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1. Introduction

This Public Demonstrator is devoted to the development and discussion of Arctic coastal specific indicators of human development and physical changes in order to track changes in the Arctic coastal zone and to evaluate the future impact of adaptation and mitigation strategies put forward in task 9.4. The main data for this report have been collected in conversations, interviews and workshops with Arctic local residents and stakeholders, as well with scientists, and have been augmented by a thorough literature review regarding existing indicators on the coastal zone of the Arctic. The work is based on the pioneering Arctic Social Indicators reports (Larsen, Schweitzer and Fondahl 2010; Larsen, Schweitzer and Petrov 2015), which provide the framework and starting point for this demonstrator.

Indicators are at least one level of abstraction removed from the environmental and societal changes noticeable to local residents and stakeholders. Thus, the relationship between input received during fieldwork and the list of indicators at the end of this report is not as straightforward as it is in our work on risks and adaptations. Also, as permafrost thaw is a physical process, the physical impacts of that process can be seen most directly. Cultural, economic, health and social impacts are in most cases indirectly related to permafrost thaw, that is that the physical process is one among a multitude of factors triggering the impact. Finally, indicator research is always dependent on the starting question – "indicator of what?".

In our case, the general direction of inquiry focused on two dimensions of permafrost thaw. On the one hand, we were interested in impacts of permafrost thaw on the social domains of Arctic human development. On the other hand, in some instances, our inquiries were formulated in order to arrive at indicators assessing the success of adaptation measures implemented to address the impacts of permafrost thaw. In the end, all the indicators addressed below are supposed to tackle the issue of Arctic human development under conditions of permafrost thaw.

As mentioned above, the (bio)physical impacts of permafrost thaw are more straightforward than the social impacts. While our demonstrator has the ambition to holistically integrate socio-cultural, economic, health-related and biophysical indicators, the latter were established in a separate process and with the input of a different set of participants than for the social indicators. As the biophysical indicators of permafrost thaw had been a well-established research tradition in Arctic science before, we will only provide a short summary of the state of the art. Input has been provided by natural scientists in the context of local workshops and/or Nunataryuk general assemblies. As will be further demonstrated below, our focus on cultural, economic, health and social indicators – based on data derived from fieldwork in Greenland, Canada, Svalbard and, to a lesser degree, Russia – constitutes the most innovative aspect of this report.

Still, the following paragraphs provide a short overview over **biophysical indicators** in relation to permafrost thaw, where data is drawn from many more sites across the Arctic and further regions characterized by the presence of permafrost. Box et al. (2019, 6ff.) identify several biophysical

Arctic climate indicators, including air temperature, arctic hydroclimatology, tundra greening as well as the state and distribution of permafrost and corresponding effects in carbon cycling. Permafrost is warming on a global scale (Biskaborn et al. 2019), a trend that corresponds well with changes in air temperature, as the graph below shows.

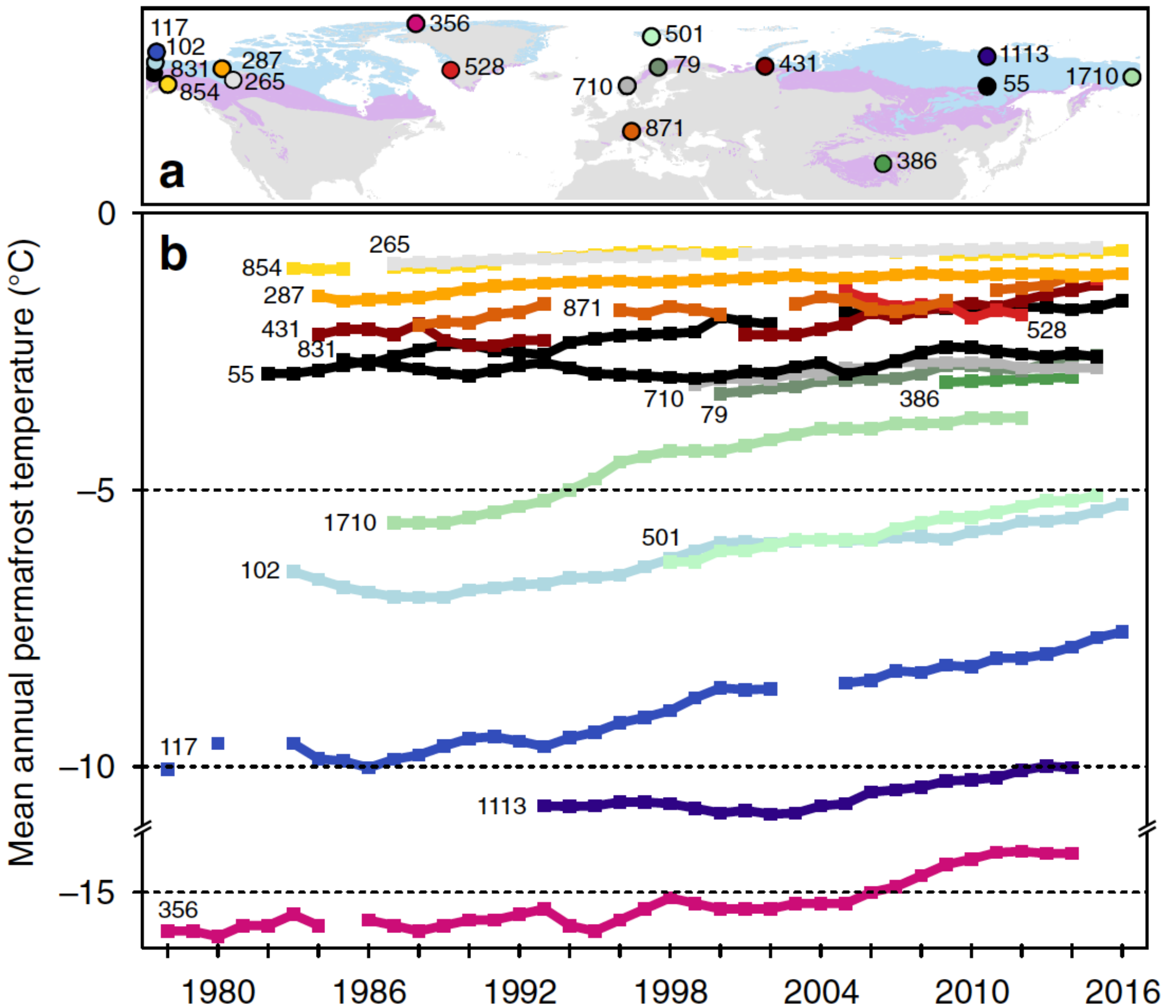

Figure 1 Long permafrost temperature records for selected sites. a Location of boreholes with long time-series data. b Mean annual ground temperature over time (Source: Biskaborn et al. 2019: 2).

Permafrost is considered an essential climate variable (ECV) by the Global Climate Observing System (GCOS), and **ground temperatures** together with **active layer thickness** are considered ECV products, i.e., measurable parameters needed to characterize permafrost. In 2022 a third Permafrost ECV product was added, which is **rock glacier velocity** (see Streletskiy 2021). However, this product only can be measured in mountain permafrost regions, which are mostly absent in Arctic tundra regions. In addition, **subsidence**, as a result of active layer thickening, gives a measure of the rate of change and is being measured in many sites. Ground ice, i.e., the water content of permafrost, is the most important factor for the rate of subsidence, however due to a lack of available data it cannot be considered a reliable indicator.

In addition to the ECVs, the Sustaining Arctic Observing Network (SAON) initiated the Roadmap for Arctic Observing and Data Systems (ROADS) process. As part of this process, SAON attempts to extend the GCOS ECVs by a further set of variables, which are of local to regional relevance. These variables are called Shared Arctic Variables. These variables are being defined based on local needs and in collaboration with people living on permafrost. The measurement of SAVs has the primary goal to serve the peoples' needs who are living on permafrost and provide information which are useful for them in order to better understand ongoing processes related to changes in permafrost and thus for example inform local to regional environmental decision-making processes. (Starkweather et al. 2021)

2. Arctic Indicators: From ASI to Nunataryuk

The Arctic Social Indicators (ASI) project (2006 -2014) has provided an important point of departure in our work to conceptualize a process for the development of Arctic social and (bio)physical indicators for monitoring the impacts of permafrost thaw and for measuring the effectiveness of adaptation and mitigation strategies. ASI was a pioneering project developed under the auspices of the Sustainable Development working Group (SDWG) of the Arctic Council and provided a follow-up to the first Arctic Human Development Report (AHDR). With its early beginning in 2006 its objective was to develop a small suite of indicators of Arctic human development within six prominent domains of human development, that could be used for tracking the state of human development in the Arctic. Since aspects of human development in the Arctic are extremely complex and highly diverse across regions, the ASI team soon realized it would be impossible to capture all aspects of human development in some meaningful manner, and above all in terms of cost and time. Every single aspect of human development (e.g., economy and material wellbeing) could potentially have a countless number of indicators (Larsen, Schweitzer and Fondahl 2010). Therefore, the approach chosen by the team was to develop and select a small, representative set of indicators for key domains of human development, that could be tracked over time and across space at limited costs in terms of money, time, and other resources. Such indicators condense real-life complexity into a manageable amount of meaningful information, and they may be quantitative or qualitative measurements.

Above all, the ASI team agreed that indicators should be clearly defined, reproducible, unambiguous, understandable, and practical (Larsen and Fondahl, 2010). But even in the best of circumstances producing indicators that are both analytically satisfactory and empirically tractable is a challenging task, as indicators must condense real-life complexity into a manageable amount of meaningful information. Indicators of human development should be relatively easy to measure in an accepted manner, stable, and suitable for use in longitudinal analyses. In his work, Harmut Bossell used a famous Einstein quote in observing that indicators should be "as simple as possible but not too simple" (Bossell 1999:11). Furthermore, it is of paramount importance that the chosen indicators reflect the interests and views of stakeholders in the localities where they will be applied (Larsen, Schweitzer and Fondahl 2010).

As discussed in the ASI work, a chosen indicator captures some of the features of a complex reality, while deemphasizing or omitting others. For this reason, developing useful indicators that are robust and valid becomes a process wherein chosen indicators are adjusted, refined, replaced, and sets of indicators may be further augmented as a particular phenomenon (such as global change and permafrost thaw) changes thru time and requires adjustments of the indicator set. ASI has constituted a step forward with its initial starting framework and a small suite of indicators that over the years have been subject to further research, applications, and testing, and ultimately adjustments.

ASI has offered a useful starting point for constructing Arctic social indicators of permafrost thaw. In particular, it has been an important point of reference for selecting quality-of-life domains for indicator development; and for thinking about selection criteria to be used as guiding principles in the process of moving from longer lists of indicators that may well contain spur of the moment indicators and could be heavily tilted toward one type of indicators, to a smaller selection of more robust and more easily measurable indicators in terms of time and resources. While selection criteria are an important part of constructing a small set of useful indicators it is also important to acknowledge that some indicators that may for instance be easily accessible, might on the other hand score lower in terms of robustness than others that are less accessible. Therefore, selection criteria serve the purpose of weighing the different pros and cons.

ASI in its first step towards producing a suite of indicators, first compiled longer lists of indicators for different domains of human development. Such longer lists naturally will include some spur-of-the-moment selection and could also have gaps in what they are meant to measure. Therefore, the second step in the ASI process was for the ASI team to review these indicators and arrive at a shorter and manageable list that was then discussed in settings with stakeholders to arrive at a robust suite of indicators that as a collective could convey something useful about the state of human development and be relatively straightforward to interpret.

ASI arrived at six criteria for selecting a manageable and robust list of indicators, and they are: data availability, data affordability, ease of measurement, robustness, scalability, and inclusiveness (Larsen and Fondahl, 2010).

- *Data availability* concerns whether the data that an indicator will use as a measure exists, and whether it is retrievable. With the Arctic undergoing rapid socio-economic and environmental changes data collected on at least a five-year frequency was preferred.

- *Data affordability* is about the costs of data collection and monitoring. Here it is important to consider whether data is available in official statistics or from regular census reports, or whether primary data collection or surveys are needed.
- *Ease of measurement* is about how easy the indicator is to measure and how straightforward the data is.
- *Robustness* considers how stable the indicator is over time, and whether it will change or remain relevant, or require frequent adjustments.
- *Scalability* considers to what extent a chosen indicator can be scaled up or down to different geographical scales (e.g., household, individual, community, regional and national level).
- *Inclusiveness* concerns whether an indicator is relevant for both indigenous and non-indigenous people, rural and urban, and all Arctic regions.

In terms of process and selection criteria ASI brings useful pillars to the Nunataryuk research, analysis, and discussion for devising Arctic social indicators of the impacts of permafrost thaw on human society in the Arctic. In addition to the selection criteria guiding the work in ASI, in our indicator development work in the Nunataryuk project we have added the important selection criteria of "**relatedness to permafrost thaw**" (see also method section further below).

Within the Nunataryuk project, not only WP 9 has been engaged with isolating indicators of permafrost thaw impacts. Most relevant in that respect is Deliverable 7.4 *Report on the social representation of permafrost thawing, including economic impact within Arctic communities: a qualitative and quantitative analytical framework* submitted by WP 7 (Jungsberg et al. 2020). In that report, the authors also addressed the economic impact of permafrost thaw (while including environmental dynamics, social impacts, and infrastructure impacts), and – to some degree – attempted to identify key indicators for these impacts. Still, they had to acknowledge that most of the suggested indicators are influenced by various factors, not solely by permafrost thaw. We consider the work presented in Deliverable 7.4 important but as its main emphasis has not been on Arctic indicators, it can only serve as a stepping stone for our Public Demonstrator. Other publications resulting from the Nunataryuk project and, at least, partially relevant for our purposes are Larsen et al. (2021) and Ramage et al. (2022). They address important issues relevant for all our sites (such as the risk framework or perceived impacts). In addition, a number of publications with data from Nunataryuk study sites have appeared and provide important materials for this analysis. Examples are works dealing with Greenland (e.g., Jungsberg et al. 2022) and Svalbard (e.g., Meyer 2022, Timlin et al. 2022). Even the Russian study sites, which could not be revisited after 2019 due to the pandemic and the war in Ukraine (see methods section below), resulted in several important publications (e.g., Doloisio and Vanderlinden 2020; Povoroznyuk and Schweitzer 2023; Schweitzer and Povoroznyuk 2022). These data have informed our thinking about Arctic indicators, although the information from Russia could not be formalized into co-produced indicators work.

Outside of the Nunataryuk project, work on Arctic indicators did not stop either with the ASI reports (2010, 2015) or related publications (e.g., Petrov 2018). The majority of these works has been situated in the biophysical realm (see, e.g., Box et al. 2019; Ritchie et al. 2021), whereas Chu (2020) deals with the intellectual history of permafrost (Chu 2020). What is most noticeable for our purposes, however, is the growing attention to the processual and methodological aspects of research in that realm (see, e.g., Allard et al. 2023; Gordon 2021; Vlasova et al. 2021). Gordon's (2021) work specifically addressing research with indigenous communities, and written from an indigenous perspective, is of particular relevance here.

If we direct our attention to specific contributions dealing with the impacts of permafrost thaw, we have been able to make use of several recent contributions dealing with specific aspects of permafrost thaw impacts: such as economic impacts (e.g., Alvarez et al. 2020; Porfiriev and Eliseev 2023), impacts on health (e.g., Revich et al. 2022) or infrastructure (e.g., Hjort et al. 2022), and society and culture (Crate et al. 2017, Crate 2021). This is in line with Gibson's (2021: 18) observation that "there has been an approximate 10-fold increase in the number of publications between 2005 and 2018 addressing impacts of permafrost thaw". Despite this multitude of contributions, however, a holistic integration of socio-cultural, economic, health-related and biophysical impacts of permafrost thaw, let alone a holistic set of indicators of these impacts, remains a desideratum. This Public Demonstrator intends to fill this void.

3. Methods & Methodology

3.1. Framework Model

The methodological and analytical framework we have been using to arrive at a shortlist of Arctic specific indicators and a model for monitoring Arctic change and permafrost thaw in coastal communities draws on the "compass model" that we introduced earlier for assessment and management of risks related to permafrost thaw (see Larsen et al. 2021 and the flowchart below). This processual and analytical model builds on the duality of risks and corresponding indicators – both as physical processes and socially constructed and perceived.

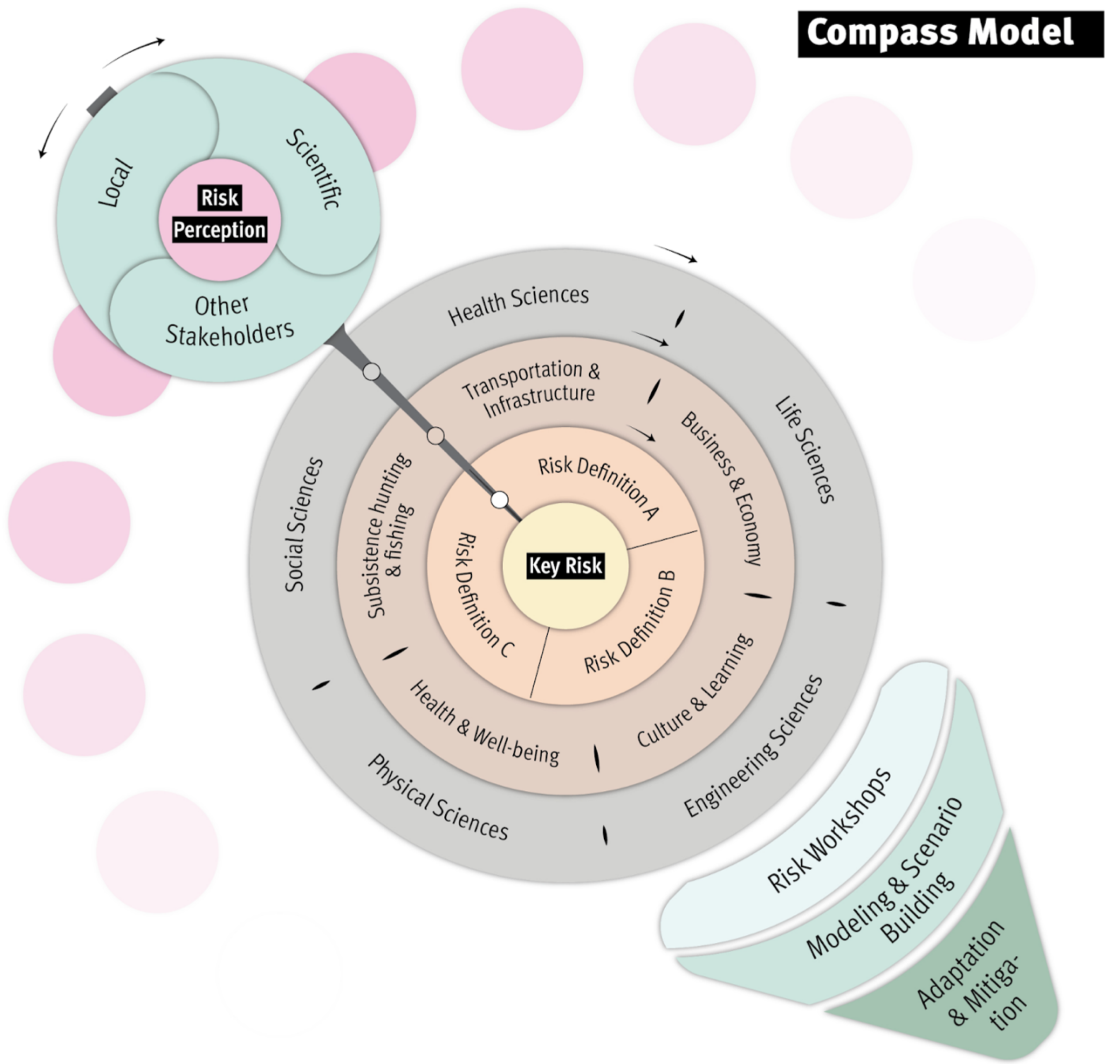

Figure 2: The "Compass model" (Larsen et al. 2021), a conceptual model to guide the identification of risks and the consequent development of adaptation and mitigation strategies in co-production with local stakeholders. Graphical illustration by Levi Westerveld—GRID-Arendal.

Central for our analytical frameworks have been the principles of interdisciplinarity, transdisciplinarity and co-production (Doering et al. 2022, Norström et al. 2020, Yua 2022). Thus, the identification of both risks and indicators of permafrost thaw has been a process of multidisciplinary collaborations and exchange of data between social and natural scientists across different WPs within the Nunataryuk project. In a similar vein, the principle of co-production was implemented through consultations and interviews with local residents and experts and community workshops in each field site.

The initial list of key themes or (life) domains where permafrost thaw has significant impacts has been developed during the process of risks' identification in Nunataryuk Deliverable 9.4 (Larsen et al. 2022). It served as a basis for discussions at an interim interdisciplinary project workshop, and consequently the modified (collapsed or/and reformulated) domains were validated in the study sites. As a result, an updated list consisting of twelve domains was elaborated and cross-checked in all study sites during workshops, interviews and focus groups with local residents. In parallel, discussions about suitable sets of social and biophysical indicators were taking place during designated interdisciplinary workshops and sessions at Nunataryuk general assembly meetings in Venice, Italy in 2018 and in Sesimbra, Portugal in 2022.

After the establishment of the domains, (ad-hoc) indicators per each domain were picked up. In this process, 60 to 90 indicators per each study site were pre-identified for the study sites in Svalbard, Canada and in Greenland. These long lists were further discussed and refined during fieldwork. A scientific brainstorming session on indicators involving social and natural scientists took place at the last Nunataryuk general assembly meeting at Lago-Maggiore, Italy in May 2023. The resulting list of collected indicators gave us additional information and food for reflection. As the next step, the long lists from each study site were distilled and reduced to shorter lists of 19-22 indicators per study site.

To arrive at the (final) list of indicators (see section 5), we applied the selected ASI criteria described above. The following selection criteria were applied: data availability, data affordability, ease of measurement, robustness, scalability, and inclusiveness. In addition to these criteria, we applied the criteria of relevance to permafrost thaw. Researchers from WP9 further applied these criteria to select the most essential cross-cutting list of nine social indicators combinable with the most significant biophysical indicators of permafrost thaw. This short list of indicators relevant to several life domains represents a comprehensive set of indicators valid across Arctic study sites in Canada and Greenland and in Svalbard, Norway. Due to challenges and limitations caused first by the pandemic of COVID-19 and since February 2022 by the war in Ukraine, no follow-up fieldwork in Russia was possible. Thus, the ongoing co-creation and validation of the indicators at local workshops and in interviews with Russian Arctic residents were lacking in the case of the Russian study sites. Therefore, a cross study site comparison based on an incomplete dataset collected in Tiksi and Bykovskiy in 2019, would be methodologically biased. Finally, it should be noted that the suggested toolkit – a short list of Arctic-specific social and biophysical indicators of permafrost thaw, waits for the next steps – application, verification and adjustment to the local settings and needs.

3.2. Community Workshops

In Longyearbyen, an indicator workshop was organized in March 2023 with a group of eleven scientists from the natural sciences and engineering, of which all are working in Longyearbyen and some are residents of Longyearbyen. The group was asked to come up with indicators of the *impacts of permafrost thaw*. The aim of the exercise was that the participants suggest a measurable quantity, something *quantifiable*, that shows something about the impacts of permafrost thaw, in each of the 12 domains. The participants were given sheets containing 12 domains and possible examples for indicators per domain. The participants were then asked to suggest indicators per domain, and they had the possibility to comment. The participants were given the instruction that the chosen indicator should be quantifiable/measurable, and ideally, *easily* measurable. Once the right indicator has been chosen, the idea is that one can follow the development of that quantity over a period of time and see if the adaptation measures that you are applying are helping or not.

In Inuvik and Aklavik, two workshops were organized in February 2023, which were similar to the one conducted on Svalbard. In Inuvik around twenty representatives from different organizations including the Aurora Research Institute, the IRC, the GTC, the JSC, the municipality, and the infrastructure department took part, whereas in Aklavik the group consisted mainly of representatives of the AHTC as well as a few Elders and the Aklavik mayor. On both days the groups were asked to come up with indicators of the *impacts of permafrost thaw*. The aim of the exercise was that the participants suggest an indicator, if possible, in each of twelve domains in total but at least in two or three domains. The participants were given sheets containing 12 domains, including possible examples for indicators per domain. The participants were then asked to suggest indicators, and they had the possibility to comment. The participants were given the instruction that the chosen indicator should be quantifiable/measurable, and ideally, *easily* measurable. Once the right indicator has been chosen, the idea is that one can follow the development of that quantity over a period of time and see if the adaptation measures that communities are applying are helping or not, i.e., if communities are adapting well to permafrost thaw or not.

In Ilulissat one community workshop and a focus group were organized in January 2023 followed by extensive interviews with representatives from industry, the private sector entrepreneurs, various departments within the Municipality, city planners, and technical experts. Workshop participants which included representatives from both the private and public sectors discussed first key risks from permafrost thaw and secondly were asked to consider quantifiable or measurable indicators that could be used to track the effectiveness of adaptation to impacts of permafrost thaw. The indicators should be relatively easy to measure and low cost in terms of time and other resources. A focus group was held at the power station and technical department of the municipality, followed by extensive interviews at the department of finance, housing corporation, and with a large number of private sector representatives. This involved a variety of formal and informal settings and close engagements and dialogues with Ilulissat residents and experts as a way of obtaining as many accounts and perspectives as possible, including different types of knowledge and experience. Interviewees were asked to first share, consider and reflect on existing or possible other adaptation strategies, and then followed by sharing and contributing knowledge and insights into a discussion of indicators (measures) to track the impact of permafrost thaw and the effectiveness of adaptation strategies.

4. Fieldwork – Main findings from study sites

4.1. Greenland – The case of Ilulissat

Interviews and community workshops were conducted in Ilulissat over the period 2019-2023 on the impacts of permafrost thaw within key life domains and in the period 2022-2023 on existing practices by locals and government to measuring and monitoring the impact of permafrost thaw and the effectiveness of adaptation strategies, but also on possible indicators where these are not currently in use. Interviews and discussions with representatives in the public and private sectors showed that the concept of indicators is difficult for many to fully comprehend or appreciate and that monitoring of the impacts of permafrost thaw using indicators is either not currently done or only to a more limited extent. In fact, most interviewees found the concept difficult to work with which limited the extent of this joint exercise and the outcome of the co-production of such indicators. Much of the time was spent explaining and discussing the concept, it's possible usefulness, criteria for selection, and how such indicators might be devised and implemented locally in the future.

The lack of full appreciation of the concept and application of Arctic social indicators of the impacts of permafrost thaw was to some extent linked to the fact that social impacts of permafrost thaw tend to be indirect and are generally intertwined with other factors complicating the task of isolating the impact caused by thawing permafrost. Also, as the impacts have been viewed largely as physical in nature, social impacts have received limited or no attention in terms of the need for monitoring. Nonetheless, some progress was made to stimulate conversation about the usefulness of indicators and what shape such indicators might take, as well as identifying what indicators are already in use (although maybe not recognized as „indicators").

To stimulate discussion key risks of permafrost thaw were briefly reviewed in Ilulissat, which was then followed by a look at existing or possible adaptation strategies locally, and next followed by a sharing of ideas and knowledge about associated measures for tracking their effectiveness (although this latter part of the discussions was felt to be difficult by many, and many did not fully appreciate the point or importance of indicators). However, during discussions of indicators much of the focus centered around cost measures. On the theme of **cost & economy** (material well-being), suggested indicators included in discussion with municipality and private sector experts "additional costs of road maintenance and repair" and "building maintenance and repair costs", as well as "changes in government budget allocation due to permafrost related costs", and "expenditures on additional spare parts and costs of additional hours for vehicle repair and service". Changes in costs seems to be a reasonable straight forward indicator to measure, although higher costs may be caused by other factors than permafrost thaw. A transport company explained that to try and conserve time and costs they invest in training of drivers, and also, they hire their own mechanics and stock up on spare parts. One interviewee explained that measuring costs is fairly simple as it is part of standard business practice in general.

Discussions on impacts on **housing and maintenance** also suggested that additional repair costs could be a valid and reasonable low-cost indicator to measure and track. Other indicators were also suggested including the measured movement of adjustable pile foundations over time. This indicator was suggested by a housing representative after discussion about possible adaptation strategies that included the "method of adjustable pile foundations". Similarly, for the domain of **infrastructure & the built environment** interviewees suggested "indicators on costs related to additional maintenance, or costs related to repairing or securing of pipes and wires from damage from permafrost thaw". But as emphasized by locals such measures although cost data is accessible and indicators could be measured at a reasonable cost in terms of money and resources, the challenge is that it would be next to impossible to isolate the costs related specifically to permafrost thaw. Technical personnel and engineers also suggested indicators such as "number/amount of movement of infrastructure, pipes, wires, masts" due to permafrost thaw and "additional time spent on repairs and maintenance".

Identifying indicators for **health & wellbeing** was complicated by the fact that identified key health risks from permafrost thaw, and associated adaptation strategies, have been limited, in part due to the fact that other factors or a multiple and complex mix of factors explain changes to health and well-being. However, a few indicators were suggested by several of the interviewees, including "reported illness related to changing water quality" (school teacher has noticed more reported illness by students – such as stomach ache due to water quality); and "reported accidents related to changing road accidents" (one transport sector representative explained that bumpy roads and changing road conditions may cause accidents – however the incidence is very low. Other factors brought up for discussion during a community workshop was that of water quality and the need to have access to tools for measuring quality. One interviewee explained that tests are performed in Nuuk, and that delays in testing can be caused by delays in flight service, or cancellation of flights. Hence, the need for local test centers was discussed. In this connection the domain of **water security** was addressed, and here the suggested indicator by various municipality representatives was a "measure of water quality", and "measure of pollution rates in water". The details of such a measure were not discussed, but the measure belongs to the group of existing measures (although as in the case of other indicators not specifically in relation to permafrost). Similarly, an indicator for **ecosystem functioning** would also include a measure of the "change in water quality".

The indicator domain of **knowledge, language & dducation** was discussed at some length with several of the interviewees pointing to the challenge with turn-over of staff, difficulty attracting and retaining workers and the potential change in demand for technical personnel and trained engineers to meet the changing needs related to damage caused by permafrost thaw. Indicators suggested included the "number of special advisors hired to advice on issues and challenges related to permafrost thaw"; and "advertised technical positions" (various municipality departments, and private sector representatives).

Cultural vitality is a domain that is challenging to devise suitable indicators for at best, but is even more complicated when it comes to the question of measuring the impacts of permafrost thaw. In interviews with tourism representatives and dogsled owners, the impact of permafrost thaw (although not an isolated factor) on the ability to drive a snowmobile or run a team of sledge dogs was discussed. Tour guides and private operators described the reduction in snow extent, the more frequent challenge of using these means of transportation and engaging in cultural practices that include dog sledding and snowmobiling as part of being in nature. While no specific indicator was suggested, from the interview data we can identify as an indicator "change in the amount of time dog sledding and snowmobiling"; or "extra time spent getting to hunting and fishing sites" (locals described how they often need to take different and longer routes due to less ice and snow). The same indicator was discussed for the domain of **recreation & being in nature** (i.e., reduced time on the land for snowmobiling and dog sledding). A related domain **food security** was touched upon in these discussions, and indicators suggested were: "Change in harvest due to changes to amount of time spent on the land and changed travel routes".

The domain of **planning & fate control** was also an important life domain in many of the discussions with local experts and stakeholders. While it was difficult to conceive of a robust and easy to measure indicator (due to the multiple and complex factors) there was some agreement that "change in amount of time spent planning" and "budget changes due to permafrost related costs" might be possible indicators, although not very precise and therefore possibly of limited value for monitoring the impacts of permafrost thaw. Also, the domain on **mobility** (travel & transportation) was part of these discussions and possible indicators included "change in travel time to fishing and hunting grounds", and "incidents of accidents" (also related to road conditions).

Here below is the final and revised list that was produced in co-production with local stakeholders.

4.1.1. List of Indicators – Ilulissat

Domains	Suggested Indicators
Costs & Economy (Material Well-being)	Costs of road maintenance and repair
	Building maintenance and repair costs
	Changes in government budget allocation due to permafrost related costs
	Expenditures on additional spare parts due to permafrost thaw
	Costs of additional hours for vehicle repair and service

Housing	Measured movement of pile foundations over time
Health & Wellbeing	Reported illness related to changing water quality
	Reported accidents related to changing road conditions
Knowledge, Language & Education	Number of special advisors hired to advise on issues and challenges related to permafrost thaw.
	Number of advertised technical jobs
Cultural Vitality	Change in amount of time dog sledding and snowmobiling
Planning & Fate Control	Change in the amount of time spent planning due to permafrost thaw
	Budget changes due to permafrost related costs
Infrastructure & Built Environment	Costs related to additional maintenance, repairing or securing of pipes and wires from damage from permafrost thaw
	Number/amount of moved infrastructure, pipes, wires, masts due to permafrost thaw
	Amount of additional time spent on repairs and maintenance
Recreation & Being in Nature	Change in amount of time on the land for snowmobiling and dog sledding
Mobility (Travel & Transportation)	Reported accidents on the land and due to travel activities
	Travel time to fishing and hunting grounds
Water Security	Measured water quality
	Measure of pollution rates in water
Food Security	Change in harvest due to changes to amount of time on the land and changed travel routes
Ecosystem Functioning	Measured water quality

4.2. Beaufort Sea Region – Canada

The ASI framework for indicators of human development was applied in the Inuvialuit Settlement Region (Petrov 2018). However, as mentioned in the introduction, this work did not include indicators of permafrost thaw and its impacts. During the workshop discussions held in Inuvik and Aklavik in early 2023, it became evident that biophysical indicators of permafrost thaw are more direct and relatively easy to determine compared to socio-cultural, economic, and health-related indicators. Although the effects of permafrost degradation on various aspects of life are generally indirect, a few indicators were suggested, particularly in the domains of **housing and health**, where concerns are frequently raised, not only related to permafrost thaw. For instance, it was proposed to examine cases of decay and mold in houses, specifically focusing on mold-related health impacts and the number of tuberculosis cases. In the domain of housing, an idea was to track the amount of money people spend on gravel for repairing their driveways. However, it was acknowledged that a family or individual may not have sufficient funds in a particular year and might decide to spend less on buying gravel, which could introduce bias.

Regarding **mobility and infrastructure**, it was suggested to monitor the budget allocations at the territorial, federal, and municipal levels for the maintenance and repair of the Dempster highway. The residents of the Inuvialuit Settlement Region and Gwich'in Settlement Area in the North-West Territories (NWT) rely on the Dempster Highway as a road connection to the South. However, the NWT and Yukon governments have been unable to reach a satisfactory agreement for many years regarding the highway maintenance of the Yukon portion. This situation negatively impacts the residents of the Mackenzie Delta Region in terms of mobility and supply. This lack of funds invested in the NWT section of this particular road infrastructure, was compared to the Yukon section, where roads and bridges are better maintained, partly due to the extractive industry's interest in a well-functioning transport infrastructure in the region. Another suggestion was to count the number of slumps along the Dempster Highway and along the Inuvik-Tuktoyaktuk Highway and calculate the road repair costs associated with permafrost thaw.

For **food security and cultural vitality**, it was proposed to use the number of fish caught and caribou harvested annually as indicators. Nevertheless, it was noted that such indicators might not be very useful for measuring the impacts and challenges caused by increased permafrost thaw. In general, it was agreed that having indicators to monitor how well communities are adapting to permafrost thaw would be useful. However, it was repeatedly emphasized that finding non-physical indicators related to permafrost thaw is challenging. Indicators may be identified, but they may not solely be linked to permafrost thaw and could be influenced by multiple factors, such as the one mentioned last. Therefore, they may indicate overall community resilience, but not necessarily the specific impacts of permafrost thaw.

Other topics discussed included the **lack of expertise** in infrastructure maintenance, leading to errors when manuals and codes are not followed, as exemplified by the case of the Inuvik Igloo church. The church had to be insulated due to high heating costs caused by rising gas prices. Faulty insulation resulted in blocked ventilation pipes, which heated the ground beneath the structure and caused thawing of the permafrost underneath. Once the error was identified and rectified, the permafrost gradually recovered. Thermistors installed beneath the church by the Aurora Research Institute were used to monitor the situation. Participants in the discussion expressed their perception that permafrost and the active layer are particularly fragile in the Beaufort Delta Region. They also highlighted the usefulness of **new technologies** like satellite monitoring, which can detect changes of only a few millimeters today. These technologies can be highly valuable for monitoring changes in both the natural landscape and infrastructure.

The following table(s) present the suggestions given for indicators during the workshops in Inuvik and Aklavik.

4.2.1. Results from Indicator Forms

Domains	Suggested Indicators
Costs & Economy (Material Wellbeing)	Community Household surveys to determine change or damage from shifting etc.
	Direct cost of permafrost mitigation measures for buildings, roads, etc.
	Government (territorial, federal, municipal) budget allocations (for road maintenance): Increases and Decreases
	1) Ice road/supply road closure and opening times (earlier/later), 2) shifting utilidors: measurement, maintenance costs (infrastructure cost), 3) slumping/failing of water control systems: number of occurrences
	1) Cost of maintaining airport runways, 2) Cost of Food Prices, 3) Government Infrastructure Maintenance Costs: Change in percentage, 4) Housing Costs, 5) Increase/Decrease of natural events per year, e.g., floods...
	1) Number of buildings being moved to avoid erosion (both coastal and along rivers), 2) Costs per community per year to move infrastructure (public & private) - also applicable to built environment/infrastructure. 3) Costs to repair relict infrastructure (e.g., old oil and gas sumps being impacted by permafrost thaw)
Health & Wellbeing	Failing residential support structures
	1) Increase in reported accidents related to on the land activities, 2) Increase in illness that would not normally affect a community
	Extent of water bodies (e.g., number studied) studied to assess whether one can safely drink water or not (due to contaminants from permafrost thaw, beaver fever from expanding range)
	Increase in new/unknown health concerns, incidents of impact on health of field workers
Knowledge, Language & Education	Percentage of time spent on permafrost issues in (research/academic) job
	1) Vacant position numbers in all levels of governments. 2) Increase in positions.

	1) Number of vacant technical positions, 2) advertise technical jobs, 3) Number of university programs addressing climate change
	Stories from Elders documenting rates of landscape change (frequency of slumps, changing river courses etc.)
Cultural Vitality	(Number of) Identified places on the land that have been affected by permafrost thaw
	Number of cultural sites lost due to coastal erosion
	Reduction or non-openings and closures of community outdoor rinks
	1) Change in number of cultural activities held per year, 2) change in the participation of cultural activities, 3) Number of persons with knowledge of hosting cultural activities
	1) Time spent repairing cabins/camps damaged by permafrost thaw impacts, 2) Ability of Elders to share stories of changes to the land in their traditional languages
Planning & Fate Control	Number of plan changes or non-compliance of existing plans, bylaws and legislation
	1) Increase in planning budgets, 2) number of changes done to approved plans, 3) increase in time spent on planning
	1) Number of planning sessions per community per year,2) number of community climate change action plans produced per year across NWT
Infrastructure and built environment	Recreational time spent at cabins
	1) Government budgets in these areas: Increase or decrease, 2) increase in maintenance costs, 3) Overall condition of infrastructure over time
	Airport runways and associated failures, can be viewed via remote sensing
	1) Increase in public sector maintenance budget 2) Number of reports filed to local government, by communities' representatives or members, 3) Reports from monitoring agencies and researchers
	1) Number of permafrost workshops in NWT communities per year, 2) costs for NWT/Arctic airports to repair runways each year, 3) retention/length of employment for municipal government staff
	Adoption of best practices for infrastructure development at all levels, impact to building code. Incidents of vehicle accidents.
Recreation & Being in Nature	Remote Arctic National Park trail closures

	Number of community feedbacks on time on the land
	1) Amount of time needed to access harvest areas (Hunting, berries), 2) Amount of time needed to get to cabins
Mobility (Travel & Transportation)	1) Number of accidents reported by hunters and trappers, 2) water monitoring data, 3) coast guard reports, 4) recreational RPAS pilots' images
	1) Length of travel seasons for different modes of travel (e.g., boat vs. Vehicle on rivers/ice roads, or ATVs vs. Skidoos), 2) Time/effort spent repairing community airstrips from potholes, cracks, etc.
Supply	Slumping images, photos of roadside pits
	1) Number of incidents reported by truckers, 2) Number of closures reported by infrastructure departments
	Cost of monitoring changes along highways (e.g., overflow at creek crossings, clearing slides)
Water Security	Measure pollution rates in the water level
	Measure changes to traditional water routes
	Measure water turbidity due to slumps and erosion runoff
	Number of Boil water notices
	1) Amount of data collected by researchers and by government agencies and 2) Number of reports made by the community
	Number of regional studies looking at contaminants in water, fish health and safety of water for consumption
Food Security	Less time on the land and how far hunters/harvesters need to travel
	Community survey/interview question: Has permafrost activity (slumps, erosion) affected your on-the land activities?
	1) Increases in the cost of food, 2) Quality and quantity of food in shops, 3) changes in food delivery (These indicators may also be affected by increase in population)
	1) Number of people using food banks (increased food costs with decreased availability), 2) Effort required to access traditional foods on the land (measurable in units of time)
Ecosystem Functioning	Monitor/measure animal health and diseases
	(Measure) effect of higher water turbidity on fish and spawning habitat
	Water quality, drinking water, flow of creeks, affected seasonal(ly?)

	Report on the number of sick animals or animals dying
	1) Number of cumulative impact studies across North that include permafrost components (both traditional knowledge and scientific sources), 2) regeneration rates of environmental disturbances (e.g., tree growth on old seismic lines), 3) success rate of hunting/fishing efforts (e.g. number caught per time unit) = indicator of population abundance/health, 4) Monitoring efforts (e.g. community-based monitoring, time spent in the field measuring environmental parameters)

4.2.2. Revised List of Indicators

The following is a revised list of indicators, based on the one above, however condensed to indicators that are at least somewhat linked to permafrost thaw and are at least in theory possible to measure. The color green indicates that the indicator is relevant to at least four of the twelve domains.

	Suggested Indicator
1	Per household maintenance repair costs due to infrastructure damages caused by PERMAFROST THAW
2	Direct maintenance and repair costs of permafrost mitigation and adaptation measures for roads
3	Ice road/supply road closure and opening times (earlier/later)
4	Maintenance and repair costs for communal infrastructure (e.g., utilidors, powerlines, airstrips, roads, foundations of public buildings such as hospitals, police and fire stations, water control systems and energy supply infrastructure etc.)
5	Maintenance and repair costs for industrial and other infrastructure (mines, oil wells, antenna parks, army bases etc.)
6	Number of reported extreme natural hazardous events per year related to PERMAFROST THAW
7	Number of buildings being moved to avoid erosion (both coastal and along rivers)
8	Reported accidents related to on the land and travel activities
9	Number of illnesses and health concerns related to mold
10	Increase in new and resurfacing health concerns that would not normally affect a community
11	Frequency of observed landscape changes related to permafrost thaw by active land users and knowledge holders
12	Number of cultural sites damaged or lost due to erosion and subsidence

13	Time spent repairing cabins/camps/houses other structures damaged by permafrost thaw impacts
14	Number of urban planning "at risk zones" from permafrost thaw
15	Number of reports and planning sessions/open hearings on permafrost issues
16	Levelness of airport runway(s)
17	Number of (hiking) trail and road closures due to permafrost thaw related issues
18	Amount of time needed to access cabins, harvesting and hunting areas
19	Number of boil water notices per year due to high water turbidity (CAN specific)
20	Increase or decrease in (un)known or resurfaced animal health issues (f.e. anthrax, mercury-related)
21	Number of permafrost thaw problems along Inuvik-Tuktoyaktuk Highway reported to permafrost scientists at Aurora Research Institute

4.3. Svalbard

In Longyearbyen, the societal impact of permafrost thaw that is of most concern are impacts on the built environment: on housing, infrastructure, and material cultural heritage. One suggested indicator for Longyearbyen was thus the annual costs of road repair. However, as was emphasized during the workshop, this indicator assumes that road repair is linked to permafrost thaw, which is often the case, but not always. Two challenges thus arise: a) are the costs directly related to permafrost thaw at all? and b) the costs are also entangled with different variables, such as supply costs and labor costs, which have nothing to do with permafrost thaw. It would be possible to adjust for that, but then the number would not be so easy to obtain.

This led to the discussion of a major difficulty with developing indicators of permafrost thaw impact, namely that it is often **hard to isolate what are consequences of permafrost thaw**, and what are consequences of other factors, for instance faulty engineering practices or lack of maintenance. Even with a seemingly straightforward indicator such as annual costs of road repair, the impact of permafrost thaw is hard to isolate from other factors. One comment from the Longyearbyen workshop was that it is "impossible" to come up with an indicator for the impacts of permafrost thaw, because "it is very hard to isolate the effects of permafrost thaw." An indicator such as the annual costs of road repair is a result of several factors, and it is hard to distinguish what is a result from permafrost thaw and what is the result of something else, for instance lack of maintenance, engineering, in- or decrease of maintenance costs due to inflation etc. Another participant commented that the domain of cost and economy in Longyearbyen has to do with tax level, and that it is difficult to see the connection to permafrost thaw. Thus, they commented, "I don't really understand this way of thinking." The indicator discussion in Longyearbyen thus reflected a main point in other discussions on risks and hazards related to permafrost thaw and permafrost thaw impacts in general: that the connections between permafrost thaw and society are often **indirect**, and that there are so many factors that contribute to the impacts we see and it is difficult to identify clear linkages. It was furthermore emphasized in the workshop that the challenge with an indicator is – contrary to discussions of risks or societal impacts – that it has to be a number, something quantifiable. As such, an indicator does not display the complexity of observable impacts that are always a result of several interconnected factors. A main take-away from the workshop in Longyearbyen is thus that permafrost thaw impacts are indirect: people are not directly impacted by active layer thickening or increase in ground temperature, but they are very much indirectly impacted, in many domains of their lives.

The participants did, however, agree that **it would be beneficial** for Longyearbyen to have a set of indicators of permafrost thaw (both biophysical and socio-cultural ones). They also concluded that whereas the natural scientists look at permafrost thaw as such, the social sciences are more interested in looking at the societal impacts, and that hence the dialogue between these two groups is essential. The Shared Arctic Variables work and the expert panels that will be created in this context is one potential avenue where this dialogue can be taken forward. This project will establish expert panels that come up with a number of observations related to permafrost that should be monitored in order for Arctic communities to better deal with permafrost and permafrost thaw.

In the Longyearbyen workshop, also **biophysical indicators of permafrost thaw** were discussed.

The following biophysical indicators were mentioned:

- Carbon cycle
- Ground formation
- Active layer thickness (ALT)
- Size of slope failures (in summer, i.e., not avalanches)
- Permafrost temperature
- Remotely sensed ground subsidence tracking
- Monitoring temperature change in ground at different levels
- Coastline tracking with satellites
- Permafrost degradation: increase of the ALT (cm/year); increase of ground temperatures (Celsius/year); development of residual thaw zones (so-called taliks)
- Ground ice thickness

Contrary to indicators of permafrost thaw impacts, the participants were in agreement that these are very straightforward. The two main physical indicators of permafrost thaw are active layer thickness and ground temperature. These are the two essential climate variables (ECVs) for permafrost as defined by the Global Climate Observing System (GCOS). These *are* already being monitored, so in the biophysical domain there is no need for defining new indicators, the participants in Longyearbyen agreed. We should make sure that we use what we already do and measure. In addition to the two ECVs, the development of residual thaw zones, *taliks*, and unfrozen water content / ground ice content, as well as deformation of slopes, were additional physical indicators that were mentioned that would complete the picture. It was furthermore emphasized that the specific landforms need to be considered. One has to take into account that the location and specific landforms will impact the indicators. For instance, towns are "heat islands", releasing energy into the ground, changing the whole thermal regime of the towns. Not all permafrost thaw is due to climate change; human influences are heavily impacting the thermal regime and changing the natural system. Thus, permafrost thaw does not necessarily mean climate-change induced permafrost thaw.

Another topic of discussion in Longyearbyen was **the aim of the indicators**. The workshop participants agreed that the challenge is that it seems impossible to separate permafrost thaw out of the complex nature of the impacts. But, as one participant asked, is that even important? What is the end goal of these indicators? One aim would be to help communities to find out whether what they are doing to face the challenges related to permafrost thaw, is working or not. In other words, if they are adapting successfully or not. If this is the direction we are going, then maybe it is not important what exactly the impact is related to. They have some challenges with roads or with other infrastructure, they are attempting to alleviate those problems, and we want to try to say if it is helping or not. The important pillars are thus risks and hazards on the one hand and adaptation measures on the other hand. To measure to what extent adaptation measures are working or not could be one rather specific goal of these indicators. Another aim would be to try to understand the impacts of permafrost thaw themselves. Both are not very straight-forward because of the complex nature of the interaction between permafrost thaw and society. To isolate the adaptation measure impact factor is also not an easy task. A main point from the discussion in Longyearbyen was that we need to define: Why do we even aim to establish indicators, what is the point?

This is related to another point of discussion in the Longyearbyen workshop, namely ***what* the indicators are measuring**. Three related, but distinct, aspects were discussed: 1. Indicators of the impacts of permafrost thaw, 2. Indicators of the adaptation measure impact factor (how well are adaptation measures working?) and 3. Arctic human development under conditions of permafrost thaw.

Specific examples of indicators were discussed in the workshop: One participant remarked that there is only one indicator that to them seemed measurable and logical for Longyearbyen, namely the number or *square meter size of slope failure within the city limit*. They stressed that again, this is not necessarily exclusively related to permafrost thaw, but it *is* related to permafrost thaw *and* related to society. One alternative way to do it would be to compare the costs for maintaining Longyearbyen with a town on the mainland, see if they would deviate, and then try to figure out what the input of permafrost is under this deviation. This would give us an idea of the input of permafrost to cost increase or decrease.

In the following we present the list of indicators suggested by the workshop participants.

4.3.1. List of Indicators

Domains	Suggested Indicators
Costs & Economy (Material Wellbeing)	Quantify the infrastructure repair / maintenance costs
	Living wage
	Costs for damage mitigation when building new infrastructure, per building, road etc. Comment: hard to be objective about this.
	Cost per building footprint m2 of suitable foundation (piles, cooling pad). Comment: increased thaw, increased cost but of course also tangled with supply and material costs and labor costs
	Ability to improve the equipment to permanently maintain a sufficient lifestyle
Health & Wellbeing	Availability of X number of types of medical doctors – yes/no
	Number of slope failures. Comment. Direct link to societal safety.
	Area (m2) of slope failures
Knowledge, Language & Education	Quantify the turnover in the different sectors in town / questionnaire on basic permafrost knowledge in new staff
	Availability of high school; travel time to school/kindergarten
	Change in number of mentions in media/scientific literature (of permafrost thaw)
	Number of students in the Permafrost courses at UNIS
	Number of publications (also including MSc and PhD theses) related to / about Svalbard permafrost. Comment: assuming increased impacts and thaw encourages more output on this topic.

Cultural Vitality	Monitor changes in cultural heritage using remote sensing and field observations of permafrost temperature and active layer thickness
	Availability of xx m2 (standard number) of area of a cultural house per inhabitant: yes/no
Planning & Fate Control	Increased costs in estimates on municipal planning
	The time in the future that is taken into account to plan something
Infrastructure and built environment	Quantify the housing / infrastructure state, deformations (using remote sensing and field measurements)
	Temperature of permafrost
	Active layer thickness
	Number of abandoned buildings because of evacuations
	Cost of 1 square meter on: a) new dwelling, b) 10-year-old, c) 30-year-old building
	Amount / cost of airport runway needed
	Number of road, housing and other infrastructure repair needs
	Number of deviations / problems reported per year
	Tracking ground subsidence using existing EO-capacity
	Monitoring extreme weather events and water run-off
Recreation & Being in Nature	Nights spent at cabins requiring crossing of sea ice (not permafrost thaw related)
	Summer foot traffic (number of people) to Sarkofagen or another specific spot. Comment: but problems with these trails are not necessarily directly linked to permafrost thaw.
Mobility (Travel & Transportation)	Quantify / measure changes in road and other infrastructure
	Price of fuel

	1) Travel time to a regional hub / capital; 2) to a non-capital transport hub; and 3) costs for 1 and 2.
	Number of reported road closures
	Amount / cost of airport runway needed
	Number of days with closed roads
	Resources spent on road/airport runway repair / reported road closures – agree with example
	Level-ness of runway?
	Frequency of re-pavement of roads and runway
Supply	Quantify the food storage for the population
	Max time between supplies
Water Security	Monitor the dam dynamics: 2 indicators: permafrost temperature + active layer thickness
	Availability of a second water source: yes/no
	Cost of $1m^3$ of water
	Water quality in Isdammen [fresh water reserve] or other rain water supplies
	TLS (terrestrial laser scanner) scanning of the dam (Isdammen) 3D shape. Comment: very Longyearbyen specific)
	Measure levels of biggest concern contaminants from mine tailing piles (not sure what those contaminants are)
	Monitoring settlement of dam structure
Food Security	Quantify the food storage for the population
Ecosystem Functioning	Comparative ratio to undisturbed case

4.3.2. Revised List of Indicators

Nr.	Suggested Indicator
1	Number of slope failures due to permafrost thaw (related to indicator on natural hazards, see above).
2	Area (m2) of slope failures (Within city limits / within a defined closeness to infrastructure. In summer, i.e., not avalanches).
3	Number of cultural heritage structures/monuments affected by permafrost thaw
4	Increased costs in municipal planning related to permafrost thaw
5	Number of abandoned buildings and cultural sites because of evacuations
6	Costs of repair of the airport runway due to permafrost thaw
7	Number of house repair needs
8	Length of road stretch repair needs
9	House owners report on numbers of houses with identified problems related to permafrost thaw (would not work in all study sites)
10	Sqm of ground subsidence within city limits using remote sensing and/or field measurements
11	Number of reported hazardous extreme weather events related to permafrost thaw per year (such as landslides or coastal erosion)
12	Maintenance and repair costs of roads and other infrastructure related to permafrost thaw
13	Number of reported road/road section closures due to permafrost thaw (slumping, landslides, coastal erosion, due to repair of permafrost thaw-related damages) per year/per 3 years
14	Costs of repair of the airport runway due to permafrost thaw
15	Level-ness of airport runway
16	Frequency of re-pavement of roads and runway due to permafrost thaw
17	Availability of a second/reserve/back-up/alternative water source: yes/no

18	Water quality: drinkable/not drinkable. Yes or no. (level of contaminants (Mercury))
19	Number of m2 of settlements in fresh water reserve

4.4. Suggested indicators by the Nunataryuk consortium

In addition to collecting potential indicators in the individual study sites, we conducted a brainstorming exercise with the Nunataryuk consortium where researchers contributed with their knowledge and suggested ways in which indicators could possibly be developed. This exercise served as a way of additional confirmation and verification of the information gathered in our study sites. The list that follows contains the revised list of indicators that were collected during the Nunataryuk General Assembly in Italy in May 2023. As with the study site lists, this revised set is based on the application of the ASI criteria and relatedness to permafrost thaw.

4.4.1. Revised List of Indicators Nunataryuk Consortium

Domains	**Suggested Indicators**
Infrastructure and built environment	Increase impoundment (thaw ponds surface increase) (comment: also, drainage)
	Number of ice cellars that can no longer be used due to permafrost thaw
	Aggregated costs for (communal/Industrial/private) infrastructure maintenance and repair due to permafrost thaw
	Yearly costs for road repairs and maintenance due to permafrost thaw
	Number of houses that are relocated, demolished or abandoned due to permafrost thaw
Recreation & Being in Nature	Number of fish caught
	Length of ice road season (Opening and Closure dates) = Number of days per year
	Number of times that cabins are releveled or moved per measuring period

Mobility (Travel & Transportation)	Road disruptions and reductions in speed limits
	Number of road disruptions due to permafrost thaw per measuring period (and number of hours/days)
	Length of ice roads season (number of days per measuring period)
Supply	Length of disruption of roads due to permafrost thaw (number of hours/days per year)
	Ground cold rooms for food conservation
	Length of Ice Road season = Number of Days
	Number of ice cellars being closed due to PERMAFROST THAW
	Number of road disruptions due to permafrost thaw per measuring period
	Mercury content in water reservoirs/bodies or viruses
Water Security	Number of PERMAFROST THAW impacts (e.g., thaw slumps, thawing around dams) to water supply infrastructure. Measurable unit dependent on each case.
	Number of boil water notices
	Level of mercury content in fish, water sources, soil etc.
Food Security	Days of no / cancelled deliveries to supermarkets because of problems related to PERMAFROST THAW
	Airstrip repairs and maintenance costs due to permafrost thaw
	Duration of ice roads
Ecosystem Functioning	Mercury content in key species, water etc.
	Mercury content in key species
Costs & Economy (Material Wellbeing)	Difference in cost-of-living index between the North and the South
	Cost of road maintenance and repair

	Perceived impact on household material wellbeing
	Household expenditures on maintenance and repairs due to permafrost thaw
	Opportunity cost of non-travel due to permafrost
	Permafrost related increase in transport costs
	Budget changes due to permafrost thaw
	Change in housing price index due to permafrost thaw
	Change in local CPI
	Change in gas prices
	Change in cost of public transportation
	Cost of relocation due to permafrost thaw
	Mental health impact of climate/environmental change in livelihood
	Increased levels of certain chemical contamination in water, including natural mercury, released industrial pollutants and microbes
	Reported increase of sickness caused by organic and inorganic contaminants due to permafrost thaw (e.g., anthrax and mercury)
Health & Wellbeing	Increase new and returned human and animal illness and deaths caused by permafrost thaw
	Number of reported health incidents that can be linked to permafrost thaw, e.g., caused by natural hazards as well as chemical and microbial contaminants
Cultural Vitality	Number of cultural (and religious) monuments and heritage sites lost due to erosion/permafrost thaw
Planning & Fate Control	Number of meetings dedicated for special emergency
	Average time spent on planning
	Number of urban relocations due to erosion, sea level rise or ground subsidence/instability

5. ASI selection criteria applied: Condensed set of social indicators

The ASI selection criteria were considered for each suggested indicator and determined our final selection. In addition to these criteria (described above), we applied the criteria of **relevance to permafrost thaw**. The following is a presentation of the indicators across study sites and domains, which as a collective represent a set of indicators of permafrost thaw impacts and of adaptation effectiveness in Arctic coastal communities. The list includes those indicators that we deem most robust regarding the ASI selection criteria, i.e., which can be monitored at a relatively low cost, and are all relevant for all study sites (with the exception of the indicators regarding ice cellars and ice roads). Note that there is no hierarchy among them, they are listed in random order and they pertain each to several of the life domains discussed earlier. While most of the indicators listed below are relevant for all study sites, and - we would argue - across the Arctic, others are more site-specific.

Cultural heritage structures: **Number of cultural heritage structures/monuments affected by/lost due to permafrost thaw**

This indicator spans various domains (Costs & Economy, Knowledge, Language & Education, Cultural Vitality, Planning & Fate Control, Infrastructure, Recreation & Being in Nature), and scores high on the selection criteria (robustness, data availability and ease of measurement, and scalability). Cultural heritage structures are directly affected by permafrost thaw for example through erosion or subsidence, and the indicator is possible to measure.

Abandoned/relocated buildings: **Number of buildings that are relocated, demolished or abandoned due to permafrost thaw**

The built infrastructure, including housing, is a main interface between society and permafrost thaw. This indicator provides a good picture of how a specific community is affected by thawing ground, including erosion. It spans various domains (Costs & Economy, Health & Wellbeing, Cultural Vitality, Planning & Fate Control, Infrastructure, Recreation & Being in Nature), and scores high on the selection criteria (robustness, data availability and ease of measurement, and scalability).

Natural hazards: **Number of reported natural hazards related to permafrost thaw per year (such as landslides or coastal erosion)**

Permafrost-thaw induced landscape changes are an issue of major concern across the study sites. This indicator is directly related to permafrost thaw and tells us something about how landscape changes affect communities. Natural hazards have the potential to affect many aspects of society, and the indicator spans various domains: Costs & Economy, Health & Wellbeing, Cultural Vitality, Planning & Fate Control, Infrastructure, Recreation & Being in Nature, Mobility and Supply. The indicator scores well in terms of selection criteria (data affordability and availability, ease of measurement, robustness and scalability).

Roads and runways: **Road and runway damage – frequency of closures and/or cost of repair**

This indicator spans various domains (Costs & Economy, Planning & Fate Control, Infrastructure, Recreation & Being in Nature, Mobility and Supply), and scores high on the selection criteria. It is one of the few areas where costs directly related to permafrost thaw and infrastructure damage can be easily assessed.

Contaminants: **Number of (reported) incidents of contamination and/or number of illnesses related to contaminants**

This indicator addresses the quality-of-life domains of Health & Wellbeing and Water & food security but is also relevant to the domains of Costs & Economy, Cultural Vitality, Planning & Fate Control, Infrastructure, Recreation & Being in Nature, and Ecosystem Functioning. The indicator is not locally specific and can be scaled up or down on different geographical and social scales. It also appears to score well in terms of the selection criteria of data affordability and availability, ease of measurement and robustness. The indicator is defined in broad and non-specific terms and any of the following more distinct versions might be considered for specific monitoring purposes:

- Reported increase of sickness caused by organic and inorganic contaminants due to permafrost thaw (e.g., anthrax and mercury)
- Increased levels of certain chemical contamination in water, including natural mercury, released industrial pollutants and microbes
- Increase in new and returned human and animal illness and deaths caused by permafrost thaw

Communal infrastructure: **Maintenance and repair costs of infrastructure**

This indicator can provide a regular assessment of maintenance and repair costs for communal infrastructure such as utilidors, powerlines, foundations of public buildings such as hospitals, police and fire stations, water control systems and energy supply infrastructure within communities. It spans various domains (Costs & Economy, Health & Wellbeing, Planning & Fate Control, Infrastructure, Mobility, Supply and Water Security), and scores well on the selection criteria, although some infrastructure repair and maintenance costs may be due to other factors. However, still this indicator would be easy to track in terms of data availability and affordability and ease of measurement.

Ice roads: **Length of ice road season per year (Opening & Closure dates)**

The length of ice road seasons is very much dependent on ground and air temperatures, and thus responds to the same factors that have a significant impact on the state of permafrost. The indicator spans various domains (Costs & Economy, Health & Wellbeing, Planning & Fate Control, Infrastructure, Recreation & Being in Nature, Supply and Food Security). This indicator is very useful in areas that have ice roads, but not applicable throughout the Arctic. In regions where it does apply it would be easy to measure at an affordable level.

Ice cellars: **Number of ice cellars per community affected by or closed due to permafrost thaw**

Ice cellars are of great cultural importance for many Arctic Indigenous Peoples. Reduced access or the loss of these storage systems is directly linked to permafrost thaw. The indicator is locally specific, as not all communities use (the same type of) underground storage systems. It spans various domains (Costs & Economy, Health & Wellbeing, Knowledge, Language & Education, Cultural Vitality, Planning & Fate Control, Infrastructure, Recreation & Being in Nature, Supply and Food Security), and scores high on the selection criteria (easy to measure in terms of time, money, and other resources).

Foundations: **Measured movement of foundations**

The built environment is a main interface between society and environmental changes, and directly affected by permafrost thaw. Subsidence, differential settlement and resulting damage to infrastructure and buildings are main concerns related to permafrost thaw across all case studies. The indicator spans various domains (Costs & Economy, Health & Wellbeing, Planning & Fate Control and Infrastructure), and scores high on all selection criteria.

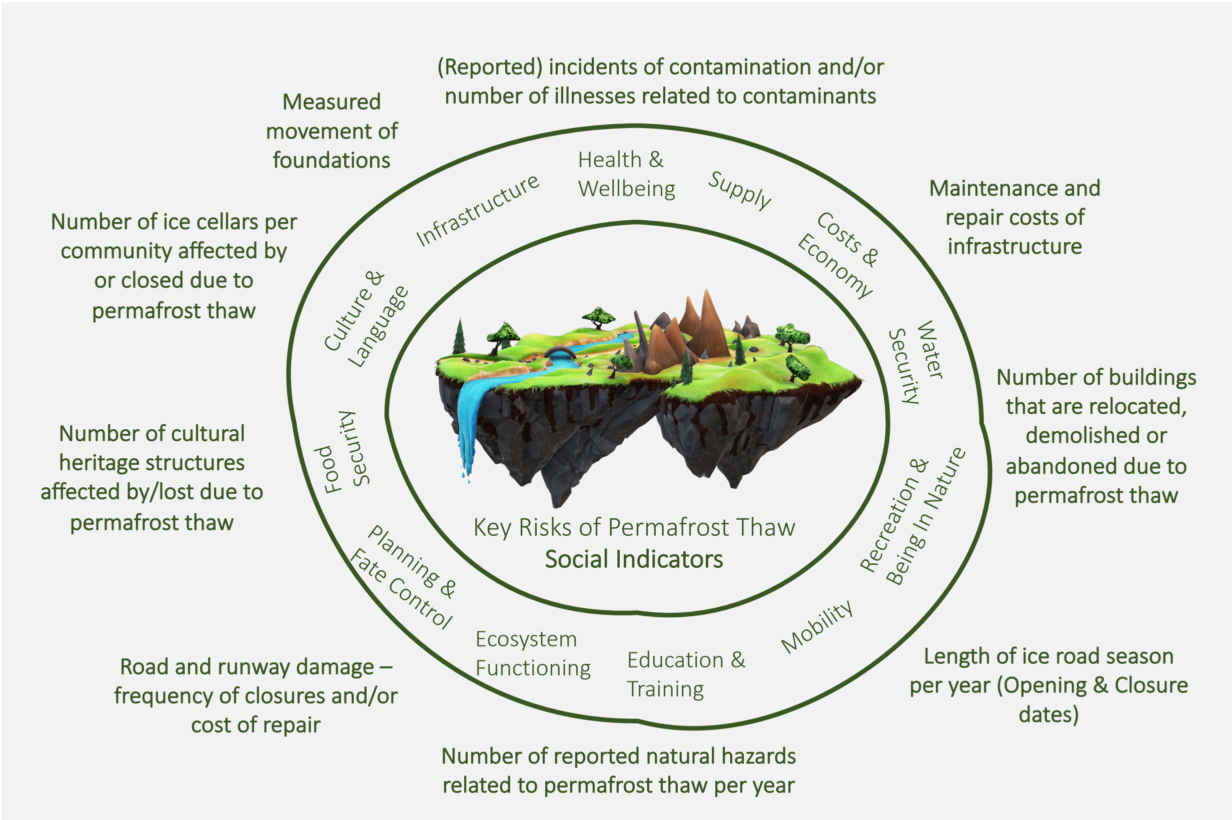

Figure 3: Socio-cultural, economic, health-related indicators of permafrost thaw impacts in Arctic communities

6. Concluding Comments and Way Forward

Together with the four biophysical indicators briefly discussed in the introduction (ground temperatures, active layer thickness, rock glacier velocity and possibly subsidence) the indicators described in this report represent a holistic set of indicators of 1) permafrost thaw, 2) permafrost thaw impacts and 3) of adaptation effectiveness in Arctic coastal communities. The nine Arctic social indicators introduced in the previous section were carefully chosen in a complex process. As mentioned above, we used a set of criteria – mostly stemming from the ASI process – that also include pragmatic considerations, that is whether data on the selected indicators are available or could be easily (and affordably) collected. In the end, the usefulness of the selected indicators will be determined by whether they are being used or not, that is whether data will be collected and, if so, whether they will impact community practices and planning activities.

A main challenge we encountered in the work of establishing social indicators of permafrost thaw impacts is the indirect relationship between the physical process of permafrost thaw and society and culture. While active layer thickness or ground temperature are physical processes that are directly linked to permafrost thaw, societal impacts of and adaptation to permafrost thaw are related to a multitude of factors. It is therefore hard, if not impossible, to isolate the societal impact of permafrost thaw from those other factors. The shortlist we came up with in this report consists of indicators that are clearly related to permafrost thaw. Yet, they are all also influenced by other environmental, economic and/or socio-cultural factors and thus have to be considered in their specific societal context.

As with any kind of social science study site activity, there were certain methodological limitations regarding data collection. In comparison to our work on risks and adaptation measures, many of our local interlocutors had difficulties in fully understanding and appreciating the task of determining indicators. As mentioned in the Introduction, this might be connected to the fact that indicators are one level of abstraction removed from observable changes. In some cases, this led to limited participation in exercises dealing with indicators and, thus, to limited data. In some cases, it was a small group of people participating in group discussions on indicators. Still, this is not fundamentally different from other knowledge co-production events in the Arctic, as it is always a challenge to reach out to all community members, and more or less impossible to engage everyone. This has the effect that some voices remain silent, as it is difficult to achieve full inclusiveness in local community events. Still, our experience was that we got a lot of input and ideas from those who participated. The lesson learned in this regard is that participation in events and activities organized for a discussion on indicators needs even more careful and thoughtful planning than other knowledge co-production events.

However, the methodological flow chart and processual model developed as part of a risk management framework has proven effective as a tool for co-production of knowledge, for organizing and conducting workshops, focus groups and interviews to collect, discuss, and reflect on indicators and effective adaptation and mitigation strategies. But ultimately, indicators (similar to the case of adaptation and mitigation strategies) presented in this research will need to be tested, validated, and adjusted in future settings between researchers and local stakeholders, and preferably in settings that include the four case study sites of the Nunataryuk project.

We were also surprised by the lack or limited extent of existing monitoring activities in some communities (typically, water quality testing is the main activity in this regard). In all communities, many participants in our conversations, interviews and workshops agreed that it would be useful to have a more comprehensive monitoring system in place, and that future changes might make such a system even more relevant. Several participants also commented that the Nunataryuk research as such and the number of re-revisits to local communities had stimulated conversation about the topic and increased interest.

While the Nunataryuk project has been extremely successful in starting these discussions and in resulting in a small and manageable set of indicators, important future steps remain to be done in the context of other projects. First of all, we need to go back to all of the communities involved and present and discuss the final list of indicators with them. As this list is based on extensive input from the study sites, we do not expect major disagreements about individual indicators but the whole set (and indicators which did not make it into the final list) might stimulate further discussions. While our set of indicators has a pan-Arctic ambition, we will encourage local communities to adjust the set to their specific demands.

As mentioned above, the set of indicators is also intended to serve as a tool for measuring the effectiveness of local adaptation measures. Thus, the way forward is to locally implement the (possibly revised) set of indicators and to make them the center of an expanded monitoring system. We are well aware that this will not just be a technocratic implementation of our results but will stimulate renewed discussions about the future aspirations of these communities. Thus, our work on indicators, apart from its academic significance, has a large applied and practical potential for the communities we were fortunate to work with.

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