn't close any more. I had to call a man to come help me look at it, and he said that it was [happening] because the ground is changing. Now, I can only close the inner door – [so it's] good we live in a small town.*

Many houses in Northwest Greenland have an entrance space with no heating. Due to changes in the ground, the woman we have just quoted cannot lock her main entrance door, just the secondary door off the small entrance space. A young man (aged 23) told us that after living for seven years in Denmark he returned to his hometown last year, to live with his grandparents. He noticed that the house had changed, so that now one door would not close, and always had an open gap of some 10 cm. In the bathroom, the floor was leaning in the wrong direction from the outlet drain, so that it now takes a lot of work to sweep water the right way after a shower.

One Inughuit woman (aged 36) explained that she had built her own house with her husband 11 years ago. Two years ago, the house started to move a little. She has been able to recognize this from the doors, the windows and the stairs inside. Her husband has fixed the doors, and fortunately the windows still open and shut. Another house owner explained how he had trouble closing one door in the house every winter, but during summer it seemed as if the ground had moved back into place, so the door could close again properly. In Qaanaaq, 73% of respondents said that they have observed differential settlement affecting their house. Another interviewee in Qaanaaq explained how two house owners were fixing the foundation themselves, using a jack to lift the foundation and adding soil and rocks to make it more stable.

Participants in both Qaanaaq and Qeqertarsuaq perceived permafrost as a challenge to the local economy. Financial capital is important when living in a house where slanting floors, deformed walls and cracked window panes occur, since these problems require additional materials (and sometimes external professional services) to repair them. This is, of course, mainly the case for owner occupiers (rather than renters), who are responsible for the repairs. Approximately 52% of respondents in Qaanaaq said that they owned the house they live in, and 25% (of the 52%) owned more than one house. Most homeowners with more than one house listed hunting cottages used for leisure trips in the natural environment as a second house. A few people owned up to three or four houses which they were renting out to others, or in which other family members were living.

Those working as professional hunters do not have a regular monthly wage, and with a volatile income, they find themselves more vulnerable to unexpected costs due to changes in the frozen ground. In Qaanaaq, 57% responded that they had a regular monthly income (Figure 3). Close to half of our respondents indicated that they had some level of debt for houses, boats, or other assets. Forty-one per cent said that they had savings and 36% that they had access to savings in case of emergency.

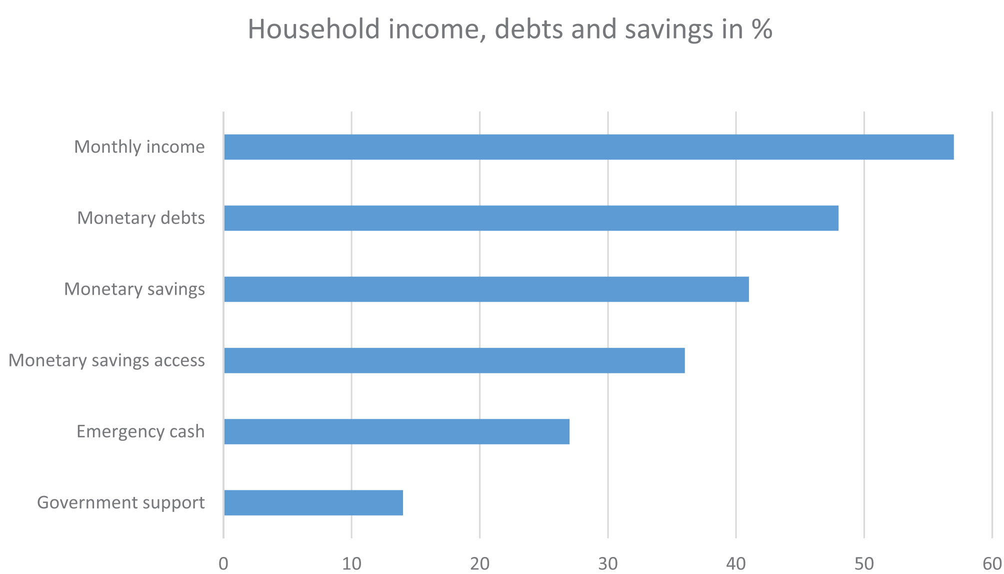

Figure 3. Participants in Qaanaaq receiving a monthly income, having debts, savings, emergency cash or receiving government support.

Men working as professional hunters usually have a volatile seasonal income. For example, during certain parts of the winter season it can be very stormy, which makes it more difficult to hunt and fish. In these situations, hunters need to have savings or to depend upon their wife's income. It is often the men who go hunting and fishing, while the women are occupied in other forms of wage labor which help to guarantee the family a steady income every month. Men without wives or partners are the most vulnerable, since they have to sustain themselves on a fluctuating income.

Assessing adaptive capacity at the community level

In Northwest Greenland, many homeowners take care of structural damage to their houses. If they do not know how to take care of these problems themselves, they hire someone locally to carry out repairs. However, it is also common simply to accept changes such as slanting floors, and wait to see whether this changes back again during the next season. Hunters adapt to the changing physical environment by looking for new hunting grounds and harvesting areas. From the questionnaire data, we can see that there is community awareness about permafrost, although many people also demonstrate that they do not always understand the connection between the changes they are experiencing and permafrost conditions.

Although many express little sense of urgency, there are also some voices expressing more urgent concern about whether communities in Northwest Greenland are properly prepared to deal with landslides, for example. In 2017, a landslide caused a huge tsunami, flooding Nuugatsiaq, and to some extent Illorsuit, two villages in Northern Greenland. Four people died, and other inhabitants living in the two affected villages were evacuated to the nearest town, Uummannaq. In such cases, institutional responsibility becomes clear. However, in the questionnaire focusing on preparedness for community adaptation, the most common answer is *other*. In their comments, respondents often say that they do

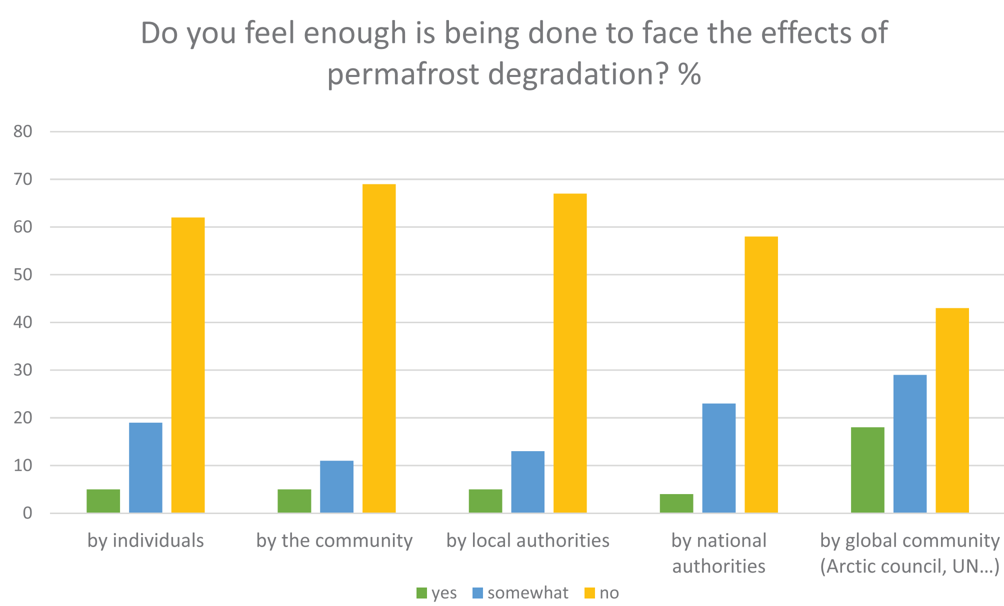

Figure 4. Participants in Qeqertarsuaq assessing whether enough is being done by different actors to face the effects of permafrost degradation.

not feel ready to face upcoming changes, and do not think any areas are better prepared than others. That said, respondents in Qeqertarsuaq and Qaanaaq expressed a need and desire for institutional efforts to support the community in making the required adaptations. Overall, participants illustrated autonomous adaptations – taking care of the adaptation needs when problems occurred. This indicates an adaptive, local capacity to manage pressing challenges related to permafrost.

Institutional organization adaptation measures for permafrost

In response to the question, '*Do you feel enough is being done to face the effects of permafrost thaw*', 69% of the participants answered *no* at the community level, and 67% *no* in terms of local authorities. Expectations of what individuals and national bodies do were only slightly less negative (Figure 4).

Participants in Qeqertarsuaq gave a general impression that more needs to be done to improve adaptive capacity for dealing with permafrost degradations. The literature on adaptive capacity confirms the role of institutions in coping with environmental change (Engle, 2011; Gupta, 2010; Siders, 2019). To assess adaptive capacity at an institutional level, the following section will examine the organizational approach to infrastructure management and planning for permafrost degradation in Northwest Greenland.

Infrastructure management

Responsibility for all public infrastructures – roads, airstrips, harbors, buildings, and houses, as well as sewerage systems, drainage and water pipes – lies with the municipalities and government. Houses and buildings include office space, classrooms, and all rental housing. Rental houses are managed by the government-owned housing company, INI. In some smaller communities, INI collaborates with the municipality's technical department. In Qaanaaq, member of staff responsible for INI at the municipal office is aware that a number of rental houses are impacted by the permafrost thawing. Each winter the floor moves 5–8 cm, and some doors cannot close. However, since the floors even out in the summer, there is currently no plan to intervene and renovate the structures.

According to one local interviewee working in the construction sector, much building activity in the 1950s and 1960s left a heritage of rapidly built houses. Today many houses with structural deficiencies are seen to have been caused more by poor building work of this kind, than by a deepening of the active layer. Our interviewee explained that although construction practices have evolved since the early days, mistakes are still being made in communities across Northwest Greenland, largely due to a lack of experience and resources. Currently, many houses are affected by active ground layer movements and by permafrost degradation.

The main strategy for both Avannaata and Qeqertalik municipalities is to build on bedrock whenever possible. Engineers and construction companies are aware of the problems occurring when building and repairing houses, and other infrastructure, in ice-rich permafrost terrain. Roads are seen as one of the biggest challenges, according to interviewees employed at Avannata and Qeqertalik municipalities. It is common for roads to 'sink' due to permafrost degradation, and for these to be repaired with temporary measures such as the accumulation of asphalt layers (with some roads now having more than a meter of asphalt, since it keeps sinking). This is a short-term solution that needs to be repeated on a regular basis. According to our interviewees in the municipal planning departments, town plans are shaped by the landscape because the current practice is to build on bedrock. However, even in Qeqertalik municipality, permafrost challenges still exist – for instance in the town of Qasigiannguit, where the foundations underneath some of the older buildings are sinking.

In Avannaata municipality, the head of planning describes the situation in Ilulissat as more manageable, compared to that in more northerly areas. In smaller communities in the Upernavik area (e.g. in Nuussuaq), several buildings and accompanying infrastructure have been damaged by the ground sinking. Skilled manpower is available to mend the resulting damage temporarily, but not in a way that is sustainable in the long term. Sometimes, sustainable long-term solutions become so complicated that specialists must be flown in, which is very expensive. Complex solutions also increase the risk of mistakes, which can be challenging when no one living locally has the necessary construction and repair expertise.

Planning for change

Our interviewees from municipal planning departments stressed that there is a need for readily accessible knowledge about permafrost conditions. From reviewing the planning strategies that set the vision and priorities for Avannaata and Qeqertalik municipalities (Avannaata, 2020; Qaatsiutsup, 2017a), we can see that there is a vision for a sustainable and economically prosperous future in both municipalities, and that the impact on society of climate change is already being mentioned. Qeqertalik still relies on the strategy from Qaatsiutsup municipality (from back when the two municipalities were one). It has not yet been able to publish a new strategy of its own. Avannaata did publish a new strategy, using the Un Sustainable Development Goals (SDGs) as a framework. The action points include Avannaata's municipal town plan considering the risk of storm surges and permafrost thaw when zoning new areas for housing. In Qeqertalik, the sector plan for traffic specifically addresses permafrost as a challenge for public infrastructure (Qaatsiutsup, 2017b).

Although the local authorities in Qeqertalik and Avannaata are aware of changes in the permafrost, there are many other development issues higher up their agenda, as evidenced by their planning strategies. Some of these priorities focus on economic development, including the expansion of the tourism industry, local democracy and citizen engagement, waste management and the local environment, access to water and sanitation and lowering social inequality. To summarize, the planning strategies in both municipalities mention permafrost, but as one challenge among many other pressing ones. As there are many other issues which require planning resources, this partly explains the autonomous adaptation response that focuses on repairing roads and other infrastructure on an ad hoc basis. One remaining component in the management of permafrost conditions for the relevant institutions is the availability of knowledge to inform decision-making about permafrost degradation. To understand this component better, the next section assesses different types of knowledge concerning permafrost change and how these can or cannot inform decision-making.

Scientific knowledge to inform decision-making on permafrost

Institutional organization requires knowledge to inform decisions on both where to build and how to repair structural damage to infrastructure. Scientific knowledge to understand

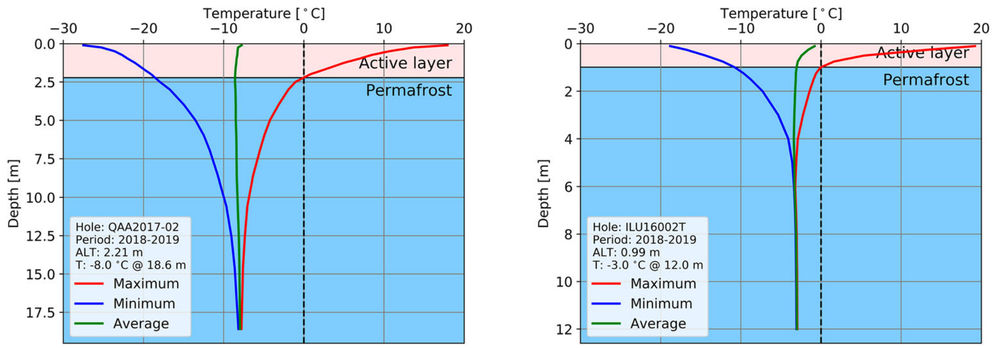

Figure 5. These trumpet diagrams show the thermal regime in the ground at the towns of Qaanaaq (left) and Ilulissat (right). The annual maximum (red), minimum (blue) and average (green) ground temperatures are plotted for the period 2018–2019. The plots also show important properties such as the active layer thickness, permafrost temperature and depth of seasonal variation.

ongoing changes is monitored from datasets of active layer thickness, ground temperature and modeling products. Some data processing is of a purely technical, scientific interest and it cannot easily be translated into planning purposes. However, in this section, we examine data derived from the physical sciences and from modeling science which could be of interest for the purposes of building adaptive capacity. Data from boreholes in Ilulissat and Qaanaaq facilitates the monitoring of changes in active layer thickness and in permafrost temperature. Figure 5 shows active layer thickness and permafrost temperatures in Qaanaaq and Ilulissat from 2018 to 2019.

The active layer in Qaanaaq deepened slightly in the period from 2017 to 2019 from 1.95 to 2.36 m. The time series is too short to conclude whether this is a trend or just the result of unusually warm summers. In Ilulissat, borehole temperature records suggest a deepening of the active layer from 0.75 m in 2016 to 0.93 m in 2018. Permafrost in Ilulissat is more vulnerable to thermal regime disturbances than in Qaanaaq, due to warmer ground temperatures, high ice content at the top of the permafrost, and increased salinity in the deeper sections of the soil profile – which causes the ground to start thawing at sub-zero temperatures. These borehole temperature measurements provide information about the current temperature regime. They serve as calibration data for ground thermal models. Calibrated thermal models can be used to produce projections of active layer thickness. Aalto et al. (2018) used a statistical model to extrapolate data on active layer thicknesses in the Arctic, including Greenland. We have used their model data to produce an active layer thickness map that also shows settlements in Northwest Greenland. The active layer thickness dataset also includes projections for 2050 to provide an idea of which areas may be expected to warm the most.

Figure 6 shows the active layer in a resolution of 1 km^2. The general trend is towards active layer deepening, with differences of up to 29.5 cm. A deepening of the active layer is an important cause of structural damage to buildings and other infrastructure. The top of permafrost is typically the most ice-rich portion, the thawing of which results in the largest volume changes to the ground. In mountainous and sloping terrain, the thawing of ice-rich permafrost may result in slope destabilization, landslides, and rock avalanches. According to the map, the active layer thickness in Qaanaaq and Qeqertarsuaq is expected

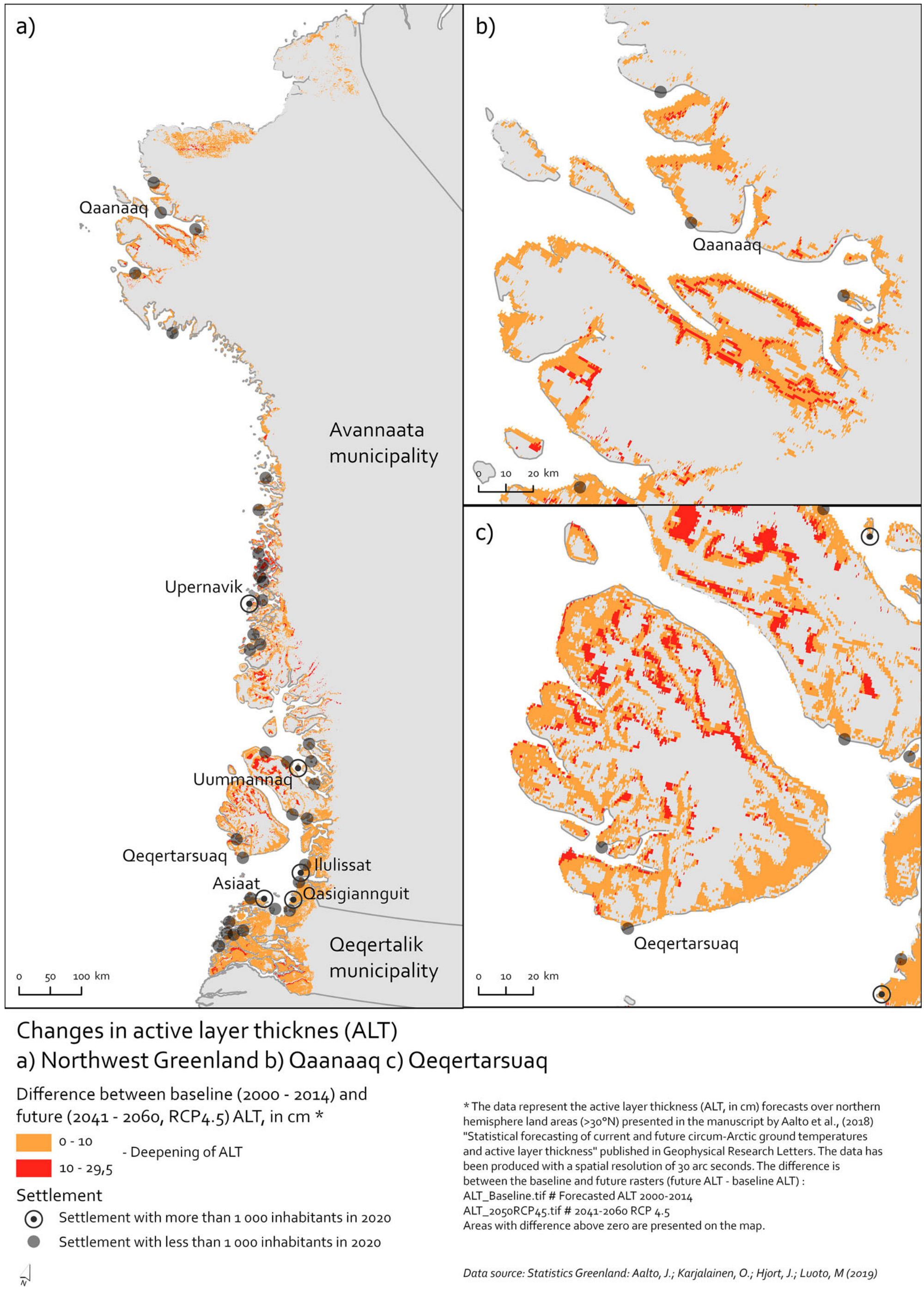

Figure 6. Map 1: Changes to active layer thickness in Northwest Greenland.

to deepen by 0–10 cm, which can cause quite a number of detrimental effects for the built environment. Other settlements, such as Uummannaq, are in an area where the active layer is expected to deepen by 10–29.5 cm, which could indicate an even higher level of risk.

However, because this is based on assumptions, there is a need for local validation to confirm these results.

Despite the obvious benefits of modeling products, the models are usually too approximate to be truly useful for local scale applications. It appears that there is no consistent collection of data to form a reliable regional database for supporting local planning. For this, information about geotechnical ground properties (including soil type, ice contents, thaw settlement projections and estimates of changes in ground mechanical properties upon thawing) would be of more practical use. The absence of further local-level projections for the active layer data is a challenge for both local and national institutions, as they seek to engage in planned adaptation activities. There is therefore a continuing need to examine local and regional soil conditions, to facilitate projections for the next few decades. Adaptation capacity is lowered by the fact that the information available to inform decision-making is limited to data of lesser value in a practical setting and on long-term development and planning.

Concluding remarks

This study has assessed the adaptive capacity to managing permafrost change by applying a theoretical framework encompassing three dimensions. The first dimension, *community awareness of permafrost change,* demonstrates that community members tend to engage in autonomous adaptation, whereby individual homeowners repair damage themselves, but also rely on support from family and friends in the local area.

For modest damage, people often accept living with various minor defects – such as not being able to close a door for half of the year, or thin cracks in the walls. Regarding larger issues, such as severe foundation settlement, people in the community help each other to repair the damage. In these cases, local networks are supportive in assisting the repair work. Sometimes extra costs are incurred because homeowners needed to hire machines or to find professional craftspeople to carry out the repairs.

The second dimension, *institutional organization of adaptation measures for permafrost*, shows that although the municipalities are aware of the impact from permafrost, there are many other issues high on their agenda, as stated in their planning strategies. The main adaptation strategy for municipalities entails building on bedrock whenever possible, and town plans are determined by the landscape to avoid building in zones with permafrost soils whenever possible. Even so, the municipalities also engage in autonomous adaptation practices involving repairing roads and other public infrastructure on an ad hoc basis. These often consist of short-term solutions that need to be repeated on a regular basis. Competing priorities partly explain the autonomous adaptation response that focuses on repairing roads and other infrastructures as damage occurs, given that there are many other issues that require public spending.

The third dimension, *scientific knowledge to inform decision-making on permafrost*, illustrates the gap between the available scientific knowledge and the type of information needed to make strategic, long-term decisions. Because the modeled projection for ALT is too coarse it does not fulfill the need for town planners and engineers. They require specific, local information for building design and construction, usually of the type obtained from field sampling and observations. With this, the study shows a need to strengthen the dialogue between researchers and the municipality to develop meaningful and societally beneficial future research questions.

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