At CENPERM, we study the consequences of climate changes in arctic ecosystems and address knowledge gaps in biogeochemical elemental cycles, which are related to current and future ecosystem responses. Our fundamental research goals and ambitions have been addressed through an interdisciplinary approach initiated in 2012, and has resulted in a combination of field manipulation experiments across sites in Greenland, as well as laboratory experiments linking physicochemical changes to biological adaptations and climatic feedbacks. The measurements are designed for testing and developing existing ecosystem models to reduce current uncertainties when simulating greenhouse gas emissions and ecosystem responses to climate change and land use management.

CENPERM uses a multi-site approach in which experimental work and measurements are made across major climate zones in Greenland. This allows a combination of site-specific, process-based investigations and upscaling along climate transects relevant for predicting regional trends in e.g., greenhouse gas (GHG) emissions. In 2012–2015, detailed measurements of ecosystem responses included seasonal emission levels and pulses of GHGs and biogenic volatile organic compounds (BVOC), changes in vegetation linked to processes such as nitrogen fixation and root growth, and changes in the subsurface thermal regime. We have described the outcome of the first four years (out of six funded by DNRF) in a separate, detailed self-evaluation report. This revised research plan therefore covers the remaining time of CENPERM (2017), as well as plans for a second period of four additional years (2018-2021).

The main aims for CENPERM are (1) to continue detailed measurements at experimental plots in Greenland with a focus on process understanding of the long-term effects of climate change treatments; (2) to quantify the role of landscape processes for elemental cycles across Greenland with a focus on water and energy balance, inorganic and organic nitrogen and carbon interactions and fluxes; (3) to feed data into detailed process-based models applied at plot and landscape scale; and (4) to bridge these simulations with large-scale ecosystem modeling across Greenland, representing climate gradients relevant to the wider arctic area.

We will continue the ongoing experimental work in Greenland and expand the scope by addressing ecosystem changes as a response to future changes in water and energy balances. We will explore the future carbon budget, which is closely linked to organic nitrogen and water dynamics, and integrate the interactions between landscape elements, including stable and unstable surface types and hotspots. We will address ecosystem changes corresponding to “stable treatment” effects (such as summer warming by open top chambers), and as a new component including “events” such as sudden erosion and near-surface exposure of permafrost, fires and short, intense periods of winter warming. In this revised research plan, the use of models will play a key role for improved process-understanding, sensitivity analysis, and for enhancing our understanding of the interactions between climate change and the transition of ecosystems. We need to capture these interactions in different spatial scales in order to be able to upscale to regional level, and also to understand the downscaling from regional climate models. For this new approach, we will apply empirical as well as mechanistic methods to describe eco-physiological and biogeochemical processes. We will also include comparisons of alternative process description models (e.g., with varying degree of complexity). Results from uncertainty-based calibrations of these models will be extensively used to further improve the understanding of scale dependencies and uncertainties of existing biogeochemical models. Both errors that are related to model structure uncertainty and to current parameter uncertainty will be investigated. After being constrained by various criteria to describe actual measurements, the models will provide landscape- and regional-scale estimates for both present-day and climate change scenarios, which will be applied to Greenland and other parts of the Arctic.
**Background and aims** Future climate changes are predicted to have the most pronounced effects in northern latitude ecosystems\(^1\); a region that recently has been subjected to marked changes following thawing of permafrost\(^2\), changes in soil temperatures, hydrological regime\(^3\), glacial retreat\(^4\), and fluvial and coastal erosion\(^5\). One of the most marked effects of permafrost thawing is the accelerated decomposition and potential mobilization of organic matter stored in the permafrost, impacting global climate through fluxes of greenhouse gases (GHG), and nutrients being transported along hydrologic pathways. This release of GHG is counterbalanced by increased production of plant biomass (the greening of the Arctic), but the net effect remains unclear due to the lack of robust estimates of net carbon balance\(^6\text{-}^9\). Empirical and process-based models are ways to integrate ecosystem processes and identify the critical factors driving the current and future carbon balance\(^7\). This balance of CO\(_2\) and other GHG is critically affected by changes in the water and energy balance, shifts in vegetation types\(^8\) and root dynamics\(^10\), landscape instability and erosion\(^5\) and the presence of hotspots in the landscape\(^11\). We have defined these points as key topics in CENPERM, and will further differentiate between steady changes, and event-driven changes such as winter warming over the course of few days, insect outbreaks, or wildfires.

![Figure 1: Landscape integration and feedback mechanisms related to movement of water (H\(_2\)O) and nutrients (e.g., nitrogen) across the landscape. Changes are driven by warming but not the least changes in the water balance.](image-url)

The large number of interacting processes (Fig. 1) highlights the need for an integrated landscape approach in our research plan. This has rarely been done for the Arctic, and is one of the reasons that climatic feedbacks from subsurface heterogeneities (e.g., permafrost thawing, changed water flow and erosion) are not currently incorporated in standard climate model projections\(^2\). Moreover, understanding the complexity of the processes involved is necessary in order to improve this representation in large-scale Earth system models. This includes the thermal conditions and phase transitions of water and ice, the lateral transport of water, nutrients, dissolved organic matter and energy, and improved knowledge of the chain of biogeochemical processes controlling organic matter decomposition and release of GHG. None of the current circumpolar permafrost models consider the spatial heterogeneity of the arctic landscape\(^8\), interactions within the landscape or abrupt thaw processes linked to erosion or sedimentation (burial of carbon). The lack of representation of active layer-permafrost-influenced climate feedback is recognized as one of the main reasons for the poor performance of climate models at high latitudes\(^7\). By addressing these components, we expect that we can markedly reduce the uncertainties in predicting future ecosystem responses to climate changes, and thereby contribute to constrain the feedbacks to the climate system.

Arctic ecosystem feedback mechanisms and processes interact on micro (~\(\mu\)m), plot (~m), landscape (~\(10^3\) m) and regional (~\(10^6\) m) scales. Within the scientific approach mentioned above, research at CENPERM will target specific challenges based on the following research questions, which reflect
the different scales upon which these need to be studied, while also targeting the interactions between these scales.

The research questions are all linked by one principal conceptual hypothesis: The future terrestrial arctic carbon budget will be strongly controlled by changes in nutrient availability, plant growth, energy and water balance, and by transport of elements by water within and between landscape units. Our approach addresses a number of specific research questions:

What are the abiotic and biotic controls of organic matter decomposition in the upper soil profile and thawing permafrost? What is the importance of soil organic matter quality, physical protection, priming due to enhanced plant growth, inorganic compounds as Si and Ca, gas diffusion, and changes in microbial functioning? How will changes in N cycling interact with organic matter decomposition and plant growth and hence influence the ecosystem C budget?

Will the on-going expansion of plants in the Arctic be limited by lack of soil water, nutrients and/or symbiotic fungal and bacterial partners? Will enhanced N fixation and mineralization lead to enhanced plant growth? Which abiotic and biotic parameters control availability of N pools to plants? How will an expanding root zone with microbiota influence subsurface water availability and movement, organic matter decomposition, GHG and BVOC emissions, and slope stability?

What is the impact of transient events on GHG and nutrient fluxes? How are GHG and nutrient budgets and transport influenced by sudden events as erosion, rapid soil burial, winter warming incidences, summer drought, defoliation by larvae, and wildfires? How frequent are these events and how are they related to landscape archives? What are the responses to the events within short-term (less than five years) and long-term time scales? How can these transient features be modeled?

What are the main pathways for, and the importance of water, nutrient and C fluxes within and between landscape types? How will lateral N flow to wetlands influence GHG emissions? How will changes in future water balance and permafrost erosion influence the distribution of wetlands, thaw lakes and other landscape types that are considered “traps” for water and nutrients. Will landscape-integrated responses vary between climate zones across Greenland (e.g., from positive water balance in South Greenland to negative water balance in North Greenland)? How will the interactions between water, nutrient and C fluxes at the landscape level influence the responses of the regionally-integrated C and N budgets to climate changes and the net export to marine waters?

How can the data obtained at plot scale be scaled to projections on regional scales? What are the current trends in changes in plant and snow cover? What local and regional impacts on the energy budget have been observed across landscape types and climate zones in Greenland? How can observed trends be used to improve projections? How can the combination of imaging (e.g., by drones), and ground truthing data gathered in conjunction with manipulation experiments further improve upscaling of data from plot scales to regional scales? What is the significance of landscape heterogeneities over time and space for upscaling? How can sudden events such as landslides be integrated with short and long-term ecosystem responses to climate changes?

Greenland is an excellent study area to explore these questions because sites and research stations across Greenland represent a unique opportunity to integrate permafrost-microorganism-plant-soil interactions, and to apply improved knowledge in quantitative modeling across multiple gradients (e.g., from mountain tops to valley bottoms, from ice sheets to the coast, and from south to north). The Greenlandic study sites represent contrasting conditions and variations within landscape, climate, and vegetation transects, all within a 100 km range from the Greenland Ice Sheet to the coast. This enables CENPERM to quantify, rank, and integrate the net effects of arctic climate changes at a landscape scale. Furthermore, Greenland hosts some of the oldest and most
comprehensive monitoring sites (Arctic Station, Zackenberg-ZERO, and Nuuk-NERO) in the Arctic, and the already established and well-developed infrastructure makes Greenland an excellent “landscape laboratory” for our research. Although Greenland itself is not considered a key player in global climate change in terms of GHG emissions (due to the limited size of the ice-free area and limited C stocks), the processes studied and the scaling are relevant to the wider polar region.

**Research strategies and potential impacts** Through our interdisciplinary team, a novel combination of methods, and access to Greenland, we address some of the most current and highly debated scientific topics: the environmental impact of current and future climate changes in the Arctic, and its implications for elemental cycles and global climate. We expect to provide new insights into the conceptual understanding of arctic terrestrial ecosystem processes as well as insights into up-scaling processes from plot level to landscape and regional scales within Greenland and surrounding areas. This will provide a link between the relevant scale for understanding processes, the interaction and integration of processes at different scales, and the relevant up-scaling for quantitative estimates of both regional and global climatic impacts.

The expected research impact can be considerable in terms of a basic understanding of the dynamics and vulnerability of arctic permafrost C and N pools to climate change. Furthermore, the planned research will have a lasting impact on research fields focusing on global GHG, carbon and nitrogen budgets, as high-quality datasets are needed to develop and validate incorporations of coupled permafrost processes in global Earth system models. Further impact will be seen on research into climate feedback mechanisms and regional effects in the Arctic, as related to landscape changes such as the overall greening of Greenland, sediment and nutrient input to coastal waters. This has important implications for farming/crop production, erosion, ground stability for infrastructure, protection of prehistoric sites, and pollution. A widespread dissemination of our results has already provided direct input into the ongoing debate on climatic tipping points and climate change mitigation.

**International conferences and internet-based and freely available data** A CENPERM-co-organized conference (PAM2017, 7th International Conference on Polar and Alpine Microbiology) is planned in Nuuk, Greenland with C.S. Jacobsen serving as the chairman of the organizing committee. A second conference is planned in 2020/21. Our data management plan ensures that quality-tested data are available through an internally-shared database, and we will make all data available online to the wider scientific community. Data will be aligned to a format similar to two Greenland monitoring data bases: PROMICE (Programme for Monitoring of the Greenland Ice Sheet) and GEM (Greenland Ecological Monitoring program).

**Citizen science** will be developed within CENPERM over the next few years. We aim to integrate volunteer monitoring with our own research by sharing sites with Greenlandic school teachers. Local school teachers in Greenland are our target, as they are positioned across Greenland; they are educated and typically have an interest in CENPERM topics. Furthermore, they have local knowledge and play a key role in educating the next generation. As noted in the self-evaluation report, we have already benefitted from involving local teachers in our field work near Arctic Station, and we have made a survey in the nearby town (Qeqertarsuaq) about our snow fence site at Disko. The results of the survey showed a great local interest in receiving information and becoming involved in our research activities. A one week course for school teachers has been taught at Arctic Station, and a new course and teaching material is planned for 2018. The concept of citizen science will be developed at two CENPERM key sites (Disko and Narsarsuaq) where local inhabitants may have a specific interest in the scientific results. Target data will be kept updated on the internet to share progress in data collection and preliminary results with locals and data will include spatial distribution of snow, coupling of manual measurements (snow water equivalents), plant phenology measurements, collection of precipitation, and observations/documentation of erosion events.
A CENPERM legacy  Beyond a final phase of CENPERM it will be worthwhile to compare CENPERM data to available data in a wider context (e.g., World Microbiome database). This will facilitate up-scaling from regional to circumpolar/global scales. The treatment sites at Disko will be maintained as part of Arctic Station monitoring and this will ensure a continuous assessment of long-term effects. A wider application with a focus on the Disko area is also planned covering social, natural and management aspects for the people living in the area. We expect that the physical Center will persist long beyond a second period, and that the interdisciplinary approach is embedded due to shared data base, network, field sites, co-supervision among CENPERM staff members.

Participants and organization  Center for Permafrost is located at the Department of Geosciences and Natural Resource Management, (IGN), University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. Key applicants (with CV) include:

- **Bo Elberling, center leader** (biogeochemistry), Professor, Department of Geosciences and Natural Resource Management, University of Copenhagen (IGN), Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: be@ign.ku.dk
- **Anders Michelsen** (plant ecology and nutrient cycling), Professor, Department of Biology, University of Copenhagen (BIO), office at CENPERM and Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark. E-mail: andersm@bio.ku.dk
- **Anders Priemé** (microbial activity and adaptation), Professor, Department of Biology, University of Copenhagen (BIO), office at CENPERM and Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark. E-mail: aprieme@bio.ku.dk
- **Per Ambus** (stable isotope specialist and biogeochemistry), Professor, Department of Geosciences and Natural Resource Management, University of Copenhagen (IGN), Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: peam@ign.ku.dk
- **Riikka Rinnan** (plant ecology and BVOC dynamics), Associated professor, Department of Biology, University of Copenhagen (BIO), office at CENPERM and Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark. E-mail: riikkar@bio.ku.dk
- **Guy Schurgers** (ecosystem and Earth system modeling), Associated professor Department of Geosciences and Natural Resource Management, University of Copenhagen (IGN), Øster Voldgade 10, DK-1350 Copenhagen K., Denmark. E-mail: gusc@ign.ku.dk

International center members  The following world-leading scientists will continue to be part of the Center. As members of the board, they will spend time in the field and at meetings. The members will ensure a direct connection to other major permafrost projects and relevant institutions:

- **Paul Grogan** (plant ecology and biogeochemistry) Professor, Department of Biology, Queen’s University, Kingston, Ontario, Canada. E-mail: groganp@queensu.ca
- **Edward Arthur George Schuur** (biogeochemistry) Professor, Department of Biological Sciences, Northern Arizona University, USA. E-mail: ted.schuur@nau.edu
- **James M. Tiedje** (microbial ecology) Distinguished Professor and Director of the Centre for Microbial Ecology at Michigan State University, USA. E-mail: tiedjej@msu.edu
- **Vladimir Romanovsky** (permafrost modeling) Professor of Geophysics, Permafrost Laboratory, University of Alaska Fairbanks, USA. E-mail: veromanovsky@alaska.edu

Key CENPERM staff and co-applicants include:

- Associate professor (IGN) **Aart Kroon** (geomorphology, coastal erosion and dynamics)
- Professor (IGN) **Thorbjorn Joest Andersen** (geomorphology, sediment transport)
- Associate professor (IGN) **Thomas Friborg** (energy budget and greenhouse gases)
- Associate professor (IGN) **Birger U. Hansen** (climate change and remote sensing)
• Senior scientist (GEUS) Christian Nyrop Albers (environmental geochemistry)
• Assistant professor (IGN) Andreas Westergaard-Nielsen (remote sensing and modeling)
• Post-doc (IGN) Wenxin Zhang (process-based modeling)
• Associate professor (BIO) Helge Ro-Poulsen (plant physiology)
• Post-doc (BIO) Kathrin Rousk (plant physiology and nutrient cycling)
• Post-doc (BIO) Jing Tang (ecosystem modeling)

The CENPERM staff has been expanded according to the focus of the research: Guy Schurgers, Andreas Westergaard-Nielsen, Wenxin Zhang and Jing Tang reflecting the focus on upscaling and modeling (theme 3) and Riikka Rinnan and Kathrin Rousk reflecting an ongoing generational shift.

**Center competences** CENPERM represents an innovative approach to interdisciplinary, fundamental research, which integrates physical, chemical, and biological landscape processes. CENPERM possesses the scientific expertise and experience necessary in order to undertake the entire approach as well as to maintain field measurements under harsh environmental conditions in the Arctic. All key members of the group know each other well and most have worked together for more than ten years. Bringing together the entire group has been recognized as a unique opportunity to integrate current know-how and expertise in arctic physical and biological processes to predict ecosystem processes and interactions in response to climate change. The combined expertise of our group will help keeping Denmark at the forefront of the field of environmental research in the Arctic. Due to the scope and complexity of the described research activities, the Danish National Research Foundation is seen as the only probable funding body.

Within the budget of CENPERM (2018-2021), we plan to attract four post-docs and four Ph.D. students, as well as visitors to the Center. The latter will be secured by the allocation of a part-time salary for visiting scientists and international members. The interdisciplinary approach is strengthened by the fact that all staff members are physically located within the Center. Co-supervision of Ph.D. students will continue to be arranged to overlap between scientific topics. **Educationally**, at least two interdisciplinary Ph.D. courses and one M.Sc. course will be organized. M.Sc students are considered very important in relation to field work and Ph.D. projects.

**Cooperation and networking** CENPERM activities have fed and will feed into global assessments and international monitoring programs (IPCC, AMAP/SWIPA etc.) in which CENPERM members are already actively participating. CENPERM will continue to build on an existing strong national and international arctic network, which is linked through ongoing and new projects. Cooperation in a Danish context is ensured within ongoing projects in close collaboration with Geological Survey of Denmark and Greenland (GEUS), Aarhus University, DTU/ Centre for Arctic Technology, the National Museums of Denmark and Greenland, and Greenland Ecological Monitoring program.

**Key collaborators (main topic):**

**Theme 1:** KK Brandt, associated prof., KU (microbial Ecology and biotechnology); NM Schmidt Senior Researcher, Department of Bioscience, Aarhus University (Biobasis Nuuk/Zackenberg); CS Jacobsen, prof., Department of Environmental Science Aarhus University (microbial genomics); C Larose, Dr. University of Lyon, France (environmental microbial genomics); L Cooper, prof. at University of Tromsø (snow fence at Svalbard); IK Schmidt, prof. at IGN, KU, (root dynamics), and A Meisner, researcher at Lund University (plant-microbe interactions).

**Theme 2:** HH Christiansen, prof. in Physical Geography at UNIS, Svalbard (geomorphology); J Hollesen, scientist, and H Matthiesen, senior scientist at the National Museum of Denmark (REMAINS and arctic archeology); P Kuhry, prof. at Dept. Physical Geography and Quaternary Geology, U. of Stockholm, Sweden; T Ingeman-Nielsen, ass. prof. at DTU Civil engineering in
Denmark (geophysics and geotechnics), GE Liston, senior researcher at Colorado State University, USA (SNOW), D Blok, researcher at Lund University (litter decomposition), JR Christiansen, scientist at IGN, KU (N fluxes and hotspots) and L Nielsen, prof. at IGN, KU (geophysics).

Theme 3: M Stendel, Senior Researcher at the Danish Climate Centre at the Danish Meteorological Institute (HIRHAM); P-E Jansson, retired Prof. from Land and Water Resources Engineering, KTH Royal Institute of Technology in Stockholm, Sweden (CoupModel); CI Voss, senior research Hydrologist, as U.S. Geological Survey, USA (SUTRA); B Smith, prof. at Lund University, Sweden (regional ecosystem modeling); S Westermann, Researcher at University of Oslo, Norway (regional ecosystem modeling); KH Jensen, Prof. at IGN, KU (hydrological modeling); D Nicolsky, researcher at Permafrost Laboratory, University of Alaska Fairbanks (numerical modeling).

Citizen and social sciences: AG Busck, associated prof. at IGN, KU (social impact assessment); AMZ Schmidt Dr at NORDECO, Wilderness Inspire (citizen and social sciences).

Center leader Bo Elberling will be head of CENPERM. Key qualifications include: science management qualifications with completed relevant training and experience; extensive field work experience, including 25 expeditions to Greenland, Svalbard, Canada and Antarctica, and key responsibility for several long arctic field trips and field courses for students at different levels ranging from high-school to Ph.D. level, and for royalties; extensive arctic scientific network, as a partner of the EU-funded permafrost project PAGE21, and multidisciplinary Adjunct Professor at the University Centre at Svalbard (UNIS, 2007-2012); a long scientific record of permafrost research in Greenland, 16 arctic research projects; and finally a research profile documented by peer reviewed publications, which encompasses the disciplines included in CENPERM (see details in the CV).

Description of institutional affiliations

All applicants of CENPERM and all Ph.D. students and post-docs are and will in the future be located at the Department of Geosciences and Natural Resource Management (IGN, UCPH). CENPERM will benefit from a close collaboration between Department of Biology, IGN, and Geological Survey of Denmark and Greenland (GEUS), including shared clean microbial laboratory facilities. GHG, stable isotope, growth cabinet, freezer and other key laboratory facilities are established at CENPERM.

Project management is a vital component of CENPERM due to its size, interdisciplinary character and integrative approach. Practical steps have been successfully implemented to optimize interactions within the project consortium. These have been described in detail in the self-evaluation report and will continue in CENPERM II. Coordination activities will aim to maintain a high degree of communication, scientific discussions, field work optimization, and synchronization of the iterative development of field validation data with model setup and parameterization. These will include the development of the data management platform and metadatabase, data-model workshops, and standardized programs and procedures. CENPERM will also continue joint summer fieldwork periods at CENPERM sites, as well as bilateral exchange visits between field experts and modelers.

A Center directional board consisting of the six national applicants (Elberling, Michelsen, Rinnan, Priemé, Ambus and Schurgers) and the CENPERM administrator will meet regularly to discuss and make all final decisions with respect to major research questions, economy, and staff members. The CENPERM leader will make any final decisions regarding CENPERM. The center directional board will hold annual meetings with the four international co-applicants to ensure progress and seek advice on major decisions (Skype meetings will be used if not all can be present at the Center). Through regular meetings, the Center directional board will be responsible for scientific progress, new hires, overall decisions with respect to external components, and routine evaluation.
Key collaborating organizations, centers and projects include: International Permafrost Association (IPA), Global Terrestrial Network on Permafrost (GTN-P), The Permafrost Carbon Network, Circumpolar Active Layer Monitoring (CALM), International Tundra Experiment (ITEX), and Nordic Network for Stable Isotope Research (NordSIR). As partner in Greenland Ecosystem Monitoring program (GEM), we are involved in data collection and have access to the GEM database. DiskoBasis, as part of GEM, has so far received funding for a data manager working at CENPERM. A 5-year GEM program application for Zackenberg, Nuuk and Disko will be submitted in December 2016. Key projects include INTERACT II (2017-2020), the snow fence experiment at Svalbard in close collaboration with E. Cooper, UNIS as a partnership in: Effects of Snow Depth and Snow Melt Timing on Arctic Plant Ecology (SnoEco) funded by The Norwegian Research Council. Measurements of BVOCs are coordinated by R. Rinnan based on additional funding from the Danish Council for Independent Research. Analysis of soil microbial responses to environmental fluctuations is coordinated with A. Meisner (Lund University) based on an International career grant from the Swedish Research Council Coping with Extremes (7.6 mio SEK, 2015-2019). A continuation of litter decomposition studies is made in cooperation with D. Blok (previous CENPERM post-doc, now Lund University) and now funded by a Marie Skłodowska Curie International Career Grant 2015 from the Swedish Research Council (5.8 mio SEK, 2016-2018). Work on archeological sites initiated in CENPERM is now continued by J. Hollesen as a separate project REMAINS funded by the Velux Foundation (5 mio DKK, 2016-2018).

Planned research program

CENPERM and associated Ph.D. and post-doc positions are organized in three research themes. Research will be carried out at different scales – all of which represent the major themes, which is integrated in a work flow of activities (Figure 2). That means that within and between the themes, laboratory experiments, field experiments, monitoring and modeling will be integrated.

Figure 2: Work flow for the different research components

**Theme 1: Ecosystem responses at plot level: Focus on experimental work**

This theme focuses on measurements of interacting processes between microorganisms, plants and the soil at plot scale in contrasting landscape and vegetation types. Experiments focus on elemental turnover by microorganisms, plants and losses by leaching as well as GHG emissions, including \( \text{H}_2\text{O}, \text{CO}_2, \text{CH}_4, \text{N}_2\text{O} \) as well as biogenic volatile organic compounds (BVOC) and \( \text{O}_2 \) exchange. Surface exchange rates will be combined with depth-specific measures of production rates based on soil gas concentrations and modeling (see Theme 3). This theme is mainly related to work at experimental sites established across ten locations from South to North Greenland (space for time
substitution), representing ecosystem field manipulations of temperature, radiation, snow depth and water availability at Disko, Nuuk, Narsarsuaq, Zackenberg and Peary Land.

**Experimental manipulations in Greenlandic ecosystems: Long-term changes.** Some arctic ecosystem components respond slowly to changes and long-term responses may differ from shorter term responses. We will maintain the emphasis on longer-term field experiments and the infra-structures established during the first phase of CENPERM, and ensure that results are directly comparable to similar and even longer-term experiments in Sweden (Abisko), Svalbard (Longyearbyen) and Canada (Daring Lake), which are used by CENPERM and affiliates.

1.1 How will ecosystem responses vary across latitudinal and altitudinal gradients and from coastal to continental areas? Current climate change manipulations at the main CENPERM sites at Disko and Narsarsuaq focus on single and combined effects of winter warming (snow fences), summer warming (open top chambers, OTC) and plant removal in a full-factorial design. Summer warming is also carried out at Nuuk, Zackenberg, and Narsarsuaq and will be made in North Greenland (Peary Land) starting in summer 2016. At Disko and Narsarsuaq, warming and ambient plots are furthermore located at two different altitudes. At all sites, measurements are made of at least wet and dry vegetation types.

**Experimental manipulations in Greenlandic ecosystems: Events.** Extreme and or sudden events may have a profound effect on tundra ecosystems, and cause the ecosystem to reach a new ecological equilibrium. Furthermore, ecosystems are more sensitive to the effects of climate change following an episodic disturbance. We propose as a new focal point to investigate several disturbances with specific importance in the Arctic: summer drought, fire, defoliation, and episodic winter warming.

1.2 Will summer droughts in the Arctic have substantial negative effects on plant growth? Results obtained at the Nuuk site indicate that a decrease in soil water may decrease plant growth and ecosystem C sink strength especially where plants grow in a shallow organic layer covering the bedrock. As the first field experiment in Greenland to mimic the effects of soil drying, separate plots with cables and infrared heaters (see below) at Disko and Narsarsuaq will be used to explore such effects of drying during the plant growing season.

1.3 Will nutrient losses following a fire event in tundra lead to irreversible changes in ecosystem function? Tundra fire is an “extreme event” which is becoming more frequent with climate change, leading to large C losses and may strongly influence arctic ecosystems, but it is luckily not seen on a widespread scale in Greenland. Fire effects on nutrient losses will be assessed in a new treatment in 2017 at Disko. Plant material will be labelled with $^{15}$N, harvested, and burned at low temperature. The ash will be returned on the surface of plots. The recovery of labelled nitrogen in plants, soil, emission of N$_2$O and leaching loss will be in focus and together with other essential nutrients (phosphorus, potassium), it will be assessed under contrasting environmental conditions (enhanced snow and summer temperature manipulations).

1.4 Will the complete removal of leaves, mimicking severe defoliation events (e.g., caused by moth larvae) lead to enhanced microbial immobilization, and hence ecosystem nutrient retention? And will subsequent plant uptake of nutrients and carbon compensate for episodic losses? Nutrient and carbon fluxes and pools will be followed in ecosystem compartments.

1.5 How will intense warming events during winter influence plant performance and nutrient availability, and are these changes more profound than longer-term warming? Short winter warming events may have marked effects on ecosystems and seem to appear with higher frequency across the Arctic. At two sites with a power supply nearby (Disko and Narsarsuaq), warming cables and infrared heaters will be installed to mimic up to two weeks of warming, including complete snow
melt and warming of the topsoil. Measurements will include both the short warming period and, more importantly, the carry-over effect on soil nutrient availability, GHG and BVOC exchange and plant growth during the following growing seasons.

**Permafrost transplantation and pan-arctic comparison**

1.6 What are the abiotic and biotic controls of organic matter decomposition/burial in the permafrost? A new experiment will focus on the transplantation of permafrost samples to two near-surface depth intervals in all treatment plots within the winter and summer warming experiments under contrasting vegetation types at Disko. These transplantations will be sampled after two and four years and treatments aim to mimic the abrupt exposure of permafrost carbon to near-surface conditions as a result e.g. of landscape collapse. The focus will be on characterizing decomposition of organic matter and differences in organic matter lability after incubation.

1.7 Are soil microbial responses to winter warming generalized across arctic ecosystems? To investigate this, nitrogen cycle process rates and N cycle microbial gene abundance will be investigated in soil cores obtained from controls and winter warmed plots from existing snow-fences in Alaska, Canada, Svalbard and Greenland. The soil will be incubated at the same temperature in the laboratory to investigate N cycling rates using 15N-labelling techniques. N cycle genes (nifH, amoA, nosZ) will be quantified in the field samples, and after incubation.

**Linking greenhouse gas (GHG) and BVOC emission to climate change manipulations**

1.8 What is the importance of events as rainfall, herbivore attack, and phase transitions during thawing and freeze-up compared to longer-term moderate changes in temperature for GHG and BVOC fluxes? Both ambient and manipulated sites will be instrumented to measure high temporal resolution H2O, CO2, CH4 and BVOC emissions year-round. Emissions will be linked to subsurface depth-specific microbial GHG production, gas concentrations as well as gas transport mechanisms. Automated chambers will be in place and one full-year measuring campaign is planned at two sites (Disko/Narsarsuaq) and will include stable isotope analysis (13C/12C) to quantify the contribution of different carbon sources to GHG emissions during winter, and burst events during thawing and freeze-up.

1.9 How are emission of BVOCs related to the below-ground production of CO2 and CH4, photosynthesis and bio-availability of substrates? BVOC emissions will be quantified along gradients, in long-term ecosystem manipulations and in mesocosms and related to substrate characteristics, on vegetation-specific basis. Amounts and sources of BVOC released from permafrost soils will be related to soil chemistry and microbial community structure using sequencing of 16S rRNA gene and fungal ITS2 fragments.

1.10 What is the importance of short-term pulses of BVOC emissions compared to longer-term trends in BVOC release? A new ultra-sensitive Proton Transfer Reaction-Time Of Flight-Mass Spectrometer (PTR-TOF-MS) will allow real-time analysis of a large range of BVOCs simultaneously. This will enable assessment of short-term emission variations, seasonal trends and bidirectional fluxes (deposition versus emission). Our recent findings demonstrate the extreme temperature sensitivity of the BVOC emissions from arctic plants. New experiments using isotope-labelling will track sources and sinks of a range of BVOC compounds in the laboratory and in the field.

1.11 Is N in thawing permafrost a major sources of “new” N for plants, and will this be lost from some ecosystem types and accumulate in other areas, or be emitted as N2O? Sources of emitted N2O
and subsurface N₂O concentration will be investigated using ¹⁵N labelling and analysis, and will be related to dissolved inorganic and organic N (including amino acids) in permafrost and active layer soil organic matter and linked to micro-topographical gradients. We will further investigate if the current “greening” of the Arctic is limited by availability of soil N, soil water and/or fungal and bacterial partners.

**Linking plant, soil nutrients and microbial activity** Links between plant communities, soil parameters and processes represent an important control over the C cycle, and the C and N cycles are intimately linked. We will explore how soil processes may influence plant performance, and how soil C and N storage, N₂ fixation, and organic matter characteristics may be affected by climate changes.

1.12 Are above- and belowground plant responses to changes linked, and what is the role of root-associated fungi in organic matter turnover and soil aggregation? In the Arctic, the below-ground plant biomass exceeds its above-ground counterpart and represents an important “hidden” component of soil nutrient cycling and ecosystem C budget. Neither the knowledge from non-arctic ecosystems, nor projections of above-ground to below-ground production reflects seasonal dynamics of root growth in arctic plant communities, and limited data are available. We have installed mini-rhizotrons at our experimental sites at Disko, which allow a long-term assessment of root responses beyond the already-reported short-term effects. Data on root dynamics in the snow fence experiments on Disko and Svalbard will be coupled with data on aboveground plant performance, soil nutrients, GHG fluxes and BVOC emissions. In addition, we will investigate if changes in mycorrhizal fungal abundance impact C sequestration, as has been shown in boreal forests.

1.13 What are the main determinants of long-term C retention or losses in warmed tundra? Our access to unique long-term experiments enables investigation of long-term changes in soil organic matter quality after multiple-decade field manipulations of temperature. Methodologies will comprise ¹³C-NMR (nuclear magnetic resonance) spectroscopy, as well as FT-IR (Fourier transform infrared) and NIR (near-infrared reflectance) spectroscopy. Analysis will also include time series analysis of changes in soil water and total C, N and P, coupled with investigations of changes in microbial activity and enzymatic production capacity.

1.14 What is the importance of N₂ fixation on ecosystem and landscape scale, as compared to other N sources such as deposition and N release from permafrost? Plant N₂-fixation and uptake including ammonium, nitrate, amino acids and peptides will be assessed under field condition using dual label ¹³C-¹⁵N pulse addition and acetylene reduction assays, with a focus on effects of moisture, temperature, and events such as freeze-thaw in early summer and autumn. Ecosystem N input via N₂ fixation under varying abiotic field conditions will be compared to other N-sources (e.g., permafrost thawing). Interactions between moss and cyanobacteria will be assessed using transcriptomics and nutrient exchange between moss and cyanobacteria will be assessed to identify limiting factors for N₂ fixation. The long-term fate of fixed N₂ will be assessed in moss-cyanobacterial associates, and in adjacent ecosystem compartments. N budgets will be made at Disko in relation to winter and summer warming treatments and in transects away from a glacier forefront. Differences in the role of parent material and trace elements, mainly basaltic material on Disko and granite in Narsarsuaq on N₂ fixation will also be investigated.

1.15 What is the role of organic N in N retention, mineralization and plant growth? We will characterize soil organic N pools and seasonal trends in N compound turnover and bioavailability. Soil and melt water will be analyzed for ammonium, nitrate and dissolved organics such as amino acids and peptides, and the turnover of organic N compounds will be determined using the ¹⁵N isotope pool dilution approach. Plant and microbial material and soil organic matter labelled with ¹³C
and $^{15}$N will be used to follow release rates of gases and dissolved, leached compounds under different active layer conditions.

### Theme 2: Landscape processes and interactions

The main question in theme 2 is how climate changes can influence energy, water and nutrient fluxes in landscape units along transects, and how these fluxes influence ecosystem functioning such as C and N turnover, plant growth, and GHG emissions. Source areas for these fluxes include on-going permafrost thawing in upland soils, snow drifts, and retreating glacial fronts. The ongoing field investigations at CENPERM will be expanded with new landscape transects. The focus will be on spatial variability and comparison of measurements among similar transects along the climate gradient in Greenland (between CENPERM sites), and other sites (e.g., in Svalbard, Longyyearbyen).

#### 2.1 What is the heterogeneity in C and N accumulation in relation to permafrost history?

Landscape-level inventories will focus on C- and N-sequestration rates and spatial trends in subsurface C and N lability in the vegetation, the active layer and the top 3 m of the permafrost zone. The chemical quality of plant/soil organic matter will be assessed using biogeochemical techniques (incubation experiments, C and N stable isotopes, extractable organics, and C:N:P ratios). Radiocarbon dating of microfossils and optically stimulated luminescence (OSL) will be used in combination with analysis of permafrost type and ice content to further assess landscape heterogeneities and permafrost history of individual landforms at key CENPERM sites.

#### 2.2 Will substrate quality and/or microbial community structure control GHG production rates in landscape units with progressive permafrost thawing?

We will use an extensive database of GHG production rates measured on permafrost cores collected from a range of permafrost types and landscape elements across the circumpolar region in CENPERM, and link this to new work focusing on chemical and microbial characterization of the cores. We will apply multiproxy approaches including lipid biomarker and NIR analyses to assess the degree of organic-matter decomposition. Experimental lab work will focus on temperature-dependence of microbial activity at and below freezing, carbon use efficiency (CUE), differences in microbial community structure, and the concentrations of inorganic elements Si and Ca, which are important for fungal growth and litter decomposition. All the permafrost characteristics will be coupled to sediment age and sedimentation rate.

#### 2.3 What are the most important factors driving CO$_2$ and H$_2$O fluxes in contrasting landscape units?

We will use mobile eddy covariance towers coupled with NDVI measurements, and vegetation analyses in the fetch of the towers to quantify variation in CO$_2$ and H$_2$O fluxes within and between vegetation types across landscape gradients. Data will be used to identify key factors (e.g., soil moisture) that control spatial trends in the fluxes. Drones equipped with standard and NDVI cameras will be used to link plot level and transect measurements to satellite images, and to link plot to regional scales.

#### 2.4 How will differences in N cycling between landscape units and their interactions influence the landscape level response to climate change?

Precipitation, atmospheric N (dry and wet) deposition, accumulation of nutrients, timing of snow/ice melt, and release of subsurface stored nutrients will be assessed in transects from source areas to lowlands (Fig. 1). N deposition will be compared with N$_2$ fixation. Functional rooting depth will be investigated using soil- and xylem-water $^{18}$O analysis combined with $^{15}$N labelling in the soil profile. N fluxes along slopes and between vegetation types will be assessed by $^{15}$N-tracing and by anion and cation exchange resins. We will measure organic and inorganic N, the timing of N-fluxes from melting snow drifts, and their fates along vegetation
types away from snow drift. Soil water will be collected using piezometers and used in combination with ion exchange membrane probes\(^4\) to quantify short and long-term soil water chemistry and fluxes.

2.5 How will glacial retreat affect plant colonization, succession and N and C cycling? This will be investigated at three transects where glacial retreat over the past 30 to 1000 years is well-documented. Investigations will integrate (1) permafrost formation and water run-off, (2) plant establishment, (3) accumulation of C, N and P in cryptogamic crust, plants, soil and microorganisms, (4) microbial community structure (microbial PLFA and qPCR of the N-fixing associated nifH gene, 16S rRNA gene and fungal ITS2), (5) soil respiration, N-mineralization and GHG fluxes, and (6) lichen and moss-associated N\(_2\) fixation rates. Emphasis will be on quantification of nutrient input by lateral flow from melt water, snow surface, deposition, and fixation, and the potential for downslope transfer.

2.6 Will permafrost thawing along landscape gradients significantly impact C and N inputs and turnover in wetland and marine ecosystems? Permafrost thawing and shoreline erosion are closely related and will cause event-driven exports of C and N to water-saturated wetlands and marine ecosystems. The effects of erosion will be investigated along transects at two key CENPERM sites (Disko and Nuuk) sensitive to changes in climate and sea level. Aerial photographs and satellite images will be used to determine erosion rates and volumetric losses of sediments and hence to estimate the loss of C and N caused by erosion. Observations will be scaled up to a regional level for the two sites. This is part of an ongoing Ph.D. study at Disko and in close collaboration with a co-financed project REMAINS linking the vulnerability of landscapes from ice sheet to the sea in the Nuuk area.

2.7 How will sudden changes in the landscape, such as landslides and soil erosion, influence net water, sediment and nutrient losses from the terrestrial ecosystem? Detailed topography, soil maps, geomorphology and dating of sediment in landscape traps (focus on wetlands and delta plain) will be used to differentiate short and long-term travel pathways of matter. Specifically, changes in current residence times of water and nutrients will be explored at Disko and in the Nuuk area (REMAINS).

**Theme 3: Integration and scaling**

The overarching objective for theme 3 is to provide large-scale estimates of changes in the physical environment and their impact on, and interactions with, biogeochemical processes. The focus is on water and nutrient fluxes across landscape pathways, the importance of hotspots and modeling episodic events to the long-term response to climate change. For this upscaling, both empirical and process-based modeling will be applied.

**Data collection and use of statistical relationships for quantitative analysis and upscaling**

3.1 What are the most important environmental controls on organic matter turnover, GHG and BVOC emissions, N\(_2\) fixation and other important ecosystem processes? Existing plot-scale observations from Greenland (CENPERM sites 2012-2017) and other sites beyond Greenland (Canada, Svalbard, Scandinavia) will be gathered, quality tested and analyzed for use in the modeling exercises described below (as forcing data, model parameters and data for calibration and validation). Structural Equation Modeling (SEM)\(^4\) will be used as a method to represent the relationship between the latent variables of interest, and their manifest or observable indicators. At our sites, interacting variables include not only temperature and water content, but also indirect climate drivers such as subsurface gas concentrations, soil water nutrients, litter fall, root growth etc.
3.2 What are, based on remotely sensed data, the trends in vegetation, land surface characteristics and permafrost indicators for Greenland over the last decades? Recent studies have shown differing trends for arctic and Greenlandic vegetation. Remotely sensed land surface properties (NDVI, vegetation classification, albedo, snow, water and ice content) will be collected and analyzed to determine variability and trends over recent decades. Sentinel-2, offering publically available data, will be used for high spatial resolution land surface classifications and detection of changes, including vegetation analysis, biomass and foliar nitrogen content. In combination with Landsat TM data, this allows for analyses reaching back to the 1980's. Frequent data from MODIS and Sentinel-3 will be used to assess changes in surface- and low altitude air temperatures (and derived products such as soil moisture and permafrost vulnerability assessment). Snow water equivalents and soil moisture will be assessed indirectly using Synthetic Aperture Radar (SAR) and indirectly using a combination of optical data from and energy balance modeling. Large scale elevation changes acquired from e.g. the ICESAT-2 satellite can potentially be used in a study linking permafrost freeze/thaw processes and melt water runoff to seasonal changes in surface elevation. Unmanned Aerial Vehicles (UAVs) will be used to generate detailed surface elevation and classification models. Linking remotely sensed products with high spectral resolution, temporal frequency and high spatial resolution allows scaling from plot to landscape and regional scales.

Permafrost and landscape modeling

3.3 How is the ground thermal regime and permafrost thawing affected by climate changes and how important is the lateral transport of heat and water for thawing permafrost in highly heterogeneous and sloped terrain? Ground thermal regimes and energy budgets will be simulated with the numerical process-oriented CoupModel, which has successfully been applied to simulate permafrost-affected ecosystems. Currently, testing for multiple sites in Greenland is ongoing, using a pseudo-two-dimensional structure allowing for a lateral flow of water and energy. CENPERM is now co-hosting the code and is involved in the future development in close collaboration with the main developer of the CoupModel platform (P-E Jansson). The energy and hydrological balance and element fluxes across the landscape will further be assessed by measuring surface and ground properties, snow redistribution and snow melt, soil water content and concentrations of inorganic/organic C and N and other elements. In collaboration with USGS (US Geological Survey, C Voss), the state of the art water-flow and permafrost model (SUTRA 4.4; SUTRA ICE) will be combined with the snow model, which has already been used at CENPERM to simulate current and future water and element fluxes. This will allow quantitative measurements of the effect of permafrost thawing on water and dissolved nutrient fluxes within the individual landscape units as well as downslope transfers between units now and in the future.

3.4 How does permafrost occurrence and vulnerability vary over the major gradients (from North to South, from ice sheet to the coast, from mountain top to valley bottom) in the Greenlandic landscape? Modeling of soil thermal dynamics and permafrost at plot and regional scales will aim to capture these gradients, and will allow Greenland to be placed in a circumpolar context in terms of energy fluxes and permafrost vulnerability. The South-West section of Greenland (South Greenland to Disko) will be assessed using the GIPL-2.1 model in collaboration with Permafrost Lab, University of Alaska, Fairbanks (V Romanovsky). The North-East section of Greenland (Zackenberg to Peary Land) will be assessed using the CryoGrid 2 model in collaboration with Oslo University (S Westermann), extending earlier plot-level simulations from Zackenberg. In both cases, regional climate data from the HIRHAM5 model will be applied as forcing.
**Ecosystem modeling** This component includes biogeochemical processes and vegetation dynamics at a range of scales in order to integrate the laboratory and field measurements to large-scale estimates.

3.5 How are landscape-scale variations in biogeochemical processes determined by variations in substrate concentrations and environmental drivers? Landscape elements in the Arctic respond differently to variations and trends in climatic drivers, and capturing these differences has proven to be important to the overall GHG balance. As a first step towards quantifying biogeochemical cycles at landscape and regional scales, we will apply a conceptual box modeling approach representing individual processes of interest, including root growth, photosynthesis, BVOC emissions, CH₄ uptake, and N₂ fixation. These conceptual models will be parameterized and evaluated based on laboratory measurements. The models will subsequently be used to assess variations within plots, between plots or within the landscape (including the role of hotspots) by forcing them with observed (3.1-3.2) or simulated (3.3-3.4) plot-scale or landscape-scale variations in substrate concentrations and environmental drivers. Model descriptions and parameterizations for these specific processes can be compared with the relationships obtained from Structural Equation Modeling and can subsequently be used in the larger-scale biogeochemical models described below.

3.6 How important are interactions between the physical environment and biogeochemical processes for capturing future dynamics? New feedback mechanisms will be built into CoupModel (linked to microbial heat production, soil type specific thermal regimes, contrasting C pools in permafrost and active layers, and feedback linked to the N cycle) in order to predict depth-integrated GHG production and consumption from seasonal scale to decadal scales. Specific tasks include: (1) to simulate observed subsurface gas concentrations and to quantify controls on microbial activity and gas transport in the growing season as well as during shoulder seasons; (2) to use multi-year measurements to provide more robust estimates of C turnover for decades across sites; (3) to assess the importance of thermal properties and water/ice content on permafrost thermal regimes and vulnerability of permafrost thawing; and (4) to explore and simulate interacting exchange of GHGs and BVOCs as well as to model treatment effects (1.1) and use sensitivity functions to project net ecosystem responses.

3.7 What is the role of plant uptake of nitrogen for ecosystem-scale carbon-nitrogen interactions? The CoupModel will be applied to study the interactions between the elemental cycles of C and N, and addresses the uptake of inorganic N and root dynamics. It will be extended to simulate the uptake of small molecular amino acids and the role of mycorrhiza, and will be used to address (1) the importance of (summer and winter) warming and snow addition on N availability; (2) the potential priming effects on soil C and N turnover; and (3) the difference in inorganic and organic N pools within and between vegetation and soil types.

3.8 What is the role of regional vegetation changes for future GHG dynamics? Simulation of regional (Greenland) and circumpolar impacts of climate change on biogeochemistry will be performed with the dynamic vegetation model LPJ-GUESS. A novel approach will be developed to capture landscape heterogeneity in vegetation models using probability density functions with the help of the conceptual model framework (3.5) and remote sensing products (3.2). This will enable us to quantify the impact of hotspots in the landscape for emissions of GHGs and BVOCs and to couple C and N turnover. The model will be applied to study the impact of climate change on greenhouse and trace gas emissions with the help of historical climate data for the 20th century (hindcasting) and Representative Concentration Pathways (RCPs) for the 21st century (forecasting), and by applying forcing data from regional (HIRHAM) and global (selected GCMs from the CMIP5 set) climate models.
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