Expert Workshop on Coupled Terrestrial Monitoring

Reykjavik | October 15–16 2024

AMAP

PERMAFROST PATHWAYS

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AMAP Arctic Monitoring and Assessment Programme

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Final Meeting report, February 2025

Executive summary

A two-day workshop was held in Reykjavik 15-16 October, 2024 with 14 invited experts with expertise on Arctic carbon monitoring to initiate discussions on coupled terrestrial monitoring of greenhouse gas fluxes and to develop recommendations for improving pan-Arctic monitoring. The program was divided into the following sessions:

- Policy Relevant Science Questions
- Current Efforts
- Monitoring Design
- Establishing Coupled Monitoring Programs and Guidelines

The workshop addressed Policy-Relevant Science Questions (PRSQs) within the Arctic Monitoring and Assessment Programme (AMAP) and their role in aligning scientific research with policymaking. The PRSQs aim to guide monitoring efforts, ensure scientific assessments meet policy needs, and provide decision-makers with reliable environmental data. Key discussion points included challenges when informing policy makers about greenhouse gas (GHG) monitoring, due to discrepancies between top-down and bottom-up budgets.

The workshop identified current carbon monitoring efforts and revealed the lack of coordination in Arctic environmental monitoring and the absence of a comprehensive overview of existing activities. It further emphasizes the need for improved coordination, funding, and integration of Arctic monitoring networks to enhance scientific assessments and policymaking.

Key messages from three breakout groups on current efforts:

- **Atmosphere:** Few Arctic atmospheric stations, with major gaps in Russia. ICOS provides high-quality data but is limited to Europe. The ARGO database is useful but not always updated.
- **Vegetation/Freshwater:** Many carbon flux networks exist, but some lack scope. Satellite data are global but often lack Arctic-specific detail. Vegetation mapping is inconsistent, especially without Russian data. Freshwater monitoring is often national and rarely measures carbon fluxes.
- **Permafrost:** Many relevant networks exist but lack coordination. Efforts are not well coordinated, but attempts have been made, for instance the GTN-P. This type of monitoring is not associated with national commitments, and long-term funding is an exception.

The session on monitoring design explored how to connect soil, vegetation, atmospheric, and freshwater processes in GHG flux monitoring. Breakout groups (Atmosphere, Freshwater, Permafrost, Vegetation) concluded with the need for better integration of monitoring efforts, improved methodologies, and alignment with global initiatives to ensure effective GHG monitoring in the Arctic. AMAP's role can be to bridge the existing knowledge gaps between top down and bottom up communities and explain the importance of both approaches for policymaking.

The session on establishing coupled monitoring programs and guidelines emphasized again the need for better coordination, Indigenous involvement, and funding strategies to establish an effective pan-Arctic coupled monitoring system. To move forward there is a need to clarify 1) Why coupled monitoring is needed and 2) What is missing in current programs. There is also a lack of coordination between existing initiatives, requiring integration of top-down (scientific) and bottom-up (community-led) approaches.The session underscored the need for better coordination, Indigenous involvement, and international data harmonization to improve Arctic environmental monitoring.

Next steps on this topic were suggested to consider drafting a paper on advancing coupled monitoring, addressing its policy relevance and benefits by identifying gaps and providing recommendations. AMAP can help to improve international comparability of national monitoring programs, ensuring standardized methodologies for pan-Arctic insights.

Picture taken from Natali's presentation at the workshop about *"Terrestrial Monitoring Needs for Understanding and Addressing Impacts of Permafrost Thaw"*

1. Introductions

The workshop was opened by the moderator Jennifer Spence, Harvard Kennedy School, who explained the purpose of this workshop, which aims to start a discussion of the complex systems involved in coupled terrestrial monitoring[1] of greenhouse gas fluxes with a focus on recommendations for how to improve broader pan-Arctic monitoring. This workshop was followed up by a breakout-session at the annual meeting of the Permafrost Carbon Network (December 2024), and is intended to be followed up by a Permafrost Pathways session at Arctic Summit Science Week (ASSW) in Boulder, CO in March, 2025.

Sue Natali, the leader of the six-year Permafrost Pathways project, gave a presentation about the need for terrestrial monitoring of greenhouse gas fluxes to understand and address impacts of permafrost thaw on global climate. This includes building a monitoring network to monitor carbon dioxide, methane and water exchange between soil, land and the atmosphere using towers. The project will install new eddy covariance equipment and expand measurements at existing monitoring sites, which are being prioritized based on a representative analysis of existing monitoring sites across the pan-Arctic region. For carbon flux upscaling, these spot measurements will be combined with remote sensing data to obtain pan-Arctic estimates of carbon dioxide and methane exchange. This monitoring should 1) ensure inclusion of Indigenous Peoples and local communities in identifying in situ monitoring needs, implementation, and communication of findings; 2) employ coupled monitoring of multiple variables; 3) be a coordinated effort among in situ, remote sensing, and atmospheric monitoring & modeling communities to identify/fill knowledge gaps and reduce uncertainties; 4) be spatially and temporally representative; and 5) cover gradients in disturbances and future conditions.

Rolf Rødven, AMAP Executive Secretary, provided an overview of AMAP's work and its main products and their use policy-making regionally and internationally. His presentation highlighted the need to integrate different scales in pan-Arctic monitoring, integrating horizontal and vertical monitoring over long time scales. He also noted the importance of harmonizing measurements in an international program.

Sarah Kalhok Bourque, director at the Crown-Indigenous Relations and Northern Affairs Canada, presented an overview of the Northern Contaminants Program (NCP) and the success with engaging Indigenous Peoples and researchers as partners in a national monitoring initiative as an example of a national program that has provided data to AMAP since 1991, when AMAP also was established. 'The NCP engages Northerners and scientists in research and monitoring of long-range transported contaminants into Canada with the aim of reducing contaminant levels and helping food choices. In designing the monitoring programs and activities, the NCP works with communities and Indigenous People. Indigenous People are embedded at all levels: local to regional to national. The NCP projects also include socio-cultural components and best

[1] **Coupled terrestrial monitoring** refers to an integrated approach to environmental monitoring that simultaneously measures multiple interconnected components of the Earth's system—such as the land, atmosphere, vegetation, permafrost, and freshwater systems—to better understand complex interactions, especially related to greenhouse gas (GHG) fluxes.

practices to bring Indigenous knowledge holders together with researchers for capacity building and sharing. Communication at all stages of a project is vital.

In the discussion of these presentations, questions of funding of monitoring activities and access to monitoring data were raised. As both funding and data access are mainly national issues, the conditions differ among the Arctic countries.

2. Policy-Relevant Science Questions (PRSQs)

2.1 Introduction to Policy Relevant Science Questions

Sarah Kalhok Bourque gave an introduction to the use of PR(S)Qs in AMAPs assessments as a tool to make relevant reports for policymakers and highlighted that the PRSQs should:

- guide research and monitoring efforts, ensuring that the work addresses pressing issues that are important for policymaking.
- ensure aligning scientific assessments with global and regional policy needs, providing actionable insights on critical environmental issues in the Arctic.
- ensure that decision-makers have access to reliable, up-to-date information to protect the Arctic while addressing international environmental and socio-economic challenges

2.2 General Discussion

The discussion on this topic addressed that the aim for using PRSQs as a tool is to elevate results to policy makers, providing them with key messages to inform decision-making. AMAP (Arctic Monitoring and Assessment Programme) has employed the PRSQs in discussions, focusing on issues like methane emissions and national efforts for harmonization, especially in light of the methane pledge. There is a need to assess what it would take to harmonize national efforts and what this means for future policy actions.

A key issue raised in discussions is the mismatch between top-down and bottom-up greenhouse gas (GHG) budgets, which complicates accurate monitoring and reporting.

Padlet exercise for suggestion PRSQs on coupled monitoring

By using the Padlet-tool, the participants suggested relevant PRSQ related to coupled terrestrial GHG monitoring in 1) general and for addressing knowledge gaps in these systems: 2) permafrost, 3) vegetation, 4) atmosphere and 5) freshwater systems.

2.2.1 General

- *What network is needed to detect a significant change in the Arctic carbon budget (e.g., switch from a net carbon sink to net source)?*
- *How do we address the UN SDG?*
- *The exclusion of Russia, territorial datawise and in terms of scientific collaboration is a major problem for accurately monitoring and answering questions relating to the current carbon balance and methane emissions. How can AMAP help facilitate resuming work in the full circumpolar North?*
- *What is the potential for mitigating increased natural GHG emissions, i.e. through equivalent and or stronger reductions of anthropogenic sources, within the context of achieving the goals of the Paris agreement?*
- *Do arctic carbon-climate feedbacks make it more challenging to achieve the 1.5 and 2 degree targets?*
- *Can a monitoring network coming from the research community inform national greenhouse gas inventories?*
- *Is the current monitoring network generally representative of Arctic environments, or are there large gaps? How do we address those gaps?*
- *How does/would coordinated Arctic monitoring contribute to evaluating the effectiveness of the Paris Agreement?*
- *What 'nature-based solutions' make sense for Arctic environments and residents, and what monitoring is required?*
- *To what extent can satellite remote sensing of atmospheric GHG concentrations complement ground-based coupled monitoring?*
- *Consider how to make use of remote sensing (S5P, CO2M) as well as drone measurements.*
- *Which types of ground-based monitoring activities are essential and which may be redundant with emerging remote sensing and modeling technologies?*
- *Can a monitoring network designed for greenhouse gas fluxes be used to monitor other Arctic climate feedbacks (e.g., albedo and other biophysical)?*
- *"How do we best communicate the risk of non-linear changes in Arctic emissions to policymakers, in particular how they can incorporate the concept of tipping points, which differs from the required responses to gradual change?*
- *How can we monitor the impact from human activities on the GHG sink/sources from natural ecosystems*

2.2.2 Permafrost

- *How do different pathways of human GHG emissions (SSP) impact climate-warming feedbacks from permafrost thaw? (e.g. can we detect the difference between 1.5 or 2 degrees global warming?)*
- *To what extent can coupled terrestrial monitoring reduce uncertainties in assessment of the permafrost-climate feedbacks? (compare cost of monitoring to the cost of not knowing risks)*

- *What monitoring is needed to detect permafrost thaw at pan-Arctic scale?*
- *Can current monitoring networks detect which permafrost regions are net sinks and which are sources?*
- *How does the permafrost thaw affect key species like reindeer, cloudberries etc and how will it affect the traditional activities like hunting, fishing that many Indigenous communities rely on?*
- *How is the infrastructure and housing affected by permafrost thaw? When is relocation necessary, or what kind of measures are needed for keeping communities on their land.*

2.2.3 Vegetation

- *How does increasing vegetation uptake compare to increasing carbon emissions from permafrost and soils?*
- *"What are the current and potential emissions from the range of arctic landscapes when taking into consideration human disturbance and effects of climate warming?*
- *Have Arctic ecological tipping points already been exceeded? Do changes happen gradually or abruptly and are new ecosystem tipping points approaching?*
- *Is our current monitoring network adequate enough to capture the extent, frequency and intensity of disturbances (extreme weather, fires, abrupt permafrost thaw, insect outbreaks etc), and does their combined impact on vegetation have the potential to offset the increased carbon uptake following from more optimal growing conditions (i.e. longer summers and CO2 fertilization)?*
- *Do we have adequate geospatial layers of vegetation communities for bottom-up upscaling?*
- *How does an increase in extreme winter weather events impact vegetation, i.e. through rain-on-snow events, false springs or frost droughts, and are we monitoring the ecohydrology of the cold season sufficiently enough to monitor these impacts?*

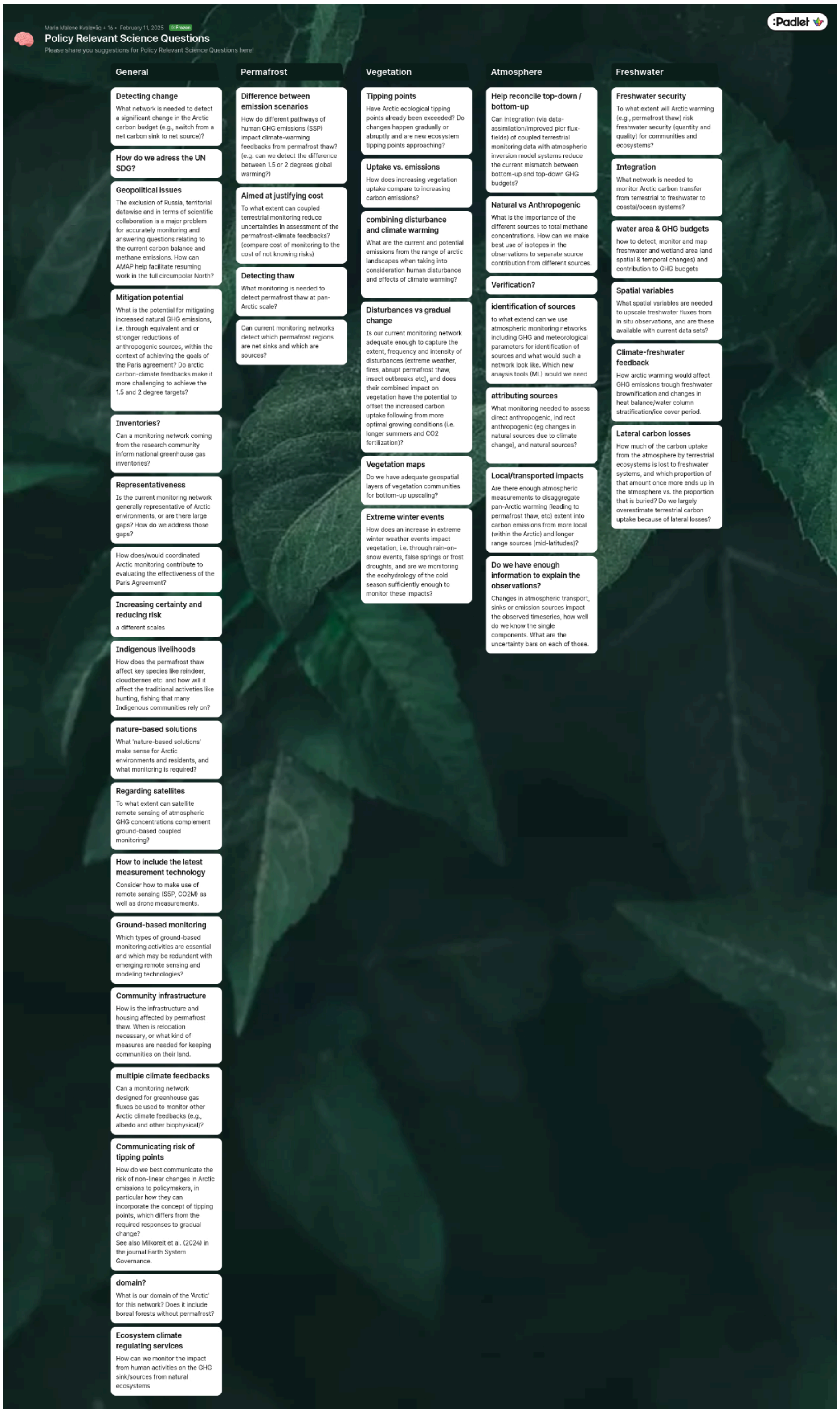
2.2.4 Atmosphere

- *Can integration (via data-assimilation/improved prior flux-fields) of coupled terrestrial monitoring data with atmospheric inversion model systems reduce the current mismatch between bottom-up and top-down GHG budgets?*
- *What is the importance of the different sources to total methane concentrations? How can we make best use of isotopes in the observations to separate contributions from different sources?*
- *To what extent can we use atmospheric monitoring networks including GHG and meteorological parameters for identification of sources and what would such a network look like? Which new analysis tools (ML) would we need?*
- *"What monitoring is needed to assess direct anthropogenic, indirect anthropogenic (e.g. changes in natural sources due to climate change), and natural sources?*
- *Are there enough atmospheric measurements to disaggregate pan-Arctic warming (leading to permafrost thaw, etc) extent into carbon emissions from more local (within the Arctic) and longer range sources (mid-latitudes)?*

- *Changes in atmospheric transport, sinks or emission sources impact the observed time series, how well do we know the single components. What are the uncertainty bars on each of those?*

2.2.5 Freshwater

- *To what extent will Arctic warming (e.g., permafrost thaw) risk freshwater security (quantity and quality) for communities and ecosystems?*
- *What network is needed to monitor Arctic carbon transfer from terrestrial to freshwater to coastal/ocean systems?*
- *How to detect, monitor and map freshwater and wetland area (and spatial & temporal changes) and contribution to GHG budgets*
- *What spatial variables are needed to upscale freshwater fluxes from in situ observations, and are these available with current data sets?*
- *How arctic warming would affect GHG emissions through freshwater brownification and changes in heat balance/water column stratification/ice cover period.*
- *How much of the carbon uptake from the atmosphere by terrestrial ecosystems is lost to freshwater systems, and which proportion of that amount once more ends up in the atmosphere vs. the proportion that is buried? Do we largely overestimate terrestrial carbon uptake because of lateral losses*



Screen shot of the PadLet Tool on the exercise on Policy Relevant Science Questions.

3. Current Efforts

As an introduction to the session, it was noted that currently monitoring is not coordinated across the pan-Arctic region and there is no comprehensive overview of existing activities.

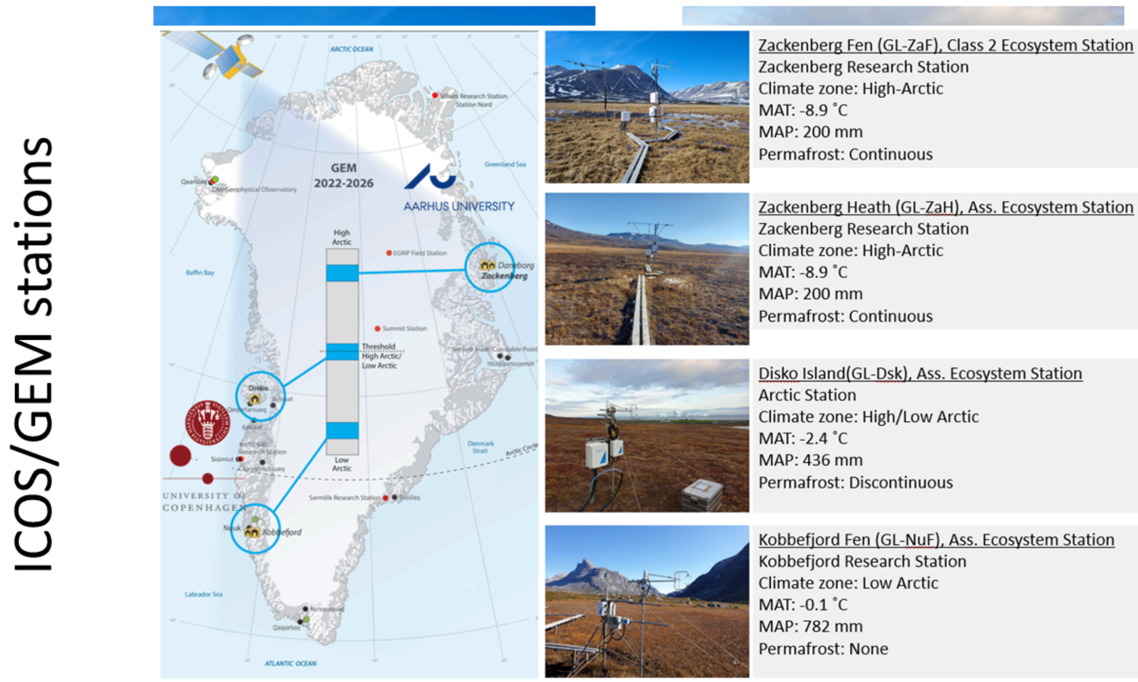
3.1 GEM - Greenland Ecosystem Monitoring

Torben R. Christensen gave a presentation on how it had been possible to establish environmental monitoring in Greenland (GEM - Greenland Ecosystem Monitoring). GEM is a coordinated long-term effort in the Arctic studying natural ecosystem dynamics across glacial, terrestrial, limnic and coastal domains, as they respond to climate variability and change. Different scientific disciplines had successfully been able to work together and measure 2000 parameters for almost 30 years.

Through GEM it has been possible to document the value of long term monitoring. As an example, he showed how warming extends deep into the soils and causes permafrost warming and deepening of the active layer. In another example, he demonstrated the value of disciplines working together, since this had allowed for explaining within-year methane release patterns as these are coupled to snow melt. In the case of certain plant and bird communities, long time series could also show that certain things are resilient and not subject to change.

It had been of value to GEM to standardise measurements to ICOS protocols, but this had also created new problems in terms of harmonising past data in older format with more modern standards. An important “data rescue” effort is ongoing in this respect.

There was a discussion about the funding for monitoring, since national science foundations are often not interested in funding this. GEM is funded primarily from the Danish Energy Agency, the Danish Environmental Protection Agency, and the Government of Greenland. The reason for this funding structure was that GEM was established to meet national commitments from Denmark and Greenland to respond to recommendations from the Arctic Council working groups AMAP and CAFF.



Overview of the ICOS/GEM stations on Greenland taken from Christensens' presentation.

3.2 Overviews of existing efforts

Three breakout groups were established, each with the task to list networks and initiatives that are already engaged in addressing the SPRQ. For each initiative, they should answer these questions:

1. Are they Arctic relevant? Do they have an Arctic scope?
2. If not, can they be developed? Should they be promoted among the Arctic nations?
3. Are their data/information comparable and accessible for AMAP assessment work and/or other scientific work?

Each subgroup listed networks and initiatives as found in Appendix X. In addition the subgroups provided these comments:

3.2.1 Atmosphere

The breakout group noted that there are few Arctic atmospheric observing stations and there are gaps, especially in Russia. The group concluded that ICOS has good measurement standards with a good resolution, but is only European. The ARGO meta database gives a good overview of current atmospheric monitoring systems, but it is not clear whether it is being updated regularly and some initiatives are missing (shipping observations for instance).

3.2.2 Vegetation/freshwater

The breakout group had sought to qualify those networks that are measuring carbon fluxes, and noted that there is an overlap in this matter with permafrost. Networks should have a comprehensive scope when it comes to carbon and should for instance also observe biomass (LTER, eLiter). The sub-group had also qualified networks after accessibility of data.

The breakout group had deliberately listed satellite data sources, since these are in principle global, but had noted that the geographical coverage of the Arctic is often poor. There continues to be a need for the ground-truthing of satellite observations. It was noted in particular that vegetation mapping for the circumpolar boreal region is generally much coarser in its vegetation classifications compared to tundra. Although high-quality data products exist for Canada and Alaska, they are not completely compatible and the lack of Russian data is a major challenge.

It was finally noted that freshwater observing is usually more nationally organised, since flooding and run-off is often of more national interest. Moreover, these rarely measure carbon fluxes.

For later discussions, the sub-group wanted the meeting to discuss 1) What is missing – gaps, and 2) Disturbances, like extreme weather, abrupt permafrost thaw and fires.

3.2.3 Permafrost

There are many networks and initiatives, and these are for good reasons relevant to the Arctic . Efforts are not well coordinated, but attempts have been made, for instance the GTN-P. This type of observation is not associated with national commitments, and long-term funding is an exception. Active layer measurements are relatively inexpensive, and this could be an AMAP recommendation.

A side topic is that mercury and radon pollution are issues associated with thawing permafrost, but are outside the scope of the current discussion.

3.3 General discussion - across networks

In the overall discussion, it was noted that data on carbon fluxes typically are months or years old before they can be publicised.

It had not been easy to identify networks outside the Arctic that could be brought into the Arctic, except for designing remote sensing missions to cover and prioritize the Arctic.

4. Monitoring Design

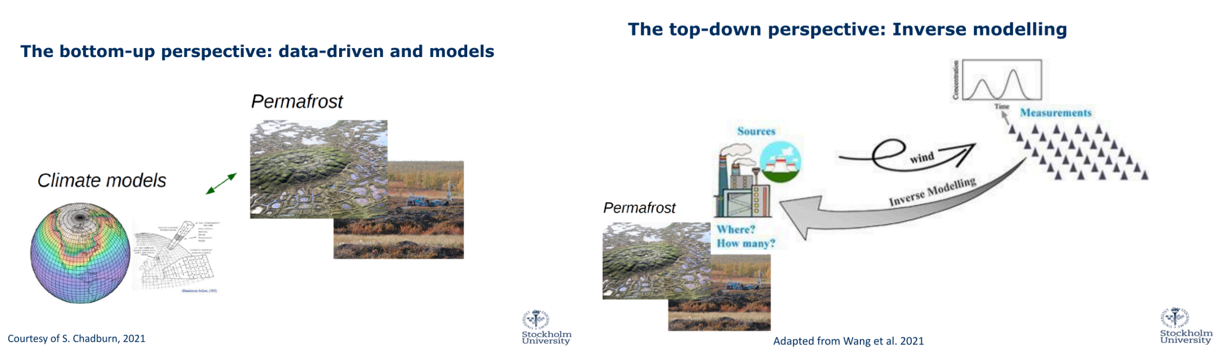
4.1 Presentation on greenhouse gas budget

Gustaf Hugelius gave a presentation with the title *The RECCAP2 permafrost region greenhouse gas budget and the possibility to reconcile top-down and bottom-up methods*. This presentation summarised findings from a recent paper (Hugelius et al., 2024). The project has the aim to produce regional GHG budgets for 2000-2020 based on the best available data and models. A distinction was made between *bottom-up* (BU) approaches, which are based on process models or data-driven GHG inventories, and *top-down* (TD) approaches, which are based on atmospheric observations and inverse modeling for GHG budgets.The project RECCAP2 project compared budgets for 14 regions of the globe of which the permafrost region overlaps several other regions. We note that in the most recent global CH4 budget (Saunois et al., in review, ESSDD), the northern high latitudes (60°N-90°N) only make up 4% of global CH4 emissions.

One conclusion from the BU perspective is that boreal forest sinks are offset by inland water, fire and wetland emissions.

The overall conclusion is that the budgets generated from the two approaches differ, and both are data-limited. In general, BU approaches consequently estimate stronger sources of GHGs compared to TD approaches. Several causes for these systematic differences, and approaches to alleviate them, are discussed in Hugelius et al. (2024). Measured as the Global Warming Potential (GWP) (which is an index to measure how much infrared thermal radiation a greenhouse gas would absorb), summed evidence points to the permafrost region being a net source of warming within 20 years (GWP-20), neutral with GWP-100 and a sink with GWP-500.

At the global level, TD is still viewed as “the truth”, and agreement must be reached between the approaches for BU to attract political attention. Gustaf Hugelius saw several opportunities, including promoting regional Arctic inversion modeling via AMAP.



Graphics taken from Hugelius’ presentation at the workshop to visualise Bottom-up and Top-down approaches to analyse green house gas budgets.

4.2 Designing monitoring

The main question of the session was: *What monitoring is needed to connect soil, vegetation, atmospheric and freshwater processes from the perspective of greenhouse gas fluxes, especially methane?* Responses were collected and an overview and a synthesis of the responses are found in Appendix C.

Breakout sessions (Atmosphere, Freshwater, Permafrost, and Vegetation) discussed these *Guiding Questions*:

- What observations/variables must be undertaken in order to address the PRSQs?
- Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?
- Do specifications for these already exist, for instance as Essential Climate Variables (ECVs).
- What is the temporal and spatial resolution needed?
- Where and by whom is this already ongoing (may have been addressed under break-out session 1)
- Can in situ monitoring can be complemented with remote sensing?
- Are relevant QA procedures in place?
- Data management arrangements: Do they already exist for the identified observations/variables or must new arrangements be made?
- What are the challenges associated with capturing disturbances in our monitoring programmes?

4.2.1. Designing monitoring: Atmosphere

Responses to the above mentioned questions were collected, and an overview and a synthesis of the responses are found in Appendix D.

In the reporting from the break-out group it was noted that key basic research questions were on the use of isotopes signatures. Drone technologies should be developed.

There is a need for aligning with global efforts, and ICOS protocols are relevant. The needed resolution is 100-1000 km, but a better density of measurement sites will be needed to detect disturbances. In general, there is a lack of data from Russia.

QA/QC procedures exist for many observables, but perhaps not for isotopes. For data management, harmonisation is still needed, and could be further developed.

4.2.2. Designing monitoring: Freshwater

Responses to the above mentioned questions were collected, and an overview and a synthesis of the responses are found in Appendix E.

In the reporting from the break-out group it was noted that there is more experience measuring fluxes over land. Methodologies must be developed, and ocean methods are usually used. There are some satellite based global databases.

4.2.3. Designing monitoring: Permafrost

Responses to the above mentioned questions were collected, and an overview and a synthesis of the responses are found in Appendix F.

In the reporting from the break-out group it was noted that a lot is known about basic processes, but representativeness could be improved. Many samples are opportunistics and an understanding of upscaling from site to the regional scale could be better known.

Temporal resolution of monitoring varies with parameters. Disturbances play a major role, and sites must be dedicated to this; could be cost-intensive.

At the global level, ICOS has good protocols, and it was recommended that connections are established with the WMO Global Greenhouse Gas Watch (C3W).

4.2.4. Designing monitoring: Vegetation

Responses to the above mentioned questions were collected, and an overview and a synthesis of the responses are found in Appendix G.

In the reporting from the break-out group it was noted that there is a need for better vegetation maps. Existing maps only cover the tundra at sea level, not at higher level (the oro-Arctic), which will double the area. The boreal area is not well covered, and information about coverage for vascular plants, mosses and lichens is needed. Basic questions include information about mosses, their thickness and species composition since this is important for permafrost thaw.

An ideal network would be able to monitor disturbances, including the state when a disturbance (like fire) hits, and the recovery of the ecosystem, but information about past history is often missing.

ICOS has relevant protocols, and for QA and data management, it would be worthwhile to establish connections to ICOS and FluxNet. An issue with Fluxnet is that it often takes years from data is collected until they are publicised.

4.2.5. Designing monitoring: General

The discussion focused on coordinating top-down modelling and ground-based upscaling. It was noted that the two communities are separate, and it is difficult to fund both bottom-up and top-down projects. An AMAP community like the present, could, however be able to explain how both approaches are important for policy making.

5. Establishing Coupled Monitoring Programmes and Guidelines

To inspire the discussion about establishing a coupled monitoring program and guidelines, Jan Rene Larsen, Deputy Secretary at AMAP Secretariat, gave a presentation about the Roadmap for Arctic Observing and Data Systems (ROADS) process established by Sustaining Arctic Observing Networks (SAON). The ROADS initiative aims to enhance and coordinate Arctic observations across multiple nations, organizations, and knowledge domains by creating a collaborative framework that integrates both scientific and Indigenous knowledge.

The Shared Arctic Variables (SAVs) concept of the Arctic ROADS process builds upon the “essential variable” planning approaches for Earth Observations adopted by the global networks like the Global Ocean Observing System and the Global Climate Observing System. The SAV concept extends that of essential variables through an emphasis on shared implementation and shared use. A benefit assessment is used to clarify those approaches. The expert panel on permafrost (active layer not GHG) in the Arctic Passion EU-project is the first to adopt the methodology from the ROADS process. It is recommended that when the permafrost activity has gone through its final phase IV, then the process can be adopted by others.

A central component of ROADS is the equitable involvement of Arctic Indigenous Peoples, ensuring that their perspectives are incorporated in designing and implementing the observing systems and the associated data systems. This inclusivity is essential for both sustainable collaboration and accurate regional insights, given the unique observational capabilities and environmental knowledge of Indigenous Peoples.

General discussion

To guide the discussion in plenary, the following questions were used:

- What policy-relevant questions will such a program contribute to answering? How can a monitoring program as discussed in earlier sessions feed into modelling efforts or inform actions related to the PRSQs?
- How do we overcome hurdles to establishing international monitoring systems?
- What could be the program within this area? Can AMAP or SAON play a role in acting as a hub for these initiatives?

To start the discussion, questions were raised as to whether there are gaps in these procedures that AMAP could fill regarding the Arctic. Also, how can the results of this monitoring be brought to the policy side?

In the discussion, the following points were made:

- AMAP has a monitoring plan with many priorities, but recently monitoring has received less attention owing to the large amount of assessment work coordinated by AMAP.

- In going forward with this work on a coupled monitoring approach, three questions should be considered: Why do we need to do this? What is the purpose? What is lacking in current programs?
- There are many ongoing initiatives, but no coordination. Better coordination is needed, especially to bring top-down and bottom-up approaches together.
- There is a need to ensure the involvement of local communities and Indigenous Peoples in monitoring activities. Indigenous communities need to be consulted before deciding to install a tower or other equipment in their area.
- Cooperation with defense activities is important especially in remote areas of the Arctic; for example, in Greenland the military gives important support. In Greenland, cooperation with the military on logistics and winter maintenance of autonomous scientific instrumentation is crucial and there is a great dependence on the military there.
- Also relevant, is the WMO Global Greenhouse Gas Watch (G3W) which "*fills critical information gaps and provides an integrated, operational framework that brings under one roof all space-based and surface-based observing systems, as well as modelling and data assimilation capabilities in relation to greenhouse gas monitoring"*. It is established to address the urgent need for information that helps to understand the impact of mitigation actions taken by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement on the state of climate. Such information will be produced in a timely manner and will take into consideration both human and natural influences on the levels of greenhouse gases in the atmosphere.

The workshop considered whether a paper should be prepared with a proposal on the advancement of a coupled monitoring program. This could include the reasons for why such an effort would be worthwhile and whether this would result in policy-relevant information. Additional experts could be added to this effort to increase the range of expertise. Part of the report could identify gaps and provide recommendations for the next steps, with recommendations based on the outcome of this workshop.

Although there is no direct funding for this work, an AMAP report containing background information on current understanding of permafrost carbon feedbacks, and associated aspects of freshwater, biological and atmospheric conditions, together with recommendations for further work could be used to obtain funds nationally or from other sources. There are a number of programs that could benefit from coordination, including bringing together top-down and bottom-up approaches. One example is the ICOS program, which has regular monitoring protocols; however, they do not monitor or take into account disturbances by design. Indigenous perspectives are important, although different approaches to observing systems are taken by Indigenous communities in North America and Europe. Local communities must also be included in these activities.

AMAP can bring an international aspect into this work. The program proposed here also expands the purpose of national monitoring programs by promoting comparable measurement methodologies and thus permitting a comparison of results between countries and the ability to understand conditions on a pan-Arctic scale .

6. Wrap-up and Next Steps

A report (this document) from the workshop will be sent to the participants for review. It will include recommendations (see below in this chapter) drawn from the discussions and padlet boards.

Upcoming Meetings and Follow-Up Sessions:

- **AGU Fall Meeting (Permafrost Breakout Session)** – 1 hour session in December, 2024 focusing specifically on permafrost disturbances, exploring essential monitoring needs and prioritizing methods for data collection.
- **Arctic Frontiers Conference** – Findings from this report will be presented in a poster session on January 27th 2025
- **ASSW (March 24, 2025)** – A 4 hour session (8am - 12) to refine and advance recommendations in this report

Recommendations:

On process:

- The participants recommended to continue the discussion with AMAP and Permafrost Pathways on establishing a pan-Arctic Monitoring system for coupled terrestrial monitoring of GHG
- Explore ICOS further and take advantage of their experience
- Still need to address knowledge gaps in future discussions

On establishing a coupled monitoring system based on existing systems:

- Take advantage of existing infrastructure
- Engagement of Indigenous peoples and local communities
- More EC flux towers in the pan-Arctic are needed
- Monitoring that is holistic should be prioritized, so that a number of parameters are measured at the same location rather than having stations that are reserved for specific parameters
- Broaden use and impact of Arctic in-situ GHG monitoring can be achieved by coordination with global efforts (e.g. WMO G3W) as well as organisations coordinating top-down budget assessments. In such contexts, AMAP can take the mandate to be the main point of contact for coordination of Arctic GHG monitoring.
- Learn from ICOS and consider their model for incentives to contribute to ICOS and sharing data. What is the funding model, also for non-EU nations?

“Low-hanging fruits” - What can we identify as easy wins, and what are more strategic considerations: Like harmonising two systems: ICOS and ‘the other system’. Top-down and bottom-up approaches. A first step towards understanding the gap between bottom up and top down would be to assess how the prior flux fields used by atmospheric inversion models (Top-down) affect Arctic GHG budgets. Since the prior flux fields could be improved with existing data, this offers a possibility to make rapid progress over a short time (see Hugelius et al., 2024).

7. Closing Remarks

In his closing remarks, Rolf Rødven was impressed by the many concrete things that had been proposed in a very short time and with a diverse group of experts. He noted that permafrost is high on the agenda and has good momentum. He believed that AMAP was in a good position to take the conclusions into action.

Brendan Rogers thanked everyone for their participation. He noted AMAP’s role in monitoring to inform political action and was happy to see AMAP taking this topic on board. He saw the need for working with the research communities to make the case for funding. The report from the workshop should be followed by a broader discussion, which should be followed by a plan for AMAP. Key words in such a plan should be a better understanding of processes, engaging with communities, and the importance of disturbances. AMAP should finally explore its collaboration with ICOS and the WMO Global Greenhouse Gas Watch (G3W).

Appendix A: Agenda

Day 1 - October 15th

9.00 - 10.30

1. Introductions

Presentations:

1) Jennifer Spence, Harvard Kennedy School, introducing the purpose and outcomes of the workshop
2) Sue Natali, Woodwell Research Center and leader of Permafrost Pathways, Why terrestrial monitoring is important and why Permafrost Pathways is supporting efforts at coupled monitoring
3) Sarah Kalhok Bourque, CIRNAC (Canada), Example from a national contaminant monitoring program and how this type of approach can be used in coupled GHG monitoring
4) Rolf Rødven, AMAP Secretariat, on pan-Arctic monitoring programmes

Discussions (Jennifer Spence)

Rapporteur: Janet Pawlak

2. Policy-Relevant Science Questions (PRSQ)

Presentation: Sarah Kalhok Bourque, CIRNAC (Canada)/AMAP, “Policy relevant science questions - What they are and how they are used”

Examples of policy relevant (science) questions:
https://docs.google.com/document/d/10dU0ERNyP3o4wP70sbj98xAyAl4clwj0lZos0ATvv_M/edit?usp=sharing

Plenary Discussion (Jennifer Spence)

1. What are the policy-relevant questions that should be formulated? What are the challenges and possibilities in establishing this monitoring program?

2. PadLet exercise
https://padlet.com/maria2731/policy-relevant-science-questions-93va9nqfch3sghkk

Rapporteur: Maria Kvalevåg

10.30 - 11.00 BREAK with refreshment

11.00-12 .00

Continue session 2

12.00 - 13.00 LUNCH BUFFET

13.00 - 14.30

3. Current Efforts

Presentation: Torben R. Christensen on coupled monitoring ability, relevance, values.

3. Currently, monitoring is not coordinated and there is no overview of existing activities. Can such overviews be established? Make a list of networks and initiatives that are already engaged in these questions, like CALM, ICOS, ArcticPASSION, Permafrost Pathways and PEEX. Also about the legacy after for instance ArcticPASSION, Nunataryuk. and POLARIN (starting in March 2024).

4. Questions:
    a. Are they Arctic relevant?
    b. If not, can they be developed? Should they be promoted among the Arctic nations?
    c. Are their data/information comparable and accessible for AMAP assessment work?

Padlet exercise - homework - for all groups:
https://padlet.com/maria2731/homework-current-efforts-networks-jvhsr2qp871odb4o

Breakout Groups::
1. Permafrost, led by Torben R. Christensen and rapporteur Janet Pawlak
2. Vegetation/freshwater, lead by Frans-Jan Parmentier and rapporteur Jan Rene Larsen
3. Atmosphere, lead by Lise Lotte Sørensen and rapporteur Maria Kvalevåg

Plenary Discussion, moderated by Jennifer Spence
- Report from breakout groups
- Current efforts in other relevant fields and how to make connections between fields

Rapporteur: Jan Rene Larsen

14.30 - 15.00 BREAK with refreshment

15.00 - 16.00
Continue session 3

16.00 END of Day 1

19.00 Workshop Dinner at FISKFÉLAGIÐ, Reykjavík, 101 Vesturgötu 2a, Grófartorg

Day 2 - October 16th

9.00 - 10.30

4. Monitoring Design

Presentation: Gustaf Hugelius on the RECCAP2 permafrost region greenhouse gas budget and the possibility to reconcile top-down and bottom-up methods

Main question of this session: What monitoring is needed to connect soil, vegetation, atmospheric and freshwater processes from the perspective of greenhouse gas fluxes, especially methane?

Padlet - Link Main question:
https://padlet.com/maria2731/monitoring-design-main-question-7dm8kk565m2ggjs6

Breakout Groups::

1. Permafrost, led by Torben R. Christensen and rapporteur Janet Pawlak

Padlet - link Permafrost:
https://padlet.com/maria2731/monitoring-design-permafrost-dz8erzfst6ed6qka

2. Vegetation/freshwater, led by Frans-Jan Parmentier and rapporteur Jan Rene Larsen

Padlet - link Freshwater:
https://padlet.com/maria2731/monitoring-design-freshwater-9rp26byxl573q71
Padlet - link Vegetation:
https://padlet.com/maria2731/monitoring-design-vegetation-wqvtclld9bjvutx3

3. Atmosphere, led by Lise Lotte Sørensen and rapporteur Maria Kvalevåg

Padlet - link Atmosphere:
https://padlet.com/maria2731/monitoring-design-atmosphere-vkvmbw4md620vzyx

Guiding Questions:

- What observations/variables must be undertaken in order to address the PRSQs?
- Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?

- Do specifications for these already exist, for instance as Essential Climate Variables (ECVs).
- What is the temporal and spatial resolution needed?
- Where and by whom is this already ongoing (may have been addressed under break-out session 1)
- Can in situ monitoring can be complemented with remote sensing?
- Are relevant QA procedures in place?
- Data management arrangements: Do they already exist for the identified observations/variables or must new arrangements be made?
- What are the challenges associated with capturing disturbances in our monitoring programmes?

Plenary Discussion, moderated by Jennifer Spence

- Report from breakout groups
- Monitoring design in other relevant fields and how to make connections between fields

Rapporteur: Jan Rene Larsen

10.30 - 11.00 BREAK with refreshments

11.00 - 12.00
Continue session 4

12.00 - 13.00 LUNCH BUFFET

13.00 - 14.30

<u>5. Establishing Coupled Monitoring Programmes and Guidelines</u>

Presentation: Facilitator on how the results from this workshop could be considered for future activities

Plenary Discussion, moderated by Jennifer Spence

- What policy-relevant questions will such a program contribute to answering? How can a monitoring program as discussed in earlier sessions feed into modelling efforts or inform actions related to the PRSQs?
- How do we overcome hurdles to establishing international monitoring systems?
- What could be the program within this area? Can AMAP or SAON play a role in acting as a hub for these initiatives?

(Padlet optional)

Rapporteur: Janet Pawlak

14.30 - 15.00 BREAK with refreshments

15.00 - 16.00

6. Wrap-up and Next Steps

Plenary Discussion, moderated by Jennifer Spence

- Session at Arctic Frontiers
- Workshop at ASSW

Rapporteur: Maria Kvalevåg

7. Closing Remarks

Brendan Rogers, Permafrost Pathways

16.00 END of Day 2

Homework:

Reading:

- AMAP Strategic Framework 2019+
- Examples of Policy relevant science questions (see separate document)
- AMAP Assessment 2015: Methane as an Arctic climate forcer: https://www.amap.no/documents/download/2499/inline page 15-25 (new)

In PadLet:

- List current monitoring efforts/networks in PadLet: https://padlet.com/maria2731/homework-overview-of-current-efforts-and-networks-jvhsr2qp871odb4o

Appendix B: List of participants and grouping

Permafrost
- *Torben R. Christensen, Aarhus University, Denmark*
- Susan M. Natali, Woodwell Climate Research Center, USA
- Gustaf Hugelius, Stockholm University, Sweden
- Elyn Humphreys, Carleton University, Canada

Vegetation/Freshwater
- *Frans-Jan Parmentier, University of Oslo, Norway*
- Virve Ravolainen, Norwegian Polar Institute, Norway
- Brendan Rogers, Woodwell Climate Research Center, USA
- Ivan Mammarella, Helsinki University, Finland
- Maret Heatta, Saami Council
- Jón Ólafsson, Marine and Freshwater Research Institute of Iceland (HAFRO), Iceland

Atmosphere
- *Lise Lotte Sørensen, Aarhus University, Denmark*
- Luke Schifl, Columbia University, USA
- Sabine Eckhart, NILU, Norway
- Stephen Platt, NILU, Norway

Names in italics are break-out group leads

Other:
Sarah Kalhok Bourque, CIRNAC, Canada

AMAP Secretariat:
- Rolf Rødven (Executive Secretary)
- Jan Rene Larsen
- Janet Pawlak
- Maria Malene Kvalevåg

Appendix C: Monitoring Needs

What monitoring is needed to connect soil, vegetation, atmospheric and freshwater processes from the perspective of greenhouse gas fluxes, especially methane?

The full series of padlet comments are tabled below. Link to Slideshow

Summary:

- Atmosphere
  - **Monitoring Needs**: Expand tall tower networks and implement systematic top-down modeling.
  - **Alignment**: Ensure monitoring aligns with Global Greenhouse Gas Watch (GGGW).
  - **Permafrost Integration**: Include extent, temperature, and active layer data, though currently lacking.
- Freshwater
  - Freshwater maps: For inland waters the Hydrosheds database: https://www.hydrosheds.org/
- Permafrost
  - **Permafrost Maps**: Show extent, temperature, and active layer variations.
  - **Earth Observation**: No time series data currently available for permafrost changes.
  - **EC Network Expansion**: Focus on adhering to ICOS standards and adding lateral flux measurements for better monitoring.
- Vegetation
  - **Vegetation Mapping**: Improved mapping is needed, particularly for boreal and regions; current maps (e.g., CAVM/CALU) exclude tundra-like vegetation at higher elevations.
  - **Key Traits for Carbon Fluxes**: Species composition, biomass, LAI, height, stomatal conductance, rooting depth, phenology, litterfall, and leaf nutrient content.
  - **Critical Environmental Data**: Includes NEE, air/soil temperature, precipitation, solar radiation, heat fluxes, soil moisture, snow depth, and carbon export (DOC/POC).
  - **Disturbance Monitoring**: Networks should capture emissions during disturbances, and recovery phases with carbon flux data.
  - **Potential CAFF Link**: Could connect to CAFF (Conservation of Arctic Flora and Fauna) monitoring initiatives

Section	Subject	Body
Permafrost	Permafrost maps	extent, temperature, active layer
	Earth Observation time series of	*No data*

	permafrost change	
	Main effort would be to expand EC network, aiming to fulfill ICOS protocol wherever possible; but addition of lateral fluxes needed	*No data*
Vegetation	Vegetation maps	We need better mapping of vegetation, especially in the boreal region. Maps exist for tundra at sea level (e.g. CAVM/CALU) but the tundra-like vegetation of the oro-Arctic is missing there.
	Key traits necessary to understand c fluxes	Species biomass LAI Height Stomatal conductance Rooting depth Phenology Litterfall Leaf nutrients content
	Important environmental data	NEE Air and Soil Temperature Precipitation Solar radiation Incoming/outgoing short and longwave radiation Latent and sensible heat fluxes Soil heat flux Soil moisture and water table depth Snow depth and SWE DOC and POC export
	Variables List for ICOS Ecosystem Stations	#rangeid=936755535
	Monitoring disturbances	An ideal network should be capable to capture:pre-existing state of the ecosystem (i.e. interannual means and variance of NEE/GPP and Reco) Emissions during the pulse disturbance Recovery from the pulse disturbance, including c fluxes
	Can/should it link to CAFF monitoring?	

Atmosphere	Denser network of tall towers	
	Systematically top-down modelling	
	Any monitoring should align with GGGW	
	Permafrost maps	extent, temperature, active layer
	No data	
Freshwater	Freshwater maps	For inland waters the Hydrosheds database https://www.hydrosheds.org/

Appendix D. Atmosphere

The full series of padlet comments are tabled below. Link to [Slideshow]

Summary:

- What observations/variables must be undertaken in order to address the PRSQs?
  - **GHG Concentrations**: Methane (and isotopes), CO2, CO, VOCs, and global HFC data.
  - **Total Column Observations**: Methane and CO2 concentrations.
  - **Measurement Tools**: Remote sensing, airplanes, and drones.
- Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?
  - **Key Questions**: Is the isotopic signature of sources constant, and are current estimates accurate?
  - **Readiness**: Sufficient knowledge exists to begin monitoring, though technical refinements are needed.
  - **Recommendations**: Define drone technology requirements, resolve engineering challenges, and improve vertical profile retrieval.
- Do specifications for these already exist, for instance as Essential Climate Variables (ECVs).
  - **Total Column**: Protocols exist via TCCON and COCONN.
  - **GHGs**: Covered by ICOS, GAW, national programs, and GGGW.
  - **Gaps**: Limited networked data over Russia; unclear if CO and indirect gases are ECVs.
- What is the temporal and spatial resolution needed?
  - **Temporal**: Hourly to 3-hourly for GHG; isotopes require weekly sampling.
  - **Spatial**: 100–1000 km for in-situ observations.
  - **Coverage Gap**: Not all Arctic Rim states are currently monitored.
- Where and by whom is this already ongoing (may have been addressed under break-out session 1)
  - Conducted by national bodies like the Norwegian Environmental Agency (climate department).
  - Supported by government agencies (mandatory and voluntary).
  - Supplemented by individual scientific research projects.
- Can in situ monitoring can be complemented with remote sensing?
  - **Feasibility**: Yes, in situ monitoring can be complemented with remote sensing and modeling.
  - **Applications**: Supports predicted concentration services, source identification, and operational emission flux inversions (e.g., ICOS framework).
  - **Tool**: ICOS operational tools like [ICOS Shiny].
- Are relevant QA procedures in place?
  - Developed and in place, especially for in-situ measurements, but can always be improved.

- Data management arrangements: Do they already exist for the identified observations/variables or must new arrangements be made?
    - **Current Status**: Existing systems for ongoing monitoring, but harmonization is needed.
    - **Recommendation**: A review or compilation of carbon observation databases and networks could be useful.
- What are the challenges associated with capturing disturbances in our monitoring programmes?
    - **Point Source**: Requires proximity to the source or favorable wind direction.
    - **High Emission Episodes**: Lack of nearby stations and observations makes defining and capturing disturbances difficult.
    - **Diffuse Sources**: Demand higher sensitivity for accurate monitoring

Section	**Subject**	**Body**
What observations/variables must be undertaken in order to address the PRSQs?	Green House Gas concentrations	Methane and isotopes CO2 CO and other indirect greenhouse gases VOCs Some of the variables are of global concern and do not need regional observations (HFCs).
	Total Column Observations	Column concentration from methane and CO2
	Remote Sensing Data	
	Airplane and drone measurements	
Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?	Is isotopic signature of sources constant or is it changing? Are they well known/ correct?	

	In general we know enough to start monitoring, but there might be technical issues etc that can be further developed	
	Recommend to define requirements for drone technology, unsolved basic engineering issues still	
	Better retrieval of vertical profiles	
Do specifications/protocols for these already exist, for instance as Essential Climate Variables (ECVs).	For total column : TCCON, COCONN	
	For GHG	ICOS, GAW, national programmes, GGGW
	Notable lack of networked data over Russia	
	Not sure if e.g. CO or other indirect gases are in the ECV	
What is the temporal and spatial resolution needed?	Time resolution: hour to 3 hours for GHG, for isotopes realistic is probably multiple samples per week	
	Not currently covering all Arctic Rim states	
	Spatial resolution for in-situ concentration observation 100-1000 km	
Where and by whom is this already ongoing (may have been addressed under break-out session 1)	National monitoring is undertaken by Norwegian environmental agency, partly climate department	

	Government agencies (some obligatory, some not)	
	Individual science research projects	
Can in situ monitoring be complemented with remote sensing/modelling?	Yes	
	Remote sensing and modeling	
	Complementing observations with modelling	Operational services for predicted concentrations and their sources could be provided. operational inversions predicting emission fluxes are used for ICOS now and could be extended. https://shiny.nilu.no/ICOS/
Are relevant QA procedures in place?	Developed and in place, especially for in-situ measurements, but can always be improved.	
Data management arrangements:Do they already exist for the identified observations/variables or must new arrangements be made?	Exists for the ongoing monitoring, but harmonisation is needed	
	Overview/Review of Carbon Observations	A compilation of different databases/networks and type of observations might be useful
What are the challenges associated with capturing disturbances in our	Point source: need to be close (or lucky with wind direction)	

monitoring programmes?		
	Biggest challenge for high emission episodes (how we define "disturbances") - are the lack of stations and observations close to the source	
	Diffuse requires higher sensitivity	

Appendix E: Freshwater

The full series of padlet comments are tabled below. Link to [Slideshow]

Summary:

- What observations/variables must be undertaken in order to address the PRSQs?
    - **Water**: Temperature, CO_2, CH_4, PAR at multiple depths.
    - **Ice**: Ice cover period, thickness, and snow depth.
    - **Climate**: Air temperature and relative humidity.
    - **Fluxes**: CO_2 and CH_4 fluxes (EC or floating chamber), sensible and latent heat fluxes.
    - **Concentrations**: Accurate CO_2 and CH_4 in air.
    - **Hydrology**: Water velocities, discharge, DOC, and other relevant inflow/outflow data.
- Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?
    - **Flux Estimation**: Need to compare indirect (dissolved concentration and gas transfer velocity) vs direct methods (eddy covariance and floating chamber) for CO_2 and CH_4 fluxes in freshwater.
- Do specifications for these already exist, for instance as Essential Climate Variables (ECVs).
    - **Existing Efforts**: ICOS Working Group is developing protocols for GHG flux measurements over water bodies (lakes, rivers, coastal waters).
- Can in situ monitoring can be complemented with remote sensing?
    - **Geospatial Needs**: Remote sensing can complement in situ monitoring by providing maps of water bodies (large and small), seasonal dynamics, lake depth, and ice on/off dates.

Section	Subject	Body
1. What observations/variables must be undertaken in order to address the PRSQs?	Required measurements for a freshwater supersite	-Water T at several depths -Water CO_2 and CH_4 at several depths -Water PAR at several depths -Ice cover period (ice on and off dates) -Ice and snow thickness -Net radiation components -Air T and RH - CO_2 and CH_4 fluxes by EC and/or floating chamber - Sensible and latent heat fluxes -Accurate CO_2 and CH_4 concentration in the air

		-Chamber fluxes -Water velocities/turbulence - Inflow/Outflow discharge, DOC, etc
2. Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?	Indirect vs direct flux estimates	For freshwater, CO_2 and CH_4 fluxes are typically estimated by using dissolved water concentration measurements together with gas transfer velocity parameterization (indirect method). The approach is taken from the ocean community. There is a need to use direct methods as well (eddy covariance and floating chamber).
3. Do specifications/protocols for these already exist, for instance as Essential Climate Variables (ECVs).	ICOS WG on flux measurements over water systems	There is an ICOS WG trying to establish protocols for GHG flux measurements over water bodies (lake, river, coastal water).
6. Can in situ monitoring be complemented with remote sensing?	Geospatial needs	Maps of water bodies (large and small), their seasonal dynamics, lake depth, ice on / off

Appendix F: Permafrost

The full series of padlet comments are tabled below. Link to [Slideshow]

Summary:

- What observations/variables must be undertaken in order to address the PRSQs?
  - **Permafrost:**
    - Temperature: Annual, 15m+ depth.
    - Active Layer: Annual, with subsidence where possible.
    - Carbon Pools, Ice Content: Decadal.
    - Organic Layer Depth: Every 5-10 years.
    - Lithology/Texture: One-time, system-dependent.
  - **Snow:**
    - Depth, duration, and thaw interactions.
  - **Carbon Exchange:**
    - Continuous, using towers, remote sensing, and modeling.
  - **Energy Budgets:**
    - Continuous with flux towers or met stations.
  - **Permafrost Degradation:**
    - No data on impacts to communities/infrastructure.
  - **Abrupt Thaw:**
    - Mapping and monitoring of extent and fluxes.
  - **Isotopes:**
    - No data on 13C/14C fluxes.
  - **Soil Moisture:**
    - Continuous, using towers, met stations, and remote sensing.
  - **Aquatic Carbon Fluxes:**
    - DOC, POC, DIC, and isotopes with freshwater groups.
  - **Energy/Water Balance & Contaminants**
  - **Indigenous Knowledge:**
    - **No data on input for site descriptions and variables.**
- Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?
  - **Network Representativeness**: Systematic analysis needed of current networks (e.g., GTN-P, EC, and tall towers) to assess their ability to detect future changes, including abrupt thaw.
  - **Arctic-Boreal Framework**: Develop a framework to characterize the full landscape and support site upscaling based on specific landscape types.
  - **Lateral Fluxes**: Monitoring of fluxes from land to aquatic systems remains challenging (no data).
  - **Power**: Develop sustainable, renewable small-scale power systems for remote monitoring locations.
- Do specifications for these already exist, for instance as Essential Climate Variables (ECVs).

    - **Thermal State of Permafrost**: An ECV with well-defined protocols.
    - **ICOS Protocol**: Can serve as a starting point, with possible permafrost-specific adaptations needed.
    - **Thaw Slumps/Thermokarst**: No common guidelines for abrupt thaw monitoring.
    - **Lateral Loss Monitoring**: Difficult to formulate protocols, especially outside well-defined catchments.
- What is the temporal and spatial resolution needed?
    - **Temporal**: Varies by variable, with both top-down and bottom-up methods required.
    - **Monitoring**: Continuous bottom-up data from EC and tall towers, though high post-processing costs limit near real-time updates.
    - **Spatial**: Each in-situ station should represent a well-defined landscape/landform type, crucial for accurate representation.
- Can in situ monitoring can be complemented with remote sensing?
    - **Satellite Data**: TROPOMI and MERLIN for CH_4, OCO-2 for CO_2, though relying solely on Satellite-GHG EO is insufficient. Data assimilation techniques combining tall towers, satellites, and possibly EC data show promise.
    - **Remote Sensing Types**:
        - **Passive Microwave**: SWE and soil moisture.
        - **Optical**: NDVI for vegetation, browning, greening, and fire.
        - **SAR**: For monitoring subsidence (abrupt thaw).
        - **Multispectral/SAR**: Surface water extent, volume, and change.
    - **ArcticDEM**
    - **ESA CCI+**: High-quality monitoring of fires, lakes, and vegetation change, should be utilized as much as possible.
- Are relevant QA procedures in place?
    - In most cases good QA/QC procedures exists for the ECVs
- Data management arrangements: Do they already exist for the identified observations/variables or must new arrangements be made?
    - Flux data: Ameriflux, ICOS, Fluxnet
    - **Low-hanging Fruit**: Use current best bottom-up data as priors in top-down inversions to improve accuracy with limited resources.
    - **Soil Data**: ISCN network is the best repository, integrates with flux networks and shares data with ISRIC annually.
- What are the challenges associated with capturing disturbances in our monitoring programmes?
    - Need specific sites designed to monitor particular disturbances.
    - Capturing a range of disturbances, ecosystems, and time since disturbance is challenging.
    - Pre-disturbance data is unlikely to be available.
    - Rapid response needed to assess disturbance impacts, requiring quick funding and equipment for post-event monitoring.

Section	Subject	Body
1. What observations/variables must be undertaken in order to address the PRSQs?	permafrost temperature	15m+ below zero annual amplitude; annual measurement
	active layer depth	incorporate subsidence where possible; annual measurement
	Carbon pools	decadal
	Ice content	decadal
	organic layer depth	5-10 years
	lithology/texture	one time measurement - spatial depends on system
	Snow	Snow depth and duration, interactions with gradual and abrupt thaw
	carbon exchange between soil and atmosphere/soil and water	-continuous -spatial extent: i) towers - use representative analysis ii) remote sensing iii) inversion modeling

	energy budgets	flux towers and/or simple met stations with air temp profiles to monitor change in energy exchange between the soil-plant-atmosphere -continuous -spatial extent: i) towers/met stations - use representative analysis ii) remote sensing iii) inversion modeling
	permafrost degradation impacts on communities/infrastructure	
	Abrupt thaw	mapping & monitoring change in extent, fluxes, vegetation change, etc.
	Isotopes - 13C/14C from fluxes	
	surface soil moisture	-continuous -spatial extent: i) towers/met stations - use representative analysis ii) remote sensing iii) inversion modeling
	Exhaustive site characterization	ICOS protocol -once
	Aquatic carbon fluxes and characterization of this carbon (with freshwater group)	carbon export from soil as DOC, POC, DIC carbon isotopes

	Energy and water balance	
	Contaminants (mercury, POPs, CEACs) in soil and vegetation	
	Input from Indigenous Knowledge holders for site description, variables of interest, etc	
2. Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?	More systematic analyses of how representative the current monitoring networks are	This includes analyses of: - e.g. GTN-P network following the method already used for EC-network in Permafrost Pathway (Pallandt et al) - extended analyses of how EC and tall tower network is able to detect/represent projected future change (different abrupt thaw etc)
	A framework for characterizing the full Arctic-Boreal landscape, to support linking individual site properties in upscaling	It is crucial to know what type of landscape each site represents, and how the spatial distribution of that specific type of landscape looks.
	Monitoring of lateral fluxes from land to aquatic systems remains challenging	
	Power	A lot of monitoring is in remote locations but depending on power. Sustainable, renewable small scale autonomous power systems should be developed in support of monitoring.

3. Do specifications/protocols for these already exist, for instance as Essential Climate Variables (ECVs).	Thermal State of Permafrost is an ECV, with well defined protocols.	
	Use ICOS protocol as a start (some specific permafrost adaptation may be needed)	
	Thaw slumps/thermokarst	Common guidelines for abrupt thaw monitoring is lacking
	Protocols for monitoring lateral loss are difficult to formulate (unless the site is in a well defined catchment)	
4. What is the temporal and spatial resolution needed?	Temporal - depends on the variable	adding info to notes in observation column
	Need to include both Top-down and Bottom-up methods (which work at different scales)	Bottom-up monitoring from EC as well as data from tall-tower should be continuous, but high cost of post-processing limits the ability to provide near real-time data and updates. Spatial scales: each in-situ station should represent a well defined (classified) landscape/landform type. Knowing what a site is representative for is crucial.
5.Where and by whom is this already ongoing (may have been addressed	See break-out 1	

under break-out session 1)		
6. Can in situ monitoring be complemented with remote sensing?	use of e.g. TROPOMI and MERLIN for CH4 concentration, OCO-2 for CO2 concentration	Initial studies (see e.g. Pallandt et al., in prep.) suggest that relying on Sat-GHG EO alone is insufficient. A promising pathway is to use data-assimilation techniques to combine all data sources into inversions (tall towers+satellites, perhaps even EC data).
	passive microwave remote sensing	SWE, soil moisture
	optical remote sensing (NDVI, etc)	vegetation parameters, browning, greening, fire
	SAR	subsidence (abrupt thaw)
	multispectral/SAR/etc	surface water extent, volume, and change
	ArcticDEM	
	The ESA CCI+ program has high quality monitoring of fires, lakes, vegetation change. Should be used as much as possible	
7. Are relevant QA procedures in place?	in most cases good QA/QC procedures exists for the ECVs, flux (ICOS) etc	

	For ICOS	
8.Data management arrangements:Do they already exist for the identified observations/variables or must new arrangements be made?	Fluxes: Ameriflux, ICOS, etc fluxnet	
	Low hanging fruit: using current best BU-data as priors in TD inversions	There is sufficient data and knowledge to significantly improve current inversion priors with relatively limited time/resource cost.
	For soil data, the ISCN network would be the best repository. It integrates with flux networks, and shares data with ISRIC annually	
9.What are the challenges associated with capturing disturbances in our monitoring programmes?	Specific sites designed and set-up to monitor a specific disturbance.	
	Capturing the range of disturbance, ecosystem, and time since disturbance	
	unlikely to have pre-disturbance info	

	response time to assess disturbance impacts	rapid response funding/equipment for instrumenting/sampling post fire or abrupt thaw, etc

Appendix G: Vegetation

The full series of padlet comments are tabled below. Link to Slideshow

Summary:

- What observations/variables must be undertaken in order to address the PRSQs?
  - **C Fluxes**: Measure CO_2, CH_4, and potentially N_2O fluxes, along with associated meteorological variables.
  - **Soil and Landscape**: Thaw depth, soil moisture, temperature, snow depth, soil composition (type, carbon, ice content), and disturbance history.
  - **Landscape Changes**: Local observations of landscape transformations, informed by traditional knowledge (e.g., changes in travel routes, shrub encroachment), to guide scientific monitoring.
- Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?
  - **Basic Research**: While there will always be basic research questions, they should not delay the implementation of comprehensive monitoring systems. Monitoring should adapt over time as systems evolve, funding changes, and new information emerges.
  - **Community Needs**: Monitoring should prioritize the needs of affected communities, such as changes in cloudberry areas (key for Indigenous communities) and grazing lands for reindeer.
- Do specifications for these already exist, for instance as Essential Climate Variables (ECVs).
  - ICOS protocols
- What is the temporal and spatial resolution needed?
  - **Towers**: Half-hourly resolution, with variable footprint based on design.
  - **Remote Sensing**: Ideally as high as possible, but at least at Landsat/Sentinel resolution.
- Can in situ monitoring can be complemented with remote sensing?
  - Remote sensing is essential to complement in situ monitoring. Ground instruments can't be everywhere, so satellite data is needed for upscaling. Direct satellite measurements of column-integrated CO_2 and CH_4 can be integrated with airborne and ground flux data to refine net flux estimates.
- Are relevant QA procedures in place?
  - Yes, for ICOS/Fluxnet
- Data management arrangements: Do they already exist for the identified observations/variables or must new arrangements be made?
  - Existing data management systems are in place but could be improved. Tower data could be better integrated with ecological monitoring in the same areas. A challenge remains in the lag between data collection and availability in databases, with no real-time monitoring or quality assurance.
- What are the challenges associated with capturing disturbances in our monitoring programmes?

- **Lack of Knowledge**: Many sites lack information on past disturbances, especially those from decades ago, which still affect ecosystems.
- **Lack of Maps/Spatial Layers**: Apart from fire data, there are no consistent spatial products to understand disturbance history or extrapolate across regions.
- **Post-Disturbance vs. Disturbance Fluxes**: Many sites capture post-disturbance fluxes (e.g., regrowth, C sequestration) but not direct emissions from the disturbance itself, leading to a bias.
- **What's Needed**: Ground monitoring sites that capture a range of disturbance histories, ecosystem types, and models to estimate direct emissions.
- **Range of Effects**: Disturbances vary widely in type, severity, ecosystems, and compounding factors, making it hard to cover all scenarios.
- **Stochastic Occurrence**: Disturbances occur irregularly and locally, making it difficult to design a fixed monitoring system; quick response systems may lack pre-disturbance data.

Section	**Subject**	**Body**
1. What observations/variables must be undertaken in order to address the PRSQs?	For C fluxes (not just vegetation)	CO2 and CH4 fluxes. N2O if possible. Meteorological variables associated with those. Thaw depth, soil moisture, soil temperature, snow depth, soil composition (type, sand/silt/clay, carbon content, ice content), disturbance history
	Changes in landscape	Local observations of landscape changes offer valuable insights into local transformations. Stories passed down through generations highlight how the landscape has evolved over time. Changes in traditional travel routes, safety measures, or the encroachment of shrubs (scrubification). Reflect the shifting environment and its impact on traditional ways of life. These observations would then guide the scientific monitoring
	See also general questions	List of variables in the general questions pad

2. Are there basic research questions that must be solved before more comprehensive monitoring is undertaken?	No	There will always be basic research questions, but this should not stop or stall us from implementing a comprehensive monitoring system. The monitoring system will inevitably change as the systems change, funding changes, and we learn new information from basic research (adaptive monitoring; Lindenmayer and Likens, 2010)
	Prioritizing community needs	What is relevant for the communities affected by the permafrost thawing should be the guiding question, such as how the important cloudberry areas are changing (key species for many Indigenous communities), how the grazing lands for reindeer is changing.
3. Do specifications/protocols for these already exist, for instance as Essential Climate Variables (ECVs).	ICOS protocols	http://www.icos-etc.eu/icos/documents/instructions#inst
	See also pad on current obs networks	
4. What is the temporal and spatial resolution needed?	Towers	Half hourly resolution, footprint variable by design
	Remote sensing	Ideally as high as possible, but at least Landsat/sentinel
5.Where and by whom is this already ongoing (may have been addressed under break-out session 1)		

6. Can in situ monitoring be complemented with remote sensing?	Yes	I believe this is a necessary component of the monitoring system. We will never have ground instruments everywhere, and will need satellites to extrapolate. The question is what type of satellite data. One general type is satellite data / products that are useful for upscaling. There are also 'direct' satellite measurements of column-integrated CO_2 and CH_4 that can be integrated with airborne and ground fluxes to constrain net fluxes
7. Are relevant QA procedures in place?	Yes, for ICOS/Fluxnet	More standardized measurements needed for chambers. But also again, see ICOS
8.Data management arrangements:Do they already exist for the identified observations/variables or must new arrangements be made?	Yes, but could be better	Tower data could be combined better with ecological monitoring in the same area. There is a challenge in the lags between data collection and availability in overarching databases. No real time monitoring with QA.
9.What are the challenges associated with capturing disturbances in our monitoring programmes?	Lack of knowledge	For some sites, there is no information on the full disturbance history of a site - primarily for disturbances that occurred decades prior (but are still influencing the ecosystem).
	Lack of maps / spatial layers	Besides fire (which still have limitations), no consistent spatial data products exist across the domain, limiting both our ability to understand disturbance history at a site and to extrapolate.
	Post-disturbance vs disturbance fluxes	Many sites are established in systems after some type of disturbance, and inherently capture post-disturbance fluxes (often regrowth and C sequestration), but don't capture direct emissions from the disturbance itself, thus representing a bias.

		This is where we need large-scale estimates of disturbances and their direct emissions
	What's needed	Ground monitoring sites that capture a range of disturbance histories and ecosystem types, maps to extrapolate, and data/models to estimate the direct emissions
	Range of effects	Large ranges of disturbance types, severities, ecosystems impacted, and compounding disturbances. May not be able to cover all gradients.
	Stochastic occurrence is challenging	It is difficult to design a fixed monitoring system that captures disturbances, because they occur irregularly and can be highly localized. Measuring the direct impact may be possible with a quick response system, but then we don’t know the preexisting state of the ecosystem.

Cover photograph: Torben Røjle Christensen

PERMAFROST PATHWAYS

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